JWST

User Documentation for Cycle 1:

Proposal Preparation

This PDF was last updated on January 23, 2020.
For the most current information, visit
https://jwst-docs.stsci.edu
and use on-line documentation.

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The NASA James Webb Space Telescope, developed in partnership with ESA and CSA, is operated by AURA's Space Telescope Science Institute.

Getting Started Guide

A general guide to getting started with planning JWST observations. See method-specific roadmaps for more detailed information about individual observing modes.

On this page

The steps below suggest a general workflow, but depending on your science goals and background, the steps and order may vary.

Know the deadlines

The Cycle 1 GO/AR proposal deadline is **8 pm Eastern Time May 1 2020**

Other deadlines and science policies can be found in the JWST Call for Proposals for Cycle 1.

Become familiar with JWST capabilities, terminology, and documentation

1. Become familiar with JWST Documentation (JDox). Consider starting with an overview on the Observatory and the four instruments: Mid Infrared Instrument (MIRI), Near Infrared Camera (NIRCam), Near Infrared Spectrograph (NIRSpec), and Near Infrared Imager and Slitless Spectrograph (NIRISS).

2. Learn about MULTIACCUM detector readouts to understand how to specify the exposure time for your JWST observation.

3. Perform a quick feasibility check with the JWST Interactive Sensitivity Tool (JIST).

4. Familiarize yourself with the many tools available to you when writing your proposal, including, but not limited to, the Exposure Time Calculator, the Astronomer's Proposal Tool, JWST Target Visibility Tools, WebbPSF, and the Background Modeler.

5. Identify instrument(s) and observing mode(s) you need to address your science goals. The observing methods and roadmaps summarize JWST observing capabilities and step-by-step observing guides. You can compare and contrast the unique observing modes from each instrument that support these different types of observations.

6. Familiarize yourself with the documentation for your chosen instrument mode, paying particular attention to things such as:
   a. whether operations such as dithering, target acquisition, mosaicking, etc., are required, encouraged, or not permitted for that mode;
   b. whether you should consider using a subarray for your observations;
   c. whether your chosen mode is multi-phase, e.g., the NIRSpec multi-object spectroscopy mode may require NIRCam pre-imaging to obtain high quality astrometry for your target list.

7. Read the JWST Recommended Observing Strategies for your chosen instrument mode for advice on which observing parameters to pick to optimize your science program.

8. Read through an example science program for your chosen instrument mode (if available) to see a complete overview of the proposal planning process, including how to construct an exposure time calculator (ETC) workbook and complete an Astronomers Proposal Tool (APT) observing template.

Determine if your targets can be observed

The entire sky is available to JWST observations over the course of a year, but only approximately 40% is accessible at any given time. Targets that need to be observed at a particular time, time separation, or aperture position angle on the sky may have significantly constrained visibility or may even be unschedulable. There is a simple tool to perform a quick assessment of schedulability of proposal targets prior to developing an APT proposal. Much of this is already integrated into APT, so accessing the separate tool may be unnecessary for most users. There are more specialized tools to help users plan coronagraphy observations and Pre-imaging observations for NIRSpec MOS mode, and there is also a tool to compute and visualize the background levels versus date for a given target.

1. Check whether your target(s) is already planned to be observed. Duplicate observations are allowed only under certain circumstances.

2. If there is a specific timing window or position angle needed for your target, use the Visibility Checker to ensure that the target is visible by JWST during that window.

3. Use the JWST Interactive Sensitivity Tool (JIST) for an *estimate* of the signal-to-noise value for a given source flux density and exposure time for your chosen instrument observing mode(s).

4. If you are planning to observe particularly faint targets, assess whether your observations will be background limited. The Backgrounds Tool will be helpful for visualizing how the background changes over time and how significantly the target visibility is constrained by this.

Use the Exposure Time Calculator to determine observing parameters

1. The Exposure Time Calculator (ETC) should be used to determine the appropriate exposure parameters (e.g., ***READOUT PATTERN*** and ***NUMBER OF GROUPS***, ***INTEGRATIONS***, and ***EXPOSURES***) needed to achieve the desired signal-to-noise ratio for your target. Video tutorials and a new user guide for the ETC are available to help you get started with the ETC.

2. Define your source(s) and scene(s) in the ETC.

3. Select an instrument and observing mode in the ETC.

4. Select instrument parameters within the instrument configuration pane on the ETC calculation page.

5. Run an ETC calculation on your defined scene.

6. Adjust the exposure time via the ***NUMBER OF GROUPS***, ***INTEGRATIONS***, and/or ***EXPOSURES*** until you obtain your desired signal-to-noise ratio (SNR):
    a. The instrument-specific observing strategies provide recommendations for how to split exposure time into ***NUMBER OF GROUPS***, ***INTEGRATIONS***, and ***EXPOSURES***, based on *observing mode*, *science use case*, *avoiding saturation*, and *minimizing cosmic ray* hits on the detector.
    b. ETC batch expansion is an efficient way to determine the SNR for a range of possible values for a given exposure parameter.

Prepare your proposal in the Astronomers' Proposal Tool

1. The Astronomers' Proposal Tool (APT) is used to set up your observing program and submit your proposal. Training examples and video tutorials are available to help you get started.

2. Fill out your proposal information in APT, e.g., ***Title***, ***Abstract, Proposal Category***, ***Science Keywords***, etc.

3. Enter your proposed target(s) (or ***OFFSET*** targets if required for your observing case). Note: for the special case of the NIRSpec multi-object spectroscopy mode, targets are not input directly, but are created by the NIRSpec MSA Planning Tool (MPT). If using this ***OBSERVING MODE***, make sure to read the extensive MPT documentation.

4. Define your observing parameters in the APT Observation Template(s) relevant for your chosen instrument (s) and ***OBSERVING MODE***(***s***). Here you would enter the exposure specifications (i.e., ***NUMBER OF GROUPS***, ***INTEGRATIONS***, and ***EXPOSURES***) that you determined via the ETC. If desired, add cross references to your relevant ETC workbook in the "ETC ***wkbk. calc***" field (strongly recommended if your program requires a target acquisition).

5. Make sure to define any special requirements (e.g., timing constraints, moving target, background limited observation).

6. View an Observation with the Aladin visualizer tool.

7. Run the Visit Planner to ensure your observations are schedulable, and resolve any errors.

8. Run Smart Accounting to determine whether overheads associated with your program can be minimized.

9. In some cases it may not be possible to fully specify a proposal at the time of submission (e.g. to resolve all errors and warnings in APT). Proposals that may be exempted from the nominal single-stream process will be described in the special submission requirements section of each call for proposals.

Write your science proposal

1. Create the PDF attachment of the proposal narrative, which includes a number of required text sections such as the Scientific Justification and Technical Justification. As a reminder, the JWST proposal review will follow a dual anonymous process, and proposals must conform with the guidelines presented in the Call for Proposals.

Submit your JWST proposal

1. Attach the PDF of your science justification to your APT template.

2. Preview the entire proposal by selecting the APT PDF Preview tool. This view will merge the information provided in APT along with the PDF attachment, and is what the Telescope Allocation Committee (TAC) will

review.

3. Submit your completed proposal with APT. Select the APT **Submission Tool** in the top tool bar and follow the instructions. In the **Submission Log** window you will see a message giving the time of the submission, the assigned proposal ID (if a new proposal), and the submission status.

4. After the initial submission, proposals can be re-submitted as needed (up to the stated deadline). Resubmitting does not change the proposal number received upon the initial submission.

Wait

After you submit your proposal, all investigators will receive an automatic email acknowledgment that the submission was received successfully. If you do not receive that email within minutes of your submission, please check the APT Submission Log Window for a problem. In addition, all investigators will receive an additional email indicating whether your proposal was successfully processed after the submission deadline. If you do not receive this acknowledgement within **72 hours** of the deadline, please submit an incident to the JWST Help Desk, as your submission was **NOT RECEIVED** and the TAC **WILL NOT** see your proposal; please provide the submission ID information from the APT Submission Log window. If there are any problems associated with your PDF attachment or APT information submitted, you will be contacted by email separately.

Notification of your proposal's status (approved or rejected) generally occurs within ~4 weeks of the Telescope Allocation Committee meeting.

Next steps for approved programs

U.S. investigators with approved JWST programs are eligible for funding. See JWST Cycle 1 Proposal Policies and Funding Support for further details.

Successful JWST observing proposals will be reviewed by a STScI instrument scientist and program coordinator. Programs may require adjustments or revisions after the award. Proposers should submit programs that are executable, but STScI expects iterative optimization between the institute and the PI of accepted Cycle 1 programs. The Instrument Scientist and Program Coordinator will iterate with proposers to finalize the observations in accordance with the TAC recommendations, under the approval of the STScI Director.

Links

JWST Help Desk

JWST WebbPSF Documentation

Instructions for Downloading WebbPSF

Published	02 Mar 2017
Latest updates	

Understanding Exposure Times

All JWST detectors integrate using a non-destructive up-the-ramp sampling technique. The exposure time is determined from the users's selection of a readout pattern and specification of the number of groups and number of integrations to use.

On this page

Introduction

See also: MIRI Detector Overview, NIRCam Detector Overview, NIRISS Detector Overview, NIRSpec Detectors

The infrared-sensitive detectors in JWST science instruments operate very differently from the CCDs that many astronomers are familiar with from ground-based work or HST's ACS and WFC3/UVIS. These IR detectors, similar to those in the Spitzer Space Telescope instruments and HST WFC3/IR, are read out using a non-destructive up-the-ramp readout technique that provides a number of advantages.

But arriving at an exposure time is not as simple as requesting a total time. Rather, the exposure time is derived from the selection of a *readout pattern* and specifying two other parameters, the *number of groups* and the *number of integrations* to include in the exposure. These are the parameters values that are available in the Exposure Time Calculator (ETC) and the Astronomers Proposal Tool (APT) for specifying exposures.

For NIRSpec, NIRCam, and NIRISS, users will select readout patterns from a menu of available options that are optimized for different types of targets. For science targets, MIRI users have two options for readout. See the specific detector articles listed above for more information.

How up-the-ramp readouts work

The up-the-ramp readout (sometimes referred to as MULTIACCUM) is the standardized readout sampling for all JWST detectors. In this readout mode, the array is read out non-destructively at intervals defined by the parameters described below during the exposure. Multiple non-destructive *frames* can be averaged by the onboard flight software into a *group* and transferred to the solid-state recorder for downlinking to the ground. This can be an effective way to reduce the total data volume that needs to be downlinked and mitigate concerns about saturation.

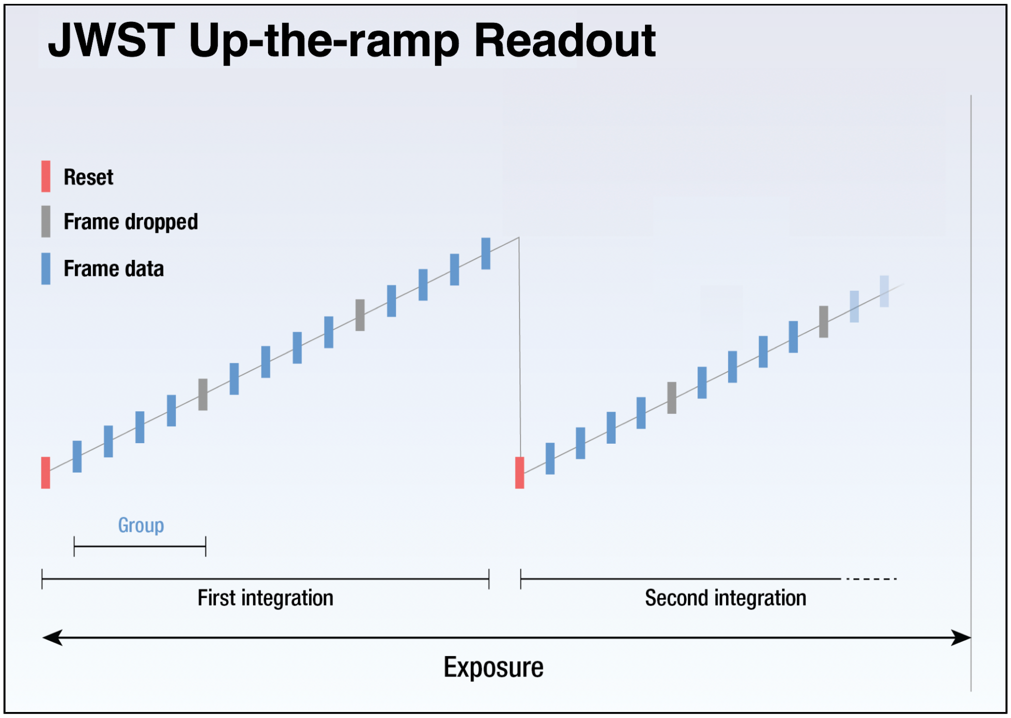
Ground-based data processing software can also correct bias drifts using reference pixels, and use up-the-ramp processing algorithms to reject cosmic rays. This approach is quite flexible since it allows for a large range of readout patterns. The instrument teams have pre-selected a relatively small set of optimal patterns for use in making observations on orbit.

Figure 1 illustrates the components of each up-the- ramp exposure:

1. N_{frames} is the number of frames per group.
2. N_{groups} is the number of groups per integration.
3. N_{int} is the number of integrations per exposure.

Note that you do not explicitly select a value of N_{frames}, but rather this parameter is encoded in the definition of the various readout pattern options that can be selected. The specifics available for each instrument and readout mode, however, can vary. Proposers should refer to specific instrument detector pages for details.

Figure 1. Generic up-the-ramp (MULTIACCUM) readout scheme for each exposure.



A general illustration of the up-the-ramp readout scheme used by all JWST Near-IR detectors. Each exposure consists of some combination of frames, groups, and integrations. The frames are not selected directly, but encoded into the selected readout pattern chosen by the user. Note that Mid-IR detectors do not have a reset between integrations, but operate on a read-reset scheme. Also, the MIR detectors do not drop any frames.

Choosing Parameters

See also: JWST Recommended Observing Strategies

Given the variables in play, there are multiple combinations of parameters that will result in the same reported exposure time. So how does one choose? There are no hard and fast rules to be applied to all cases. However, here are some guidelines to consider. The detailed instrument strategy articles may be helpful for specific cases.

For a given integration time, a larger number of N_{groups} is nominally preferred, primarily to mitigate cosmic rays. However, each saved frame contributes to the total data volume, so observers may want to consider a readout pattern that reduces N_{groups} while still preserving total integration time.

Adding multiple integrations to an exposure will also increase the exposure time. Breaking exposures into multiple integrations ($N_{int} > 1$) will be most useful for bright sources that would saturate in longer integrations. For faint source observations, $N_{int} = 1$ (or at least a low number) may be preferred for each exposure.

Finally, recall that it is recommended that most datasets obtained with JWST instruments be dithered. Each selected dither position is a separate exposure, so the total exposure time you will get depends on the number of dither steps you specify. You should note that by default the Exposure Time Calculator is providing information on individual exposures, so you can specify the number of exposures to estimate the impact of multiple dither positions.

Published	02 Mar 2017
Latest updates	• 09 Jan 2020 Final minor text modifications for 2020 Cycle 1. • 16 Sep 2019 Revised description with more focus on user experience and additional descriptive material.

Methods and Roadmaps

Articles on the methods and intricacies of space-based infrared observing with JWST are available to provide guidance for creating sound observing programs. These include example science programs and recommended observing strategies.

Expand all Expand all Collapse all Collapse all

Published	15 May 2017
Latest updates	

JWST Imaging

Several JWST instruments have imaging capabilities, covering different fields of view and wavelengths.

On this page

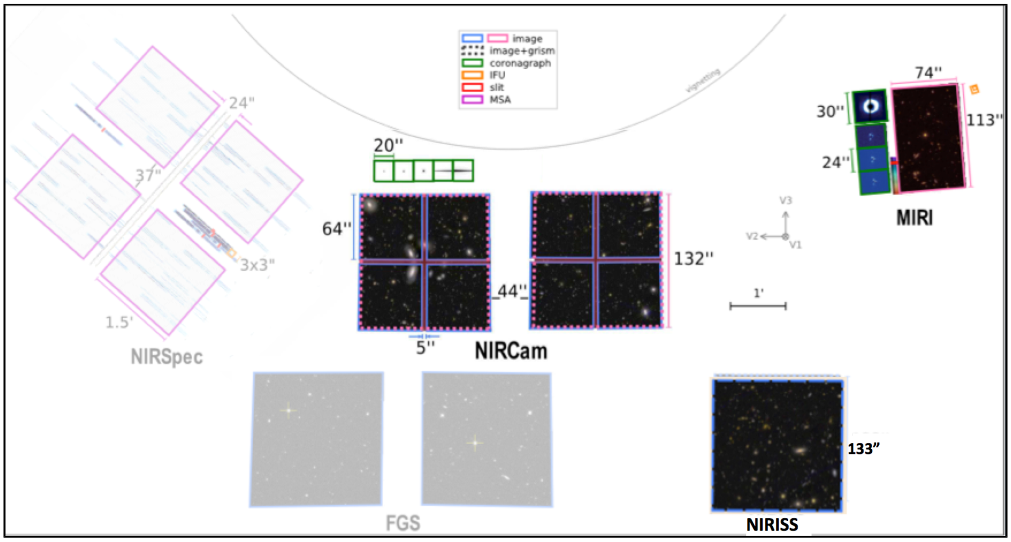
Standard imaging overview

Main articles: MIRI Imaging, NIRCam Imaging, NIRISS Imaging
See also: JWST Mosaic Overview, JWST Dithering Overview
See also: Imaging Roadmap

MIRI, NIRCam, and NIRISS are the imaging instruments on JWST. The wavelength ranges and available modes of use are summarized in Table 1. The "main article" links above connect you to the details for each instrument. Note that NIRISS imaging is only offered as a parallel observing mode. Figure 1 shows the relative positions of these imaging fields of view in the JWST focal plane.

In addition, an Imaging Roadmap article is available for planning imaging observations. If you plan to use imaging in coordinated parallel mode, see the Coordinated Parallels Roadmap.

Figure 1. Imager fields of view in the JWST focal plane



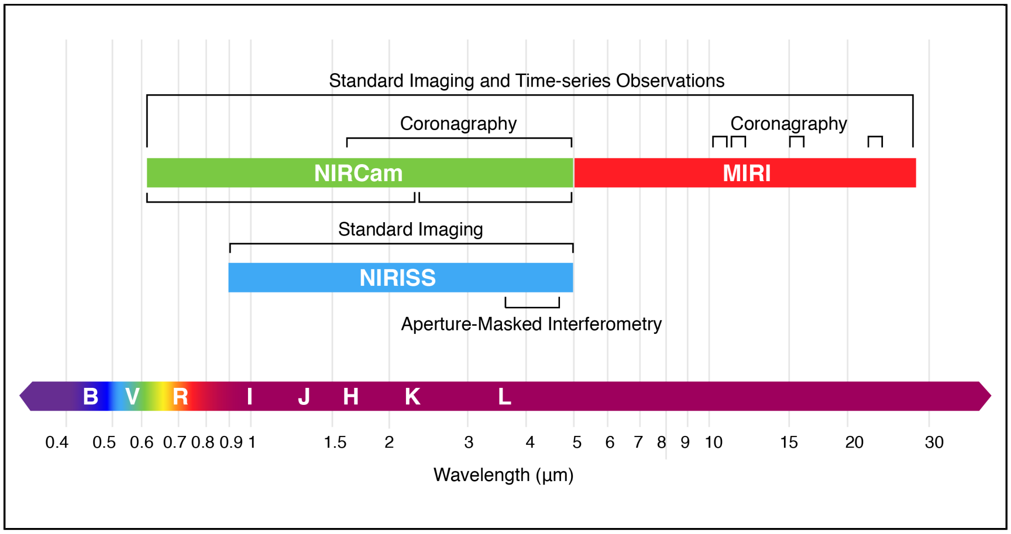
The 3 imaging instruments (NIRCam, NIRISS, and MIRI) are highlighted here in the JWST focal plane. FGS indicates the Fine Guidance Sensor fields of view, used for guiding.

Table 1. Summary of JWST's standard imaging capabilities

Instrument	Wavelength range	Mode of use
NIRCam	0.6 µm < λ < 5 µm	Primary or parallel
MIRI	5.6 µm < λ < 25.5 µm	Primary or parallel
NIRISS	0.8 µm < λ < 5 µm	Parallel only

For convenience, Figure 2 provides a visual representation of the relative wavelength coverage. JWST time-series observations (TSO) and high-contrast imaging (HCI) also use the imagers and are shown for completeness. However, they involve specialized operations that are described elsewhere in JDox.

Figure 2. Summary of JWST's imaging capabilitities



Wavelength coverage of each instrument, highlighting different imaging capabilities. Note that standard imaging with NIRISS is allowed in parallel mode only.

NIRCam provides imaging in 2 wavelength ranges simultaneously over the same 9.7 arcmin² field of view (via a dichroic): 0.6–2.3 µm (0.031"/pix) and 2.4–5.0 µm (0.063"/pix). It uses 2 near-identical side-by-side modules, separated by a 44" gap. NIRCam's short wavelength channel also has small 4"–5" gaps between detectors.

MIRI offers imaging at a complementary wavelength range, from 5.6 to 25.5 µm over a 3.1 arcmin² field of view, and has a detector plate scale of 0.11"/pixel.

NIRISS offers 0.8–5.0 µm (0.065"/pix) imaging in a 4.84 arcmin² field of view and many of its filters are essentially identical counterparts to the NIRCam filters. Consequently, NIRCam and NIRISS can be used in parallel to increase the sky coverage at a particular wavelength. *NIRISS imaging is not offered as a primary mode.*

All the standard imaging modes offer a mosaicking capability for observing larger areas. Dithering is also recommended for imaging to improve data quality.

Imaging spatial resolution

Details about the point spread function (PSF) FWHMs for each instrument are summarized in Table 2. More information is available in these articles:

- NIRCam Point Spread Functions
- Near Infrared Imager and Slitless Spectrograph (Table 1)
- MIRI Point Spread Functions

Table 2. Information on imaging spatial resolution

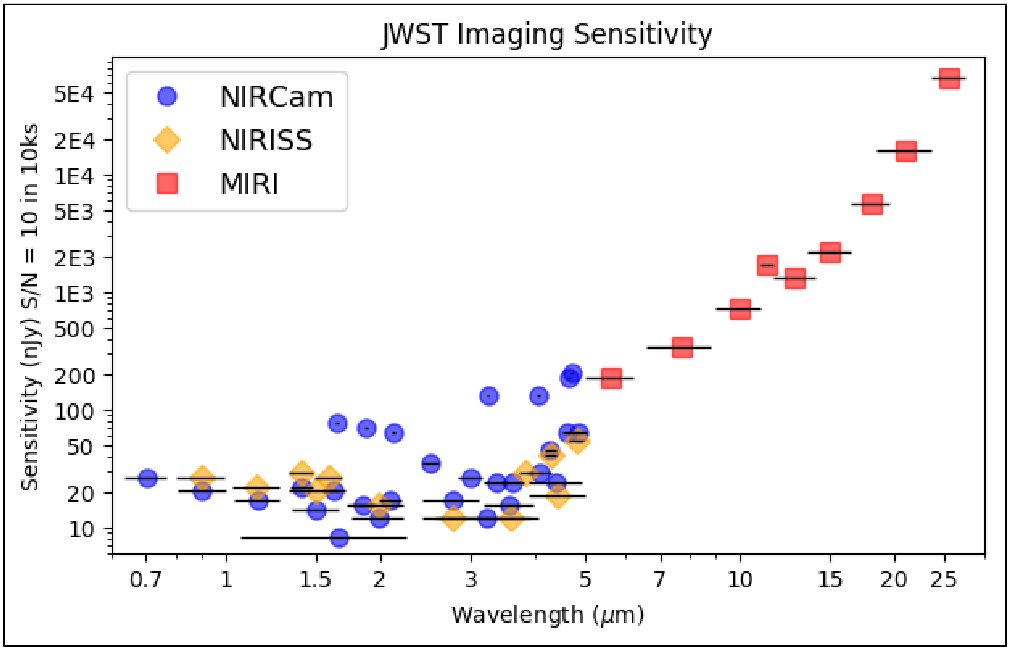
	PSF FWHM (pix)	Plate scale	Nyquist sampled
NIRCam	0.987–2.341 (SW) 1.340–2.574 (LW)	0.031 (SW) 0.063 (LW)	>2 µm (SW) >4 µm (LW)
NIRISS	2 pix @ 3.4 µm	0.066	>3.4 µm
MIRI	1.00–7.45	0.11	>6 µm

Imaging sensitivities

Main articles: NIRCam Imaging Sensitivity, NIRISS Sensitivity, MIRI Sensitivity
See also: NIRCam Detector Readout Patterns, MIRI Detector Readout Overview, NIRISS Detector Readout Patterns, JWST ETC

The sensitivity of each JWST imaging filter is summarized in Figure 3. The JWST Exposure Time Calculator (ETC) was used to estimate the signal to noise (S/N), with readout patterns chosen to reach approximately 10 ks in each instrument and using a benchmark background, as described in the JWST Background Model article. Also, consider using the JWST Interactive Sensitivity Tool to explore the relevant parameter space for the various imagers.

Figure 3. JWST imaging sensitivity



The S/N = 10 detection limits of JWST's imaging instruments in 10 ks, shown for every available filter. The horizontal error bars represent the width of the filter. Sources are assumed to have a flat spectrum in nJy and a benchmark background, as described on the [JWST Background Model](#) article. Please use the [JWST Exposure Time Calculator (ETC)](#) to calculate sensitivity estimates for your specific proposed observations.

Published	29 Nov 2017
Latest updates	• 13 Nov 2019 Revised and streamlined information for support of Cycle 1. • 26 Apr 2019 Updated links, including to the new imaging Roadmap article. Simplified and clarified text.

Imaging Roadmap

A roadmap to guide users, step-by-step, through the process of designing a JWST imaging observing program using NIRCam or MIRI.

On this page

Main article: JWST Imaging

Each step listed below is followed by a list of articles with additional details.

Preliminary considerations

Note: NIRISS imaging is only offered for coordinated parallel observations. For this reason NIRISS links below are shown in parentheses.

1. Choose the instrument(s) suitable for your science based on needed wavelength coverage. NIRISS imaging may be obtained in parallel with NIRCam, offering sensitivity and wavelengths similar to NIRCam and extending the spatial coverage to a nearby area.

   NIRCam Imaging (0.6–5.0 μm), NIRCam Imaging Recommended Strategies
   MIRI Imaging (5.6–25.5 μm), MIRI Imaging Recommended Strategies
   (NIRISS Imaging (0.8–5.0 μm), NIRISS Imaging Recommended Strategies)

2. Decide on whether you will observe with multiple instruments simultaneously.
   Coordinated Parallel Observations

3. Consider using the quick-look JWST Interactive Sensitivity Tool (JIST) to obtain a sense of the signal-to-noise and exposure time parameter space you may require for your target(s).

   Work through the steps below for the primary imaging instrument before adding the coordinated parallel observations, which may be imaging or some other allowed mode.

For each instrument you will use for standard imaging, proceed through the steps below.

Standard imaging

1. Check the feasibility of your observations to achieve your science goals.
   NIRCam Imaging Sensitivity
   MIRI Sensitivity
   (NIRISS Imaging Sensitivity)

2. Select your wavelength coverage and filters.
   NIRCam Filters
   MIRI Filters and Dispersers
   (NIRISS Filters)

3. Consider the areal coverage needed and whether mosaicking of the instrument field of view will be needed.
   NIRCam Mosaics
   MIRI Imaging Mosaics
   APT Simple Mosaic Example
   Use the Aladin viewer in APT to view instrument fields of view on sky images.

4. Based on the brightness of your target, determine whether a subarray is needed to avoid saturation. (Subarrays are not offered for the NIRISS imaging mode.)
   NIRCam Bright Source Limits, NIRCam Detector Subarrays
   MIRI Bright Source Limits, MIRI Detector Subarrays

5. Select a dithering strategy.

   NIRCam Dithers and Mosaics
   MIRI Dithering
   If proposing coordinated parallel observations, consider:
   Coordinated Parallels Custom Dithers

6. For selected instrument(s), calculate the required exposure times using the JWST Exposure Time Calculator (ETC).

   JWST ETC Imaging Aperture Photometry Strategy

7. Fill out the Astronomers Proposal Tool (APT) for your observations.
   NIRCam Imaging APT Template
   MIRI Imaging APT Template
   (NIRISS Imaging APT Template)

8. If adding coordinated parallel observations, now is the time to do that. See the separate Roadmap for coordinated parallels.

Go to the Getting Started Guide to complete the steps for proposal submission.

Published	30 Apr 2019
Latest updates	23 Dec 2019 Reviewed and updated for Cycle 1 release.

JWST Slit Spectroscopy

JWST provides slit spectroscopy in 2 instruments: Near Infrared Spectrograph (NIRSpec) and Mid-Infrared Instrument (MIRI).

On this page

Main articles: MIRI Low Resolution Spectroscopy, NIRSpec Fixed Slits Spectroscopy

Spectroscopic slits are narrow apertures in the optical path designed to allow light only from the intended scientific target onto the detector array. These slits are usually narrow in the dispersion direction, which limits the size of the target in the wavelength direction and improves the spectral resolution. JWST offers spectroscopy in fixed slits in 2 instruments, NIRSpec and MIRI, which generate spectra covering wavelength ranges from 0.6 to 5.3 μm and 5 to ~12 μm, respectively.

Available spectroscopic slits

Main articles: NIRSpec Fixed Slits, MIRI Spectroscopic Elements (LRS)

NIRSpec offers slit spectroscopy in 5 apertures, which are described in detail in NIRSpec Fixed Slits Spectroscopy. MIRI offers slit spectroscopy in a single aperture with the low-resolution spectroscopy mode.

Table 1. NIRSpec and MIRI spectroscopic slits

Instrument	Slit	Size (arcsec)	Size (pixels)
NIRSpec	S200A1, S200A2, (S200B1)	0.2 × 3.2	2 × 32
NIRSpec	S400A1	0.4 × 3.65	4 × 36
NIRSpec	S1600A1	1.6 × 1.6	16 × 16
MIRI	LRS	0.51 × 4.7	5 × 43

The NIRSpec S1600A1 slit is optimized for time-series observations.

Summary of available options

The NIRSpec slits can produce spectra with resolving powers of roughly 100, 1,000, and 2,700. At the lowest resolution, a full spectrum from 0.7 to 2.3 μm can be generated in one grism setting. At the higher resolutions, 4 settings are required for full wavelength coverage.

The LRS on MIRI produces a spectrum from 5 to 12 μm, with spectral resolving power increasing from ~40 at 5 μm to ~200 at 12 μm. The long wavelength cut-off for the LRS is a soft number because the prism transmission decreases rapidly from 10 μm to longer wavelengths while the resolution grows higher. The quality of the flat fields and photometric calibration begins dropping past 10 μm and will not be reliable past 12 μm.

Comparison to ground-based slit spectroscopy

The primary advantage of spectroscopy from JWST is that telluric absorption does not limit the wavelength coverage, making it possible to observe in spectral regions inaccessible from the ground and to obtain continuous spectra from 0.6 μm all the way to the LRS sensitivity cut-off past 12 μm. In addition, since JWST is unaffected by atmospheric turbulence, the spectroscopic slit truncates less of the light from a target and the angular resolution in the cross-dispersion direction is closer to the diffraction limit. Finally, the cold operating temperatures of JWST and the resulting low backgrounds from the telescope leads to much better mid-infrared sensitivity than can be achieved from the ground.

Dithers and nods

> *Main articles: JWST Dithering Overview, NIRSpec Dithers and Nods, NIRSpec FS Dither and Nod Patterns, MIRI LRS Dithering*

Dithering in slit spectroscopy may help mitigate the effects of bad pixels, detector effects, and improve spatial and spectral sampling. In addition, the different pointings can provide background observations around point (or compact) sources. When the step size is relatively large and exposures can be pairwise subtracted, this background removal strategy is typically referred to as *nodding*.

NIRSpec fixed slit spectroscopy offers both nodding with large-scale offsets and subpixel dithering. A variety of options are available for both types of dithers. The user can select either one strategy, or combine both.

The MIRI LRS template offers an ***ALONG SLIT NOD****** option, where the target is placed alternately at 30% and 70% of the slit length (approx. ±0.9" or 8.25 pix from the slit center). A ***MAPPING*** mode is also offered, where the user can define a number of offsets in the spatial and/or spectral direction. These dither types can be combined with mosaic settings to perform a dither pattern at each mosaic pointing position.

For more information, please see these articles:

- JWST Dithering Overview
- NIRSpec FS Dither and Nod Patterns
- MIRI LRS Dithering

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Transmission losses

See also: MIRI Target Acquisition, NIRSpec Target Acquisition

It is inevitable that the spectroscopic slit will truncate some part of the point spread function (PSF), leading to transmission losses in the resulting spectrum. These losses are a function of wavelength because the size of the PSF is a function of wavelength. Transmission losses also depend on the location of the source within the slit, with greater losses closer to the edges of the slit. Given the importance of source placement in the slit, target acquisition is recommended for slit spectroscopy observations.

For JWST, these pointing errors can be expected to be on the order of 7 mas (the precise value of the mean error depends on the distance the telescope moves). Pointing errors on this scale are almost negligible compared to the size of even the smallest fixed slit, 200 mas on NIRSpec. Consequently, it's expected that the transmission function (transmission vs. wavelength) will be almost the same from one spectrum to the next and thus straightforward to correct in the pipeline.

A couple of caveats are important. First, the transmission function for an extended target, even if it is compact, will differ from that for a point source, which could lead to more significant issues, especially if the target is mispointed. Second, mispointings are more likely when an offset source is used for target acquisition. In that case, any errors in relative positions between the source chosen for target acquisition and the scientific source could seriously impact the quality of the spectrum. As an example, even relative positional errors of only 50 mas are halfway from the centerline of the smallest NIRSpec slit to its edge, if the user is unlucky enough for the error to be in that direction. For this reason, target acquisition on the science target is usually the safest option, provided that it is a point source.

Scattered light and saturation

The NIRSpec slits are relatively safe from scattered light because they are in the gap between the 2 halves of the MSA and most of the shutters will be closed.

For the MIRI LRS, on the other hand, contamination from the imager field of view should be considered. During LRS observations, any sources in the imager field will also be dispersed. Because of the broad passband of the LRS prism, these sources will easily saturate in the field. Very bright or saturated sources can cause detector artifacts along rows and columns around the bright source. These can, in principle, cause systematics in the LRS spectrum during slit spectroscopy observations. Very bright sources located in the imager field may also cause some light to scatter into the LRS slit spectral region. If possible, *observers should avoid having very bright sources in the imager portion of the detector field of view whilst exposing with LRS*, in particular in the region immediately adjacent to the slit (this can be checked using the Aladin visualization option in APT). If they find a potentially troublesome source, it may be necessary to constrain the roll angle of the telescope to keep this source off of the imaging array during an integration. The full detector read out will be available to observers, allowing any such sources, if present, to be identified, which can help with data analysis.

Published	29 Nov 2017
Latest updates	• 28 Mar 2018 Updated the along slit nod locations for MIRI LRS dithering

JWST Slit Spectroscopy Roadmap

A roadmap to guide users, step-by-step, through the process of designing a JWST slit spectroscopy observing program using NIRSpec or MIRI.

Each step listed below is followed by a list of articles with additional details.

1. Choose which instrument you wish to use, based on the wavelength range of interest. Roughly, 5 um is the boundary between NIRSpec and MIRI.

2. Choose your method of target acquistion.
NIRSpec Target Acquisition - NIRSpec has three options. In brief, ***None*** is not recommended, and ***WATA*** will generally suffice.
MIRI LRS Slit Target Acquisition - TA is recommended for the LRS slit.

3. Decide if a mosaic or a single slit pointing is desired. See the detailed mosaic guides for more information
NIRSpec FS and IFU Mosaic APT Guide
MIRI LRS Mosaics

4. Decide on the slit(s), subarray(s), grating(s), and filter(s).
NIRSpec Dispersers and Filters- NIRSpec provides many options.
For MIRI, you should choose FULL subarray in the APT to ensure that you observe in the slit. If a spectral resolving power greater than 200 is desired, then the MRS may be a better choice.

5. Choose a dither pattern.
NIRSpec FS Dither and Nod Patterns - NIRSpec offers many patterns.
MIRI LRS Dithering - If observing a compact or point source in the LRS slit, use the standard two-nod dither. If observing a more extended source, place it in the center of the slit (with the MAPPING dither) and use a background observation. See LRS Recommended Strategies and APT Targets - backgrounds for more information.

6. Calculate exposure times, both for TA and for science observation, using the Exposure Time Calculator (ETC). Both NIRSpec and MIRI provide a great deal more information on readout modes:
NIRSpec Detector Readout Modes and Patterns
MIRI Detector Readout Overview

7. Create an APT file. Step-by-step instructions are available for both NIRSpec and the MIRI LRS:
NIRSpec Fixed Slit Spectroscopy APT Template
MIRI LRS APT Template
For questions about the APT not covered by the two links above, see the JWST APT Overview.

Go to the Getting Started Guide to complete the steps for proposal submission.

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JWST Wide Field Slitless Spectroscopy

JWST slitless spectroscopy uses a grism to disperse light from all targets observed in the field. Planning is required to mitigate overlapping spectra.

On this page

Main articles: NIRCam WFSS Recommended Strategies, NIRISS WFSS Recommended Strategies
See also: NIRCam WFSS Science Use Case, NIRISS WFSS Science Use Case

Several of the JWST instruments offer a slitless spectroscopic mode. Slitless spectroscopy is particular in that every source in the field results in a dispersed spectra. This mode differs substantially from regular direct imaging observations and slit spectroscopy. Some of the similarities and differences between imaging and slitless observations that can impact observing strategies and planning are discussed below.

JWST slitless spectroscopic modes

Main articles: NIRCam Wide Field Slitless Spectroscopy, NIRISS Wide Field Slitless Spectroscopy

WFSS mode disperses the light of any object that is within the field of view of the instrument. This often results in hundreds, if not thousands of spectra that often overlap in the final observation. This mode is similar to the HST NICMOS, ACS and WFC3 grism observations. NIRCAM and NIRISS both implement WFSS using two different grisms that disperse the spectra either horizontally or vertically onto the detector. This allows for the dispersed spectra to overlap in completely different manner without having to change the orientation of the whole JWST telescope.

The following table summarizes the WFSS modes of NIRCAM and NIRISS.

Table 1. Summary of WFSS modes in NIRCAM and NIRISS

Instrument	Wavelength (μm)	Pixel scale (mas/pix)	R	Field of view	GRISMs
NIRCam	2.4–5.0	65	~1,600 at 4 microns	2.21' × 2.21'	GRISMR (horizontal) GRISMC (vertical)
NIRISS	0.8–2.2	65	~150 at 1.4 microns	2.2' x 2.2'	GR150C (horizontal) GR150R(vertical)

Similarities to direct imaging

Main articles: NIRCam Imaging, NIRISS Imaging

Slitless spectroscopy consists of inserting a disperser (in most cases a grism) into the optical path of light that would otherwise result in a regular image. All of the JWST slitless modes use the same detector for both direct imaging and slitless spectroscopy. Slitless observations are subject to some of the same limitations as direct imaging observations. Just like imaging data, slitless data will be affected by the background level, bad pixels, and cosmic rays. The consequences of these are dealt with in a similar fashion as direct imaging: observations should be dithered and on-the-ramp-fitting used to mitigate the effects of cosmic rays.

Similarities to slit observations

See also: JWST Slit Spectroscopy

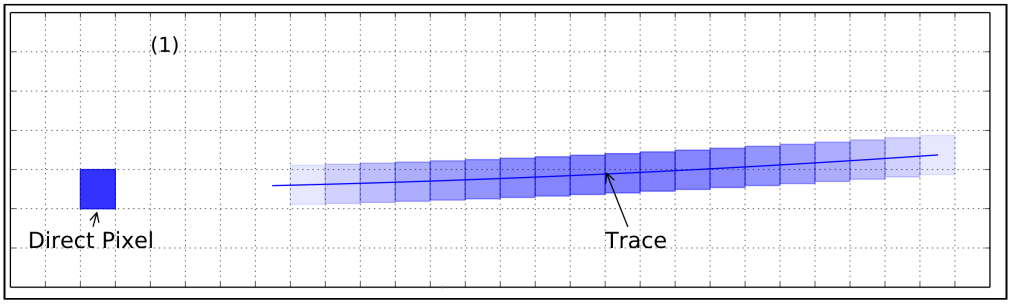
Slit and slitless observations disperse light from an object in a very similar way. In both cases, the trace of the dispersed spectra is determined by the dispersing element, and if more than one object is present in the field or slit, multiple spectra will be generated. Both slit and slitless observations often have more than one dispersed orders, and in both cases the instrument can be designed to disperse spectra horizontally or vertically.

Peculiarities of slitless observations

Slitless spectroscopy however differs from direct imaging in some crucial ways. Since a disperser is inserted into the field of view, the light from every point on the sky is dispersed, resulting in a much larger background level than with slit spectroscopy. Light that would have been incident on a given detector pixel will be dispersed, or spread out as a function of wavelength.

This is illustrated in Figure 1 that shows how light that would normally be incident on a given pixel is instead dispersed onto the detector (defining what is referred to as the "spectral trace," shown by a solid blue line). In this particular example, a spectrum is dispersed in the horizontal direction, as would be the case when observing with the NIRCAM R grism. Some JWST grisms disperse spectra in the vertical direction (such as the NIRCAM C grism, the NIRISS GR150R grism, and the MIRI prisms). Also shown is the effect of the sensitivity variation, as a function of position along the trace (i.e., wavelength), using different shades of blue.

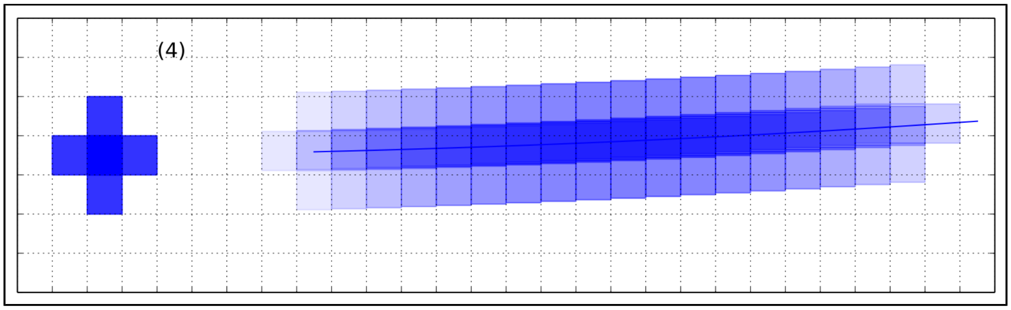
Figure 1. Single dispersed pixel



Spectral confusion and contamination

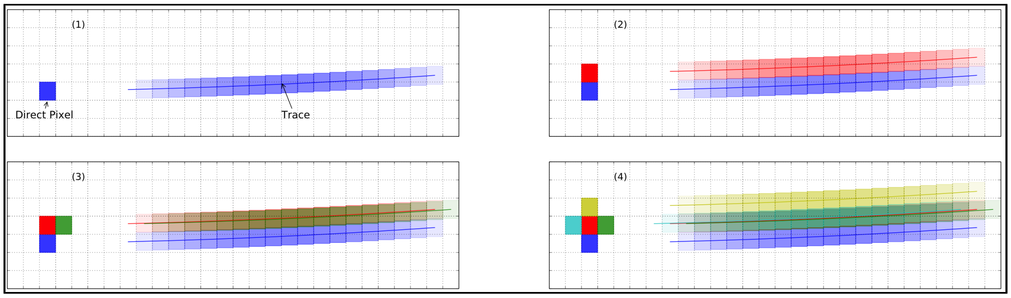
When light from a source that occupies more than one pixel in the direct image is dispersed, light from adjacent pixels can now overlap, smearing and lowering the effective spectral resolution of the slitless spectrum of an extended source. This is illustrated in Figure 2.

Figure 2. Dispersed extended object



If the source exhibits color gradients across the pixels it occupies in the direct image (e.g., an object with different colors in different pixels), then the resulting dispersed spectra from adjacent pixels are combined mainly in the dispersion direction, as shown in Figure 3.

Figure 3. Multiple pixel dispersion and self contamination



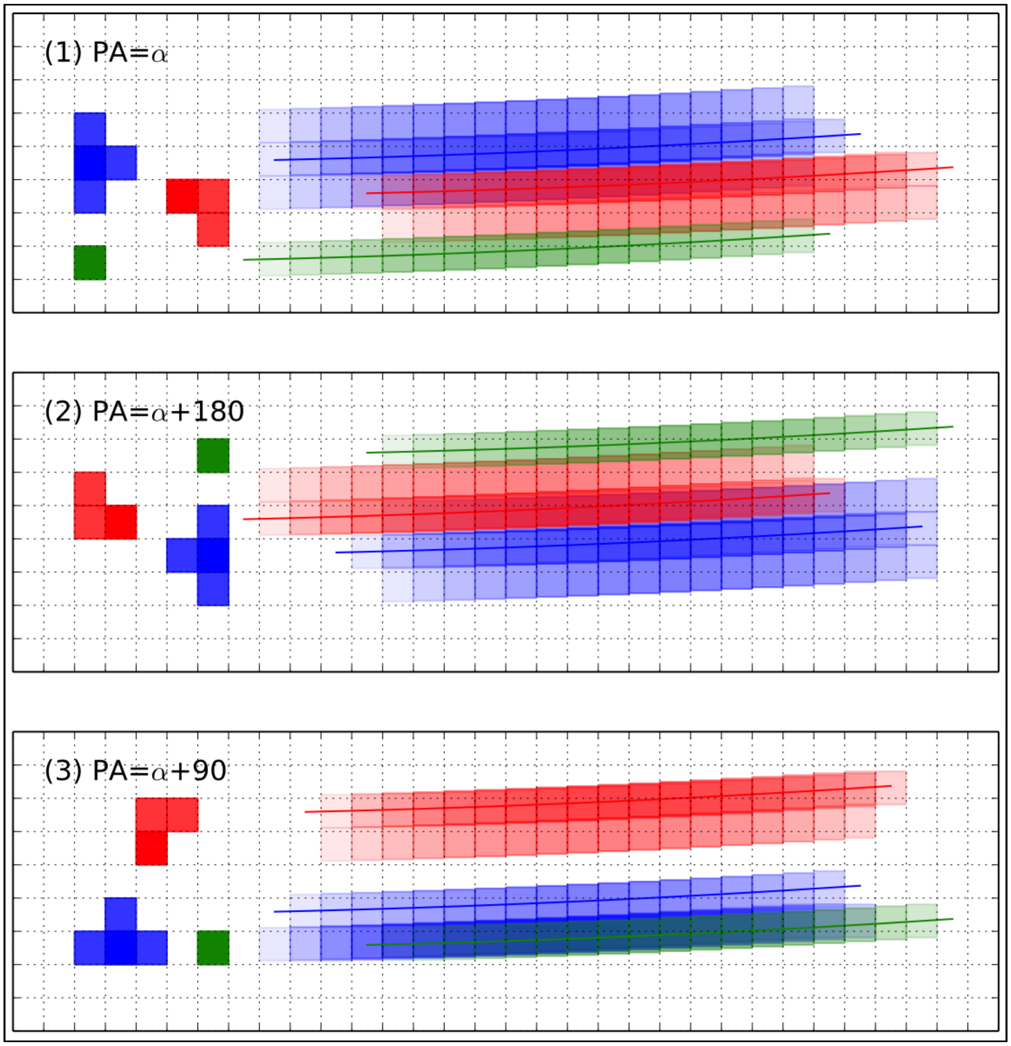
Multiple spectral orders

The discussion above referred to first order spectra. Dispersers have been designed to produce very little light in higher order spectra. Still, one should include these higher orders in contamination estimates. For instance, the repressed second order of a very bright nearby source could negatively affect the first order spectrum of a science target. Determining the impact of second order spectra contamination requires a careful simulation of the observations. For NIRCAM, second order spectra only impact a small number of GRISM+filter combination and this is described in the NIRCAM documentation.

Nearby source contamination

Contamination can also be caused by objects that are visually near a source of interest. Since the light from every object is dispersed in the same direction, overlap can occur. Observing these sources using different position angles on the sky will result in different types of contamination.

Figure 4. Spectral contamination from nearby sources



Background and field of view limits

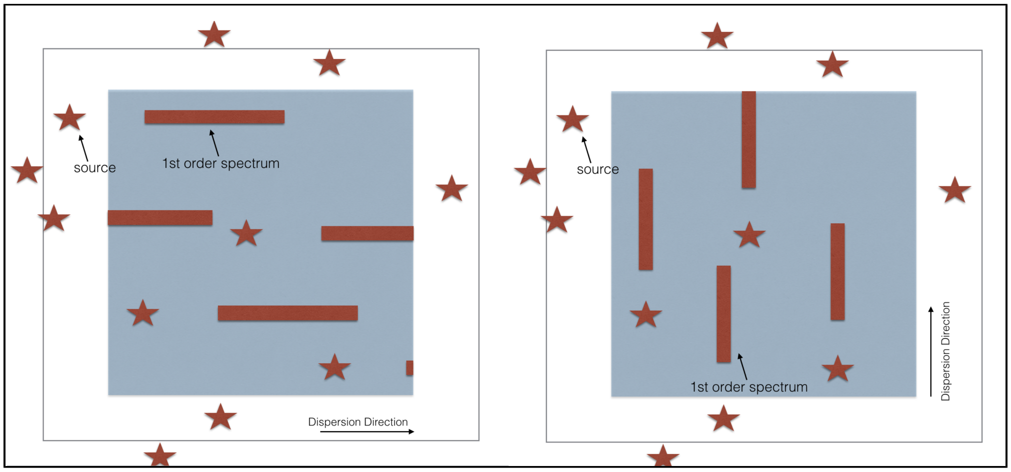
Main articles: NIRCam WFSS Field of View, NIRCam WFSS Backgrounds
See also: NIRISS Mosaics

The background of WFSS slitless observations cannot be expected to be as spatially flat as that of direct imaging. This is because the field of view has a limited size and this results in a deficit of dispersed light on the edges of the slitless observations. If spectra are dispersed nearly horizontally, then the background will be lower on the left and right edges. Similarly, top and bottom edges will be affected when light is dispersed vertically. The strength of this effect is dependent on the size and throughput of the multiple orders of the dispersed spectra.

Additionally, the field of view of the dispersing element is larger than the focal plane array; light from the background as well as objects that are outside of the field of view of a direct image will be dispersed onto the detector.

Figure 5 shows the effect of the field of view limits with instruments performing WFSS (such as NIRCAM and NIRISS), with spectra being dispersed horizontally as well as vertically.

Figure 5. WFSS field of view



Planning observations

> *Main articles: NIRCam WFSS Recommended Strategies, NIRISS WFSS Recommended Strategies*
> *See also: JWST Position Angles, Ranges, and Offsets; NIRCam WFSS Template APT Guide; NIRISS WFSS Template APT Guide*

The combination of the dispersed background and dispersed light from other sources can quickly become a limiting factor when observing faint targets. Contamination can be difficult to estimate, and realistic simulations of slitless data are the only definitive way to plan observations if contamination can be significant or needs to be avoided. This requires prior knowledge of all the sources in (and nearby) the field of view, as well as their approximate spectroscopic characteristics (e.g., continuum slope and intensity). Images obtained using broadband filters are a good way to determine the location as well as the color of each source, providing information that can be folded in when generating simulations.

In cases where contamination needs to be avoided, multiple orientations on the sky can be simulated and the best one can be selected. In the case of JWST, not all position angles are available to an observer at any given time, so careful planning and timing can be required. NIRCAM and NIRISS have two distinct dispersers, allowing for spectra to be dispersed either horizontally or vertically. Combining these observations allows for possible decontamination of the spectra.

Published	09 May 2017
Latest updates	• 27 Aug 2019 Table 1 updated

	• 01 Oct 2019 updated to focus on just WFSS. slitless spectroscopy modes that are used for time series are now represented in the TSO articles.

JWST Wide Field Slitless Spectroscopy Roadmap

A roadmap to guide users, step-by-step, through the process of designing a JWST slitless spectroscopy observing program using the NIRISS and NIRCam wide field slitless spectroscopy (WFSS) modes.

On this page

Example science cases that use the NIRISS WFSS and NIRCam WFSS modes may be found in these articles:
NIRISS WFSS with NIRCam Parallel Imaging of Galaxies in Lensing Clusters
NIRCam WFSS Deep Galaxy Observations

Each step listed below is followed by a list of articles with additional details.

Preliminary Considerations

Spectral wavelength coverage for the science case, and spectral overlap in crowded fields are important considerations when choosing filters and grisms for designing WFSS observations. Make sure to read the recommended strategies to see what options are suitable for the specific science case.

NIRISS WFSS recommended strategies
NIRCam WFSS recommended strategies

The WFSS modes may also be used for coordinated and pure parallel observations. This roadmap only focuses on the use of WFSS for prime observations.

Step-by-Step Guidelines

1. Choose the instrument (NIRISS, NIRCam, or both) to use for the science case, based on the wavelength coverage.
   NIRISS Wide Field Slitless Spectroscopy (0.8–2.2 μm)
   NIRCam Wide Field Slitless Spectroscopy (2.4–5.0 μm)

2. Choose the blocking filters that cover the wavelengths of interest.
   NIRISS Filters

NIRCam Filters

3. Check the the direct image and grism (line and continuum) sensitivities in the WFSS mode(s) and wavelength(s) of interest.
   NIRISS Sensitivity
   NIRCam Sensitivity

4. Choose one or both of the orthogonal grisms. Use of both grisms may be needed to disentangle overlapping spectra in crowded fields as discussed in the recommended strategies articles linked above.
   NIRISS GR150 Grisms
   NIRCam Grisms

5. Decide on the dither pattern required to mitigate detector defects, and achieve the required pixel sampling. NIRISS WFSS mode operates at shorter wavelengths where the PSF is undersampled, so dithering is required.
   NIRISS WFSS Dithers
   NIRCam Wide Field Slitless Spectroscopy Dithers

6. Decide whether mosaicking is required to cover the target field for the science program.
   NIRISS mosaics
   NIRCam mosaics

7. Decide the readout pattern to use.
   NIRISS Detector readout patterns
   NIRCam Detector readout patterns

8. Use the Exposure Time Calculator (ETC) to determine the exposure parameters for the direct images and for the dispersed images from the grisms.
   JWST ETC Imaging Aperture Photometry Strategy
   JWST ETC Aperture Spectral Extraction Strategy

9. Fill out the Astronomers Proposal Tool (APT) for NIRISS WFSS or NIRCam WFSS.
   NIRISS Wide Field Slitless Spectroscopy APT template
   NIRCam Wide Field Slitless Spectroscopy APT template

10. Define mosaic parameters in APT (if needed by science program).
    APT Mosaic Planning

11. Follow the instructions for coordinated parallels if attaching parallels to the WFSS prime observations.
    APT Coordinated Parallel Observations
    Coordinated Parallels Roadmap

Go to the Getting Started Guide to complete the steps for proposal submission.

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Latest updates	

JWST High-Contrast Imaging

High-contrast imaging (HCI) with JWST will allow observers to obtain images of faint sources located near bright point sources

On this page

Main articles: NIRCam Coronagraphic Imaging, MIRI Coronagraphic Imaging, NIRISS Aperture Masking Interferometry, HCI Roadmap
See also: NIRCam Coronagraphic Imaging Recommended Strategies, MIRI Coronagraphic Recommended Strategies and NIRISS AMI Recommended Strategies

High-contrast imaging (HCI) is used to obtain images of faint sources ("companions") located near bright point sources ("hosts"). Typical hosts are stars and quasars. Companions include exoplanets, circumstellar structures of gas and dust, and luminous feeding zones around supermassive black holes. In normal imaging, a faint companion could be swamped and lost in the noise of diffracted light in one of the wings of the host. HCI strategies—comprising special optics, observing procedures, and post-processing—are designed to reduce the impact of host light at the position of the companion, in order to make the companion detectable against the residual noise.

In HCI, the reduction of wing light from the host occurs in two steps: optical cancellation and image subtraction. Optical cancellation is achieved by special optics, using pairs of masks located on the focal and pupil planes. Image subtraction is performed in post-observation processing by differencing a scaled PSF reference image and a science image.

JWST offers 3 HCI designs for optical cancellation: 2 types of coronagraph and one interferometer (see HCI Optics). Subsets of these designs are implemented in NIRCam, MIRI, and NIRISS:

- Lyot coronagraph (LYOT; 5 implementations in NIRCam, one in MIRI)
- 4-quadrant phase mask coronagraph (4QPMC; 3 implementations in MIRI)

- aperture masking interferometer (AMI; one implementation in NIRISS)

The instrument-specific modes for HCI, including allowed mask-filter combinations, are described in:

- NIRCam Coronagraphic Imaging
- MIRI Coronagraphic Imaging
- NIRISS Aperture Masking Interferometry

There are 2 primary performance metrics for HCI: (1) the inner working angle (IWA) and (2) the limiting contrast, $C_{limit}(s)$, which is a function of apparent separation (s).

For more detailed information about JWST HCI options, see the references listed below.

High-contrast imaging articles

JWST User Documentation Home
Acronyms and Abbreviations

Observing modes

MIRI Coronagraphic Imaging
NIRCam Coronagraphic Imaging
NIRISS Aperture Masking Interferometry

Instrument

MIRI Coronagraph Masks
NIRCam Coronagraphic Occulting Masks and Lyot Stops
NIRCam Filters for Coronagraphy
NIRISS Non-Redundant Mask

Detector

Understanding Exposure Times
MIRI Detector Readout Overview
MIRI Detector Subarrays
NIRCam Detector Readout Patterns
NIRCam Detector Subarrays

NIRISS Detector Readout Patterns
NIRISS Detector Subarrays

Operations

MIRI Coronagraphic Imaging Target Acquisition
NIRCam Coronagraphic Imaging Target Acquisition
NIRCam Coronagraphic PSF Estimation
NIRCam Coronagraph Astrometric Confirmation
NIRCam Small Grid Dithers
NIRISS Target Acquisition
NIRISS AMI Dithers

Performance

MIRI Bright Source Limits
MIRI Sensitivity
HCI MIRI Limiting Contrast
NIRCam Point Spread Functions
NIRCam Bright Source Limits
HCI NIRCam Limiting Contrast
NIRCam Sensitivity
NIRISS Bright Limits
NIRISS Sensitivity
HCI NIRISS Limiting Contrast

Recommended strategies

MIRI Observing Strategies
NIRCam Coronagraphic Imaging Recommended Strategies
NIRISS AMI Recommended Strategies

Science use cases

MIRI and NIRCam Coronagraphy of the Beta Pictoris Debris Disk
NIRISS AMI Observations of Extrasolar Planets Around a Host Star

Astronomer's Proposal Tool

JWST Astronomers Proposal Tool Overview
HCI APT Instructions
HCI APT Coronagraphic Sequence Examples
MIRI Coronagraphic Imaging APT Template
NIRCam Coronagraphic Imaging APT Template
NIRISS Aperture Masking Interferometry APT Template
APT Target Acquisition
APT Special Requirements

Exposure Time Calculator

JWST Exposure Time Calculator Overview
HCI ETC Instructions
JWST ETC Coronagraphy Strategy
JWST ETC Target Acquisition
JWST ETC to APT Interface Support Information

Proposing tools

JWST Coronagraphic Visibility Tool Help

References

Beichman, C. A., et al. 2020, *PASP*, 132:1007
Imaging Young Giant Planets from Ground and Space

Beichman, C. A., et al. 2010, *PASP*, 122:162
Imaging Young Giant Planets from Ground and Space

Boccaletti, A. et al. 2015, *PASP*, 127, 633
The Mid-Infrared Instrument for the James Webb Space Telescope, V: Predicted Performance of the MIRI Coronagraphs

Girard, J. et al. 2018, SPIE, 106983V
Making good use of JWST's coronagraphs: tools and strategies from a user's perspective

Greenbaum, A.Z., Pueyo, L., Sivaramakrishnan, A. et al. 2015, *ApJ*, 798, 68
An Image-Plane Algorithm for JWST's Non-Redundant Aperture Mask Data

Published	18 May 2017
Latest updates	

HCI Roadmap

A roadmap to guide users, step-by-step, through the process of designing a JWST high-contrast imaging (HCI) observing program.

On this page

See also: Getting Started Guide

High-contrast imaging (HCI) observations can be some of the most complex to schedule with JWST and for that reason the workflow of this roadmap is considered iterative. When planning HCI observations many parameters come into play and for some science cases, it is not always initially apparent which HCI mode—if at all— will provide you with the best scientific results; users may find themselves returning to earlier steps and/or stages before "linearly" producing their proposal and Astronomer's Proposal Tool (APT) files.

Stage 1 – Become familiar with the HCI capabilities and instrument-specific modes of JWST

In extension to the steps suggested in the Getting Started Guide ("Become familiar with JWST capabilities and terminology"), users should consider the following in particular to high-contrast Imaging:

1. Which of the JWST observing modes enable HCI?

MIRI Coronagraphic Imaging between 10 and 23 µm.

NIRCam Coronagraphic Imaging between 1.8 and 5 µm.

NIRISS Aperture Masking Interferometry enabling high spatial resolution, moderate-contrast imaging between 2.7 and 4.8 μm.
Imaging & IFU Spectroscopy with non-coronagraphic PSF subtraction strategies enabling moderate-contrast imaging[1].

2. What HCI optical designs are offered by JWST?

You should familiarize yourself with the advantages, limitations and functionality of each particular HCI design, as well as which scientific investigations they are optimized for.

HCI Optics:

- Lyot-type Coronagraph: five implementations in NIRCam, one in MIRI.
- Four-quadrant phase-mask coronagraph (4QPMC): three implementations in MIRI.
- Non-redundant mask (NRM): one implementation in NIRISS.

3. What are the allowed mask-filter combinations for each of the HCI modes?

MIRI: focal plane coronagraph masks
: (3x 4QPMs, 1x Lyot spot) each of which images to a different pupil mask and coronagraphic filter combination.

NIRCam: sets of 5x occulting masks
: (3x round, 2 bar-shaped) usable with a subset of permitted filters depending on the selection of mask.

NIRISS: a 7 hexagonal hole
: (generating 21 baselines) Non-Redundant Mask in the pupil plane usable with 4 NIRISS filters to enable AMI mode.

4. What are the primary performance metrics for HCI?

Inner Working Angle (IWA)
Limiting contrast, $C_{limit}(s)$:

HCI MIRI Limiting Contrast
HCI NIRCam Limiting Contrast
HCI NIRISS Limiting Contrast

5. # What are the predicted performances[2] of the instrument-specific modes?

MIRI: achievable IWAs of 0.34–2.16″

(1 λ/D for 4QPMs, 3 λ/D for Lyot) and typical contrasts[2] achieve 10^{-4} to 10^{-5} for separations larger than 0.5″–1″.

NIRCam: achievable IWAs of 0.14–0.89"

(round and bar-shaped occulters optimized for 6 λ/D and 4 λ/D, respectively) and contrasts typically $\sim 10^{-6}$ or better at 1″ IWA and beyond.

NIRISS AMI: achievable IWAs of 0.089–0.15"

(1 λ/D) and contrasts typical contrasts $\sim 10^{-4}$ at separations of ~70–400 mas.

Imaging and IFU Spectroscopy:

(with non-coronagraphic PSF subtraction) achievable contrasts ~ 10^{-3} to 10^{-4} and IWAs somewhere between those of AMI and Coronagraphy for a given filter.

6. # What are the fundamental physical limits for detection?

Photon Noise of the stellar Point Spread Function (PSF):

MIRI Point Spread Functions
NIRCam Point Spread Functions
NIRISS Point Spread Functions

Detector noise:

MIRI Detector Performance
NIRCam Detector Performance
NIRISS Detector Performance

Background Noise (zodiacal light + thermal emission) esp. longward of ~15 μm.

7. # What are the operations unique to HCI?

MIRI Coronagraphic Imaging
 Target Acquisition, HCI Small Grid Dithers
NIRCam Coronagraphic Imaging
 Target Acquisition, Coronagraphic PSF Estimation, Astrometric Confirmation Images, Small Grid Dithers
NIRISS AMI
 Target Acquisition, Dithers (not recommended), and Observing calibrators close in time to the targets.

8. What are the recommended observing strategies pertaining to HCI?

JWST Coronagraphic Sequences
MIRI Coronagraphic Recommended Strategies
NIRCam Coronagraphic Recommended Strategies
NIRISS AMI Recommended Strategies

Stage 2 – Compare your parameter space to the performance limits and capabilities of the HCI observing modes

1. Identify the wavelength range(s) of interest for your intended science. How does this influence (or limit) your choice of science instrument(s), mask(s) and filter(s)?

MIRI coronagraphic imaging:

3x 4QPMs operating with narrow-band filters centered at 10.65, 11.4, and 15.5 µm and 1x Lyot coronagraph working in a broad-band filter centered at 23 µm.

NIRCam coronagraphic imaging:

1x extra-wide, 4x wide-, 10x medium- and 2x narrow-band filters (depending on the selection of coronagraphic mask), in the wavelength range 1.82–5.0 µm.

NIRISS AMI:

in order to enable AMI mode, the NRM will be used in conjunction with one of the 3x medium-band filters centered at 3.8, 4.3 and 4.8 µm (F380M, F430M, F480M) or a wide-band filter centered at 2.77 µm (F277W).

2. Determine the apparent separations, between your host and companion source(s) at the time of observation. Which instrument(s) and mask-filter combination(s) can achieve the required working angles?

HCI Inner Working Angle
Throughput vs. apparent separation for combinations of coronagraphic mask and filter

3. Determine the companion contrast(s) at the wavelength(s) of interest. Are your observations feasible given the contrast limits of the instrument(s)?

Note: when referring to a companion, the term "contrast" corresponds to the ratio of the companion's observed flux to that of its host. An observation is estimated to be feasible if the companion-to-host flux ratio is greater than the "limiting contrast" C_{limit}(s).

> Modeling may be required to extrapolate shorter wavelength measurements to 3 – 23 µm regime for these predictions (e.g. to determine companion contrasts at MIRI wavelengths from far infrared or submillimeter data).

Contrast Considerations for JWST HCI

HCI MIRI Limiting Contrast
HCI NIRCam Limiting Contrast
HCI NIRISS Limiting Contrast

4. ## For coronagraphic observations, how important is the azimuthal coverage around your science target?

MIRI coronagraphic imaging
- with the 4QPMs, the linear boundaries between adjacent quadrants attenuate light, reducing sensitivity in the field along the four edges of the mask.
- with the Lyot coronagraph, the Lyot spot is suspended in the focal plane by two supporting struts in the mounting bracket, which themselves block light in the FOV.

NIRCam coronagraphic imaging
- the round occulting masks provide 360^{o} azimuthal coverage around the bright object.
- the bar occulting masks sacrifice some FOV in the direction along the bar, as a function of azimuth around the bright object.

5. ## Is it possible that your scientific goals can be achieved with non-coronagraphic PSF subtraction?

For moderate contrasts (~ 10^{-3} to 10^{-4}) and/or point source detections well in the background limited regime, it might be wise to opt for one of the standard imaging modes.

JWST Imaging

Stage 3 – Select a PSF calibration strategy

All HCI observations with JWST require the measurement and calibration of stellar point spread functions (PSFs) in some way for post-processing contrast reduction. For any PSF calibration strategy, the observing and data processing techniques are interdependent.

Skip to Interferometry Calibration Strategies ↘

Coronagraphic PSF subtraction strategies

In order to achieve the necessary high-contrast and recover faint sources surrounding the science target, one must calibrate and subtract out the PSF of the central source.

1. **Consider the degrading factors that may limit the PSF calibration and what steps you will take to mitigate them.**

   These include wavefront drifts of the observatory, PSF star color differences, self-subtraction biases (especially for disks), imperfect target acquisitions, line-of-sight jitter and dynamic wavefront error.
   JWST Wavefront Sensing and Control
   PSF Subtraction: the effect of spectral "mismatch"

2. **Which observing technique(s) will you include in your PSF subtraction strategy?**

   Each PSF calibration and subtraction method has a corresponding observing strategy. The imaging techniques are combined with post-processing optimization algorithms (such as LOCI[4] and KLIP[5]) to generate an optimal synthetic reference PSF, to be subtracted from the science target image.

   Will you employ the Referenced Differential Imaging (RDI) technique? — ***Required***

   In this technique, the observation of a nearby star is used to generate an unresolved, high signal-to-noise (SNR) PSF to subtract from the science target.
   ⊖ The RDI technique is sensitive to wavefront drifts and PSF star color differences.

By scheduling the Science and PSF reference observations back-to-back in a sequence, the effect of wavefront drifts should be minimized.

Will you employ the Angular Differential Imaging (ADI) technique? — *Recommended*

In this technique, the science target is observed at two different roll angles and is used as a self-reference for PSF subtraction.

ADI allows for PSF subtraction at nearly the same spacecraft attitude (for wavefront stability) and helps mitigate detector artifacts.

However ADI comes at the cost of self-subtraction biases, especially given the limited available roll (~10deg) of JWST.

For robustness, it is strongly recommended to obtain observations using both RDI and ADI PSF calibration techniques. You can deviate from this plan if desired, but you must explain your alternate PSF subtraction strategy in your proposal.

See the Standard Coronagraphic Sequence.

Will you employ the Small Grid Dithering (SGD) technique? — *Optional*

This technique involves performing sub-pixel dithers of the PSF reference target, to build a mini library of reference images that effectively samples the PSF diversity close to the center of the coronagraphic mask.

The SGD technique can be used to mitigate possible misalignments between science and reference images, reducing the contrast loss from TA (pointing offset) residuals to a negligible level (10x contrast improvement for MIRI, 3-5x improvement for NIRCam)

However, SGDs come at the cost of (5-9x) longer PSF star exposure times.

The SGD technique is optional, and should only be used when the highest quality PSF subtraction is needed.

HCI Small Grid Dithers
NIRCam Small Grid Dithers
JWST Coronagraphic Sequences: Use of the small grid dithering technique

Non-coronagraphic PSF subtraction

Using the same PSF subtraction methods, it is also possible to achieve high performance with non-coronagraphic imaging modes, such as direct imaging in filters that may not have coronagraphs available, or using one of JWST's integral field spectrographs in NIRSpec or MIRI. The contrasts achieved with such modes, even with careful PSF calibration, will not equal the contrasts achieved with the coronagraphs—but even “moderate” contrasts can still offer compelling science capabilities. Such observations are already planned for Cycle 1 by both GTO and ERS teams.

Interferometry Calibration Strategies

For NIRISS AMI, the observations of calibrator stars are used to measure, then remove, instrument systematics. The PSF (or interferogram) produced by the NRM has a narrow central core which is surrounded by an extended skirt created by interference between pairs of apertures. These fringes in the outskirts of the NRM PSF are easily measurable due to their relative brightness and wider angular extent, making instrumental effects easier to calibrate out of science data.

1. Which observing technique(s) will you include in your PSF calibration strategy?

Will you observe a PSF reference calibrator?

The observation of a calibrator star allows for the instrumental systematics (affecting interferometric observables) to be measured. The reference PSF is used to calibrate out the instrumental contributions to closure phases (CP; the sum of three phases around a closed triangle of baselines) and squared visibility amplitudes (SqV), during the third stage in the calibration pipeline (CALWEBB_AMI3).

> Near-contemporaneous acquisition of target and point source calibrator data is desirable, except for very low contrast needs: if contrast limits are not very demanding, a reference star from an unrelated observation, or possibly an analytically generated reference PSF can be used.

AMI-specific treatment of limiting contrast
NIRISS AMI Recommended Strategies

Will you employ the Kernel phase imaging technique?

In this technique, one or more direct images using the CLEARP aperture and the same suite of FW filters as those used for the NRM images are obtained for PSF characterization.

Stage 4 – Assess target visibilities and allowed position angles

The following steps should be used in conjunction with those outlined in the Getting Started Guide ("Determine if your targets can be observed").

1. **Familiarize yourself with JWST position angles, coordinate systems, and related nomenclature to understand the telescope's pointing constraints.**

   JWST Position Angles, Ranges, and Offsets
   JWST Observatory Coordinate System and Field of Regard
   JWST Field of View
   JWST Instrument Ideal Coordinate Systems

2. **Determine the viewing constraints placed on your target(s).**

   JWST Target Viewing Constraints

3. **Using at least one of the JWST target visibility tools, assess your target visibilities and allowed position angles versus time.**

   JWST Target Visibility Tools
   JWST General Target Visibility Tool (for all instrument modes)
   JWST Coronagraphic Visibility Tool (for coronagraphic modes)
   → Synergy between the target visibility tools

4. **In the case of known or expected companions, consider whether your observations require any restrictions on the orientation of the instrument field of view (FOV)/ detector being referenced.**

especially in relation to any instrumental obstructions, such as cross pattern for the MIRI FQPM, bars for NIRCam, or outside of gaps in the uv-pane coverage for NIRISS.

For coronagraphy, the CVT provides visualizations of the focal plane projected onto the sky, which is useful for evaluating the placement and orientation of known science sources on the coronagraphic masks.
Using the CVT: Adding companions to the primary target

- **Determine the aperture position angle(s)/ date(s) at which your companion(s) are nominally visible.**

  JWST Position Angles, Ranges, and Offset

5. **If implementing the ADI technique in your PSF calibration strategy *(during the* *Select a PSF calibration strategy* *stage)*:**
   Check how the instantaneous roll flexibility changes over the the particular visibility period.

This instantaneous roll flexibility is approximately ±5° from nominal, but varies with time and look direction between ±3.5° to ±7°.
JWST Target Viewing Constraints

- ### Assess how potential rolls of the telescope will change the positions of the companion(s) relative to any instrumental obstructions.

  JWST Position Angles, Ranges, and Offsets

6. ### In the case of coronagraphy, consider whether your goals call for a larger roll offset on the science target than can be obtained instantaneously in a single visibility period.

   Certain science cases may require a follow-up at some more substantial angular offset (e.g. 30° offset) relative to the first observations—for instance, to recover part of the scene that may be blocked by the selected mask. In such cases, the observation will have to be scheduled at a significantly later time. Coronagraphic observers will want to assess their potential targets carefully, and when possible, select targets above 45° ecliptic latitude if they require large offsets in PA between observations.

   The Coronagraphic Visibility Tool (CVT) can be used to assess the availability of multiple position angles, and estimate what the time separation will be. It is expected that each sequence will contain an observation of a relevant PSF reference star, since the PSF will likely change between the two epochs.

Stage 5 – Use the Exposure Time Calculator to determine observing parameters

Estimating exposure times is a science-critical aspect of HCI observation planning. Once target visibility is confirmed and a PSF calibration strategy adopted, the JWST Exposure Time Calculator (ETC) should be used to determine the exposure parameters needed to achieve the desired signal-to-noise (SNR) on your target(s). Aside from the directions in the Getting Started Guide, the following are advisable for HCI:

1. ### Define your Scenes and Sources.

Create a *Science Scene* and populate it with the source targets

The Science scene should contain the source targets for observation and all other nearby sources that could contribute to both the observed target and background fluxes. The bright ("host") source should be placed in the center of the scene and the reference PSF source(s) at a significant Offset (e.g. 10 arcsec).

> At this stage, a copy of the bright target can be used as a proxy for the reference PSF source—that is, until a physical PSF calibrator has been identified (*see Select a suitable PSF calibrator*).

Faint sources must be placed within a square centered on the scene center for each instrument/mode pairing.
→ for MIRI the scene is a 8.91" square centered on the coronagraphic masks.
→ for NIRCam the scene is a 6.36" square centered on the coronagraphic masks.
→ for NIRISS the scene is a 5.31" square centered on the NRM.

Create a *Reference Scene* and populate it with the reference PSF source.

In order to facilitate Target Acquisition calculations for the reference PSF source, a dedicated "Reference" scene—containing only the reference PSF target—is required. The reference PSF source should be positioned at the center of the scene (offset 0,0).

2. Initiate calculations for each of your planned observations.

Calculations are performed from the **Calculations** page where the user specifies the desired input parameters in the **Configuration** pane: (1) instrument and mode, (2) scene, (3) background model parameters, (4) instrument configuration, (5) detector setup, and (6) the strategy for calculation of the SNR (and contrast for coronagraphic modes).

JWST ETC Creating a New Calculation
HCI ETC Instructions
JWST ETC Coronagraphy Strategy
JWST ETC Imaging Aperture Photometry Strategy

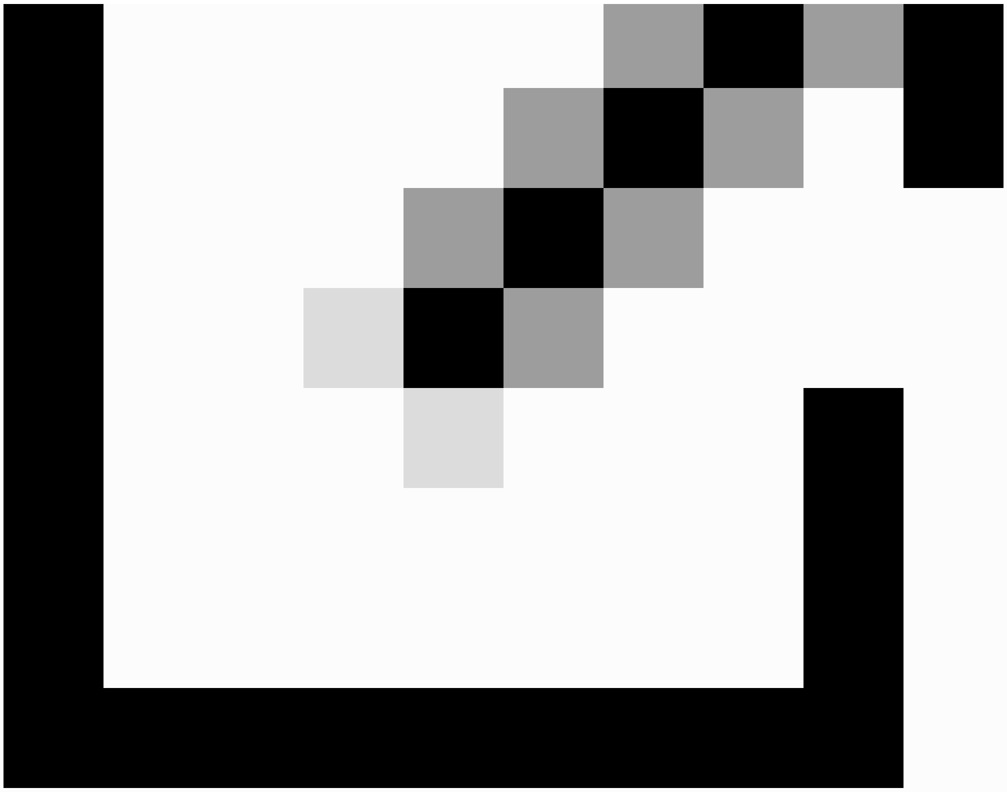
3. Adjust the exposure time via the NUMBER OF GROUPS, INTEGRATIONS, and/or

EXPOSURES until you obtain the desired SNR and contrast on your target.

Understanding Exposure Times
MIRI Generic Recommended Strategies: How many groups and integrations should I use?
NIRISS AMI Recommended Strategies: Estimating number of groups for an exposure

For NIRISS AMI, there is an advanced Python tool and precomputed contrast curves found at https://github.com/agreenbaum/ami_sim

and hbp://maestria.astro.umontreal.ca/niriss/AMIcontrast/index.php



, respectively.

4. # Check your individual calculations for detector saturation.

The user checks for saturation using the **Saturation** tab in the **Images** pane on the **Calculations** page in the ETC.

While some saturation may be tolerable, only partially-saturated pixels will be recoverable. In saturated regions, the photometric accuracy will be sub-optimal and the contrast will most likely be affected at or close to the IWA; consequently, faint portions of the astronomical scene that overlap with saturated pixels may not be properly detected.
JWST ETC Reports, JWST ETC Calculations Page Overview, JWST Coronagraphy in ETC: avoiding saturation

Using the Saturation Map, check if any saturated pixels overlap with faint sources/features in the astronomical scene.

In the event of saturation, it may be possible to recover pixels at the expected position of the companion by modifying the exposure parameters: proceeding by trial and error, vary the

readout pattern, N_{groups} and/or N_{ints} until all pixels at the expected position of the companion are no longer saturated.
JWST ETC Images and Plots

5. # Initialize Target Acquisition (TA) calculations for each of your observations.

All HCI observations will require a science instrument assisted TA procedure—this includes both science and reference PSF observations.
JWST ETC MIRI Target Acquisition
JWST ETC NIRCam Target Acquisition
JWST ETC NIRISS Target Acquisition

6. # Run your TA calculations and examine the output information.

JWST ETC Outputs Overview

a. ## Does any saturation occur?

Saturation should be avoided during target acquisition for optimal performance. If any fully or partially saturated pixels are present in the TA exposure, the ETC will issue a warning. The recommendation is to adjust your exposure parameters (e.g., by decreasing the number of groups) to avoid saturation.
MIRI Outputs for TA
NIRCam Saturation limits for TA
NIRISS Outputs for TA

b. ## Does your exposure specification allow you to obtain the minimum required SNR for the TA procedure of the instrument mode?

MIRI Coronagraphic Imaging TA

requires a SNR ≥ 20 to obtain an absolute centroid accuracy of ≤ 10 and 22.5 mas for the 4QPM and Lyot coronagraphs, respectively.

NIRCam Coronagraphic Imaging TA

requires a SNR ≥ 30 to obtain a centroid accuracy ≤ 0.1 pixels for the TA source.

NIRISS TA

requires a SNR ≥ 30 to achieve a centroiding accuracy of ≤ 0.15 pixel for the TA source.

Stage 6 – Select a suitable PSF calibrator

If you have established the need for a PSF reference target according to your PSF calibration strategy designed *(see Select a PSF calibration strategy)*, this section is relevant. Otherwise, you may skip this stage and Finalize your observing strategy.

1. Select a PSF reference calibrator with consideration of the following criteria:

a. Well-known: Is the target a known good PSF reference star?

Selecting a reference PSF source that has been perviously observed interferometrically/coronagraphically (or from the ground with adaptive optics) and found to be single, is recommended. "Good references" are usually stars that are not astrophysically contaminated (i.e., without additional astrophysical signal from a debris disk or companion).

MIRI Coronagraphic Recommended Strategies: choosing a reference PSF target

NIRCam Coronagraphic Recommended Strategies: Selection of PSF Reference star

NIRISS AMI Recommended Strategies: Choosing an optimal calibrator for NIRISS AMI

There exist a handful of external resources that can helpful in the search for a known PSF reference target. See Selecting PSF reference stars with Simbad and Selecting PSF reference stars with SearchCal for more information.

b. ## Schedulability: Do the visibility windows of the science target and PSF calibrator overlap at the time of the desired observation?

Unless on-orbit experience shows that the need for contemporaneous imaging can be relaxed, the JWST project requires observations of the science target and PSF reference star to be executed together, in a back-to-back sequence of observations.

Users should aim to observe the science and PSF reference observations as close together in time as possible, in order to minimize changes in the PSF and obtain the lowest possible limiting contrast.
Checking visibility of PSF reference stars
Coronagraphic Visibility Windows
JWST Wavefront Sensing and Control

c. ## Proximity: Is the PSF calibrator in relative proximity to the science target?

In order to limit thermal changes and minimize telescope overheads.
HCI PSF Reference Stars
Slew Times and Overheads

d. ## Avoidance of Binary: Is the PSF calibrator a single and unresolved source?

This can be addressed by selecting a known good PSF reference star. If the PSF reference star is not well known and/or has not been previously observed with high spatial (e.g. < 0.1") resolution imaging or interferometry (a.), it is recommended to perform further archive checks or seek another PSF reference star.
HCI PSF Reference Stars

e. ## Spectral Type: Does the PSF calibrator the share the same spectral properties as the science target?

This has a stronger impact at shorter wavelengths and with wider filters. Spectral mismatch may generate extra noise during the process of photometrically rescaling the reference and allow possible under- and over-subtraction of the PSF.
Effect of spectral "mismatch"
High-Contrast Imaging Inner Working Angle

f. ## Brightness: Is the PSF calibrator similar in magnitude to the science target?

Whenever possible, it is recommended to use a reference PSF that is brighter than the science target because the process of flux rescaling also scales the noise. Selecting a calibrator that is as bright as (or brighter) will help achieve the same signal-to-noise ratio in comparable exposure times.
Effect of spectral "mismatch"

2. **Return to your previous workbook the ETC to amend the spectral properties of the reference PSF source and finalize the exposure parameters of your calculations.**

Stage 7 – Finalize your observing strategy

In previous stages, you have made a series of choices concerning the content of your observing program—in this stage, you will decide on an observing strategy with which to structure this content. This observing strategy should be designed to mitigate performance degradation and yield the best possible scientific results, with the least possible overheads.
MIRI Observing Strategies
NIRCam Observing Strategies
NIRISS Observing Strategies

1. ## Consider the total number of observations you will require for your observing program.

Note that PSF Reference observations should be observed using the same telescope optical configuration, so that no wavefront correction should occur between any of the observations.

The inference of the above is that observations in different filters require individual PSF reference observations.

2. At the observation level: consider how you will organize (group) your observations.

Observations that need to be executed together in time should be grouped together in "sequences". Details of these sequences will depend on the science goals of your program.

Science and Reference PSF observations

For all HCI modes, Science and PSF reference star observations must be grouped into sequences—the goal is to minimize changes in the optics that might alter the PSF between observations.
HCI Coronagraphic Sequences
NIRISS AMI Recommended Strategies: Observing calibrator(s)

3. If your sequence of observations involves the use of multiple filters and/or occulters, you should consider following the optimal efficiency scheduling strategy.

With the optimal efficiency strategy, observations for a given target are organized—in each filter and occulter—to minimize the number of rolls and slews. This strategy increases the time between an observation of a target in a given filter and the corresponding reference PSF star observation in the same filter, but it results in more efficient use of the observatory. With the optimal wavefront stability strategy, standard sequences are executed consecutively in each filter to minimize the chance of any wavefront changes, which comes at the cost of increased number of slews and rolls for the telescope.
JWST Coronagraphic Sequences: Standard sequence implementation for multiple filters and occulters

Linking too many observations together into a sequence can make the total execution time long, to the point that the observations cannot be scheduled. Therefore, you should seek to strike a balance between efficiency and the pragmatic aspects of scheduling observatory activities.

You may find it instructive to inspect the reports that are generated by running **Smart Accounting** in APT. These files provide a more detailed breakdown of where various overheads are being charged and will help you understand the tradeoffs in efficiency for the different models. See the articles on the APT Visit Planner and APT Smart Accounting for more information.

4. Do your observations call for a more substantial position angle offset (e.g., 30° offset) on the science target than can be provided instantaneously in a single visibility window?

For instance: to recover a part of the scene that would otherwise be blocked by a selected mask. The possibility of such an offset depends strongly on the ecliptic latitude of the target and must be scheduled at a significantly later time. The CVT can be used to help assess this. This special requirements should only be used when truly necessary for the science.
JWST Coronagraphic Sequences: Larger roll offset case

5. If your program consists of a set of science targets that are clustered on the sky in close proximity and schedulable at the same time:

is it possible implement the *shared reference survey strategy*?

Whereby multiple science targets are paired with an individual PSF observation, in the normal coronagraphic sequence?
JWST Coronagraphic Sequences: Shared reference survey case
Coronagraphic Visibility Tool

Is it possible to incorporate the *self-referenced survey strategy*?

Under the assumption that some science targets will be for science, but others—those not showing surrounding structure—will be used for PSF reference observations?
JWST Coronagraphic Sequences: Self-referenced survey case

6. **For all coronagraphic imaging programs: it is highly recommended to perform the standard coronagraphic sequence, or a derivative of it.**

JWST Coronagraphic Sequences

7. **Do your science goals call for high accuracy astrometry?**

If so, perhaps you should obtain NIRCam images for full field astrometry (FFA) in addition to your HCI science data.
NIRCam Coronagraph Astrometric Confirmation Image

Stage 8 – Prepare your proposal in the Astronomers' Proposal Tool

Aside from the steps described in the Getting Started Guide roadmap, consider the following particular to HCI:

1. **Organize science and PSF calibrator observations into sequences (to be scheduled back-to-back).**

You may find it useful to collect all observations that pertain to a particular coronagraphic sequence into a single Observation Folder, and additional folders for other sequences.
HCI Coronagraphic Sequences

2. **Use the PSF Reference Observations section to indicate which observations produce PSF references and to specify to which science observations they**

should be linked. The PSF reference star must be in the same FILTER and SUBARRAY.

You may find it very helpful to use designations in the Name in the Proposal field (Fixed Targets form) to clearly indicate which targets are intended for science and which are PSF reference stars, as appropriate. These designations will show up in the pull-down menus in other parts of APT, to help you build up your observation sequences. Furthermore, if you have a large number of science targets and PSF stars to keep track of, you may find it useful to do so using the the comment box.

JWST HCI in APT: Setting links between PSF reference and science observations
→ MIRI Coronagraphic Imaging APT Template: PSF Reference Observations
→ NIRCam Coronagraphic Imaging APT Template: PSF Reference Observations
→ NIRISS AMI APT Template: PSF reference observations

3. ### If excluding the observation of a PSF reference target justification must be reflected in the Additional Justifiction section.

NIRISS AMI PSF reference observations

4. ### Are NIRCam full frame astrometric (FFA) images are needed?

If so, indicate Yes in the Astrometric Confirmation Image Parameters template panel and enter the appropriate exposure information for these images.
NIRCam Coronagraphic Imaging APT template: Astrometric Confirmation Image Parameters

5. ### For Coronagraphic Imaging modes: Do any of your observations require the small grid dithering (SGD) technique?

This selection can be made in the observation template by choosing the appropriate Dither Type, in the MIRI template, or Dither Pattern in the NIRCam template.
Specifying SGDs in APT

6. ### Add any the necessary Special Requirements:

Timing Special Requirements,
Aperture Position Angle Special Requirements

Video tools are available for: Adding Special Requirements in APT

SEQUENCE OBSERVATIONS... NON-INTERRUPTIBLE to force the Visit Planner to look at the collective schedulability of the entire set.

Note that APT will execute the observations in a **Sequence Observations ... Non-interruptible** grouping in the order of increasing observation number. If you drag and drop the order of your observations in the APT tree editor, make sure the desired sequence of observations is still in increasing order of observation number. If it is not, edit the observation numbers so that ordering is achieved.
APT Visit Planner

APERTURE PA OFFSET ... for roll-dithered science target observations.

Set the offset angle, or offset angle range between two roll-dithered observations. If a second sequence at a larger PA offset is needed, the Aperture PA Offset ... special requirement must still be set between the two sequences. The cases needing this level of attention to detail should be investigated ahead of planning, with a visibility tool (*See Assessing target visibilities and allowed position angles*).

APERTURE PA RANGE ... fix the allowed degree range of absolute PA on an observation.

This is only necessary if a known structure around a given target (say a disk or known planet) needs to be positioned as to avoid structures in the instrument field of view.

> Users should only constrain the requested angles when necessary to support their science goals and that even when an angular constraint is placed, the larger the range that can be allowed the better (from the standpoint of allowing scheduling flexibility). As an exercise, the user can try editing the special requirement that sets the allowed range of angles on the first observation and re-run the Visit Planner to see how the allowed time window changes.

7. ## Verify your observation set-up.

i. The APT Aladin Viewer can be used to visualize the field of view on the sky for planned JWST observations.

Verify that the position angle(s) and roll dither(s) of an observation/ visit have been specified as intended.
JWST APT Aladin Viewer
Video tutorials are available for: Aladin Overview in APT: part 1, Aladin Overview in APT: part 2, Using Aladin and APT Visit Planner Together

ii. Run the APT visit planner.

Check scheduability of observations, check constraints and see whether guide stars are available to support the observations.
APT Visit Planner
Video tutorials are available for: Reviewing Errors and Warnings

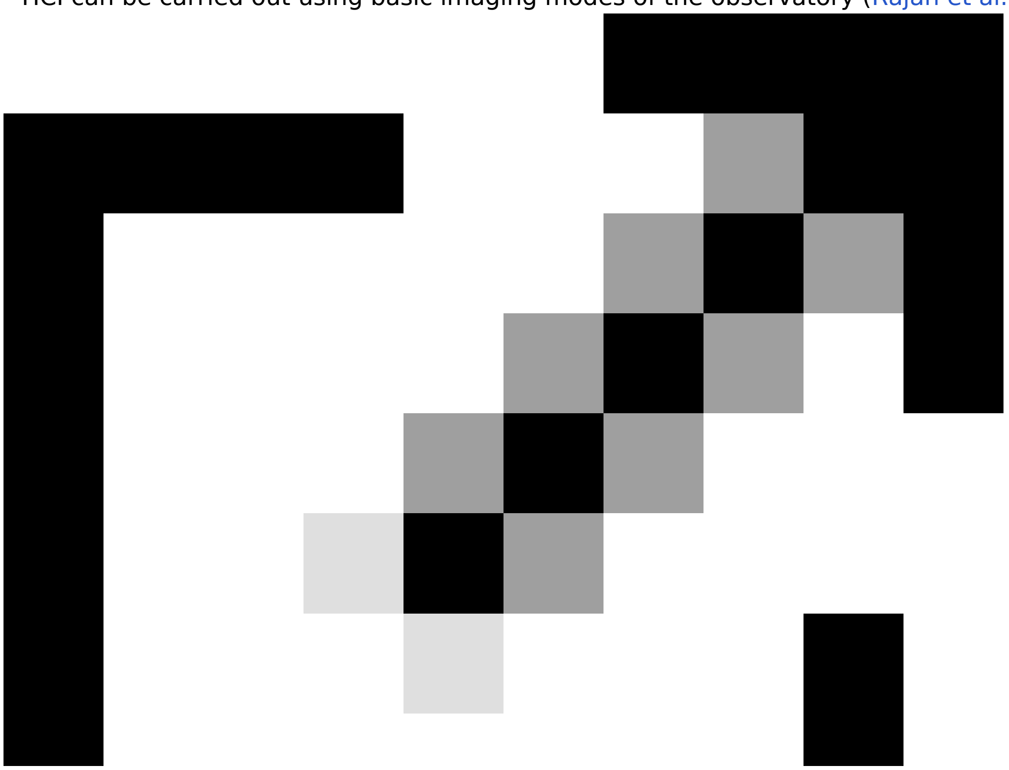
iii. Create Target Confirmation Charts.
to verifyithat the input target coordinates will position the telescope in the correct place. APT Target Confirmation Charts

8. **Using the Smart Accounting Reports are you able to identify the trade-offs in efficiency (science time/total time) for different observation strategies?**

Note: programs that minimize the number of major slews and the number of visits will typically achieve a higher efficiency than programs with large numbers of slews and visits.
APT Smart Accounting, Slew Times and Overheads, JWST Observing Overheads Summary, Instrument Overheads

Footnotes

[1] HCI can be carried out using basic imaging modes of the observatory (Rajan et al., 2015



; Durcan, Janson, and Carson, 2016

), as well as using IFU strategies similar to Konopacky et al. (2013)

, however these modes are not yet covered in the documentation.

[2] Based on performance simulations and contrast predictions based on the latest information on the as-built telescope and instrument properties, including both static and dynamic contributions to wavefront error (Perrin et al. 2018)

[3] We report all contrasts as 5σ post-processing contrasts after single reference star subtraction.

[4] KL image projection (KLIP) algorithm (Soummer et al. 2012)

[5] "locally optimized combination of images" or LOCI algorithm (Lafrenière et al. 2007)

[4] ***Bold italics*** font style is used to indicate parameters, parameter values, and/or special requirements that are set in the APT GUI.

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Soummer, R., Pueyo, L., Larkin, J. 2012, *ApJ*, 755, L28
Detection and Characterization of Exoplanets and Disks Using Projections on Karhunen-Loève Eigenimages

Published	06 Jul 2019
Latest updates	• (enter date using //) Briefly describe change

HCI Proposal Planning

A list of articles about high-contrast imaging proposal planning instructions.

Expand all Expand all Collapse all Collapse all

Published	28 Nov 2019
Latest updates	

HCI ETC Instructions

The JWST Exposure Time Calculator (ETC) develops and evaluates the complex, multi-source astronomical scenes that are characteristic of JWST high-contrast imaging (HCI).

On this page

ETC functionalities for coronagraphy

The standard coronagraphic sequence—not yet fully supported by the ETC—will combine 2 complementary PSF subtraction strategies:

- *referenced differential imaging* (RDI), which involves subtracting a coronagraphic image of a nearby PSF reference star
- *angular differential imaging* (ADI), which involves differencing 2 coronagraphic images of the bright host source that differ only by a telescope roll of ~10°

Thus, when fully implemented, the standard coronagraphic sequence will involve a minimum of 3 observations:

1. A science observation with the host centered in the coronagraphic mask
2. A second science observation after a telescope roll, with the host centered in the coronagraphic mask
3. A PSF reference observation with the PSF reference star centered in the coronagraphic mask

Adding small grid dithers (SGDs) of the PSF reference star is a future variant of the standard coronagraphic sequence. SGDs can increase the confidence that misalignments between the position of the science PSF and reference PSF relative to the coronagraph masks have a minimal impact on the final contrast.

The example ETC computations below capture the current scope of functionalities for coronagraphy and are limited to only the standard coronagraphic sequence elements 1 and 3, listed above, because the ADI processing is not currently supported by the ETC.

in the absence of on-sky data, it is hard to predict PSF stability to the degree that has been achieved with the Hubble Space Telescope. As a consequence, until we get data, the ETC does not support either ADI or SGD—only RDI.

In its current implementation, the ETC is mainly useful for 2 tasks: (1) investigating detector saturation and (2) computing the signal-to-noise ratio (SNR) of a faint companion source under the *ideal contrast* assumption. Ideal contrast is the most optimistic assumption possible because it assumes one type of noise is dominant: the counting statistics of collected photons (shot noise). See HCI Contrast Considerations for more information about the "ideal" assumption.

The ETC treats residual flat field noise. The flat field error is a division by ~1 (the flat field is normalized), with a variance of 1/ff_electrons. Note that the value of the flat field response is constant for multiple exposures and multiple integrations, so $N_{exposures}$ > 1 does not decrease the residual flat field noise. To reduce it, a user either has to improve the flat field or dither with >1 pixel offsets. The most apparent effect for everyday ETC use is that residual flat field noise sets an upper limit on the achievable SNR.

The SNR source must lie within a square centered on the coronagraphic mask, aligned with detector rows and columns, with sides of 101 pixels for NIRCam or 81 pixels for MIRI.

This article is about ETC functionalities specific to coronagraphy. The reader is encouraged to become acquainted with the general ETC documentation, which covers the underlying algorithms, synthetic astrophysical scenes, simulated JWST exposures, step-by-step ETC operations, and best practices. The reader should take particular cognizance of this article: JWST ETC Coronagraphy Strategy.

Avoiding saturation

In high-contrast imaging (HCI), the host source can be orders of magnitude brighter than the companion source. Therefore, deep coronagraphic exposures call for a large dynamic range, notwithstanding that the coronagraphic mask (occulter) blocks a significant amount of light from the host.

If the exposure time (which involves the number of up-the-ramp, non-destructive reads in an integration), or if the number of groups (N_{groups}) is too large, then saturation will occur, starting with detector pixels close to the image of the coronagraphic mask on the detector.

Because saturation is nonlinear, and because post-observation image processing procedures are based on linear combinations of images, saturation cannot be calibrated away or compensated for by the data pipeline. As a consequence, if faint portions of the circumstellar scene overlap with the saturated pixels, those portions may not be properly detected.

Therefore, saturation is a potential show stopper for programs involving faint features at small apparent separations.

The ETC separately flags pixels that are expected to saturate at some point within a ramp. This feature lets users make subtle distinctions to deal with saturation. For example, if a ramp goes into saturation at, say, N_{groups} = 10, the slope may still be accurately recoverable by discarding from the analysis only the individual frames where saturation has occurred.

The user checks for saturation using the **Saturation*** tab in the **Images** pane on the **Calculations** page in the ETC.

In some cases, warnings in the ETC **Reports** panel will indicate whether some ramps may still be useful. The user must proceed by trial and error, varying the readout pattern and N_{groups} until all pixels at the expected position of the companion are not saturated. Note that if at least one pixel in the scene is saturated, the ETC will produce a warning.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

PSF subtraction strategy

Currently, the PSF subtraction strategy is called "optimal." The ETC quantifies the shot noise in the wings of either the host or reference sources, as appropriate, at the position of the faint companion source.

The ETC engine is designed to support predictions of coronagraphic performance, including estimates of the PSF using one or multiple reference images. The **Strategy** tab of the GUI calls for choices of reference target and PSF calibration method. Nevertheless, as discussed in JWST Coronagraphic Observation Planning and HCI Coronagraphic Sequences, until calibration programs have quantified the on-orbit stability of the optics, it will be difficult to quantify the expected performance of the various options for PSF subtraction, and therefore, to estimate the limiting contrast*(C_{limit})*. As a consequence, we direct the user to the WebbPSF tool, discussions of limiting contrast, and details on how to design a coronagraphic sequence.

Note that even when higher fidelity statistical models of the PSF are available, limiting contrast will always ultimately be limited by the accuracy of the PSF subtraction, rather than on photon statistics and the actual exposure time. Because limiting performance is controlled by systematic effects—fluctuations in the observatory optics between exposures—doubling or tripling the exposure time won't help.

On the other hand, if the stability time of the optics is longer than the total duration of the observations—the sum of all exposure times and overheads—then the calibration is said to be "ideal," and the residual noise may be solely controlled by shot noise in the wings of the host and reference sources.

The ETC computes the SNR at that position, and the user can proceed iteratively by increasing or decreasing exposure time until the SNR is acceptable. The related user inputs to the ETC are the number of groups, integrations, and exposures: N_{groups}, N_{int}, and N_{exp}. These three numbers set the total exposure time on the source.

Since March 2018 (patch release ETC 1.2.2), users can download the "Unsubtracted Science Scene" or the "PSF Subtraction Source only" as well as perform sub-optimal subtractions as described in the JWST ETC Coronagraphy Strategy page. The image registration, treatment of the noise and background have not changed and are somewhat optimistic.

The next section provides an example of ETC calculations under the "ideal" assumption.

Example of ETC calculations for high-contrast imaging

Tables A–D show the input values and computational results for an ETC study of an analog of the β Pictoris system, comprising a circumstellar disk and a self-luminous planetary companion. These observations use the MIRI four-quadrant phase mask (4QPM) coronagraph that is optimized at λ_0 = 11.3 μ.

For PSF subtraction in this example, only referenced differential imaging (RDI) is used, with a PSF reference star at an apparent separation significantly larger than that of the host and companion sources.

In Tables A–C, the column headers identify the suite of ETC inputs for coronagraphic observations, presented here in approximately the same order as the user encounters them on the ETC interface.

The column footers, in italics, assign an ordinal label to each input, to facilitate the descriptions and comments.

This section assumes some user familiarity with the general ETC documentation.

> ⚠ Web users may click on Tables A–D for a larger view.

Table A. Sources

<table>
<tr><th rowspan="2">Source</th><th rowspan="2">Name</th><th colspan="2">Continuum</th><th colspan="2">Normalization</th><th colspan="3">Shape</th><th colspan="3">Offset</th></tr>
<tr><th>System</th><th>Sp/Teff</th><th>Bandpass</th><th>Brightness</th><th>Type</th><th>A+</th><th>A–</th><th>X</th><th>Y</th><th>PA</th></tr>
<tr><td>1</td><td>star</td><td rowspan="3">Phoenix</td><td rowspan="3">A5V</td><td rowspan="4">Bessel K</td><td>3.5 Vega</td><td>point</td><td colspan="2">n/a</td><td>0</td><td>0</td><td>n/a</td></tr>
<tr><td>2</td><td>disk</td><td>4 Vega</td><td>extended</td><td>1″</td><td>2″</td><td>0</td><td>0</td><td>45°</td></tr>
<tr><td>3</td><td>reference</td><td>3.5 Vega</td><td>point</td><td colspan="2" rowspan="2">n/a</td><td>10″</td><td>10″</td><td rowspan="2">n/a</td></tr>
<tr><td>4</td><td>planet</td><td>BB</td><td>1700°</td><td>15 Vega</td><td>point</td><td>–1″</td><td>–2″</td></tr>
<tr><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td>A5</td><td>A6</td><td>A7</td><td colspan="2">A8</td><td>A9</td><td>A10</td><td>A11</td></tr>
</table>

Table A is a list of notional values of ETC input parameters for four sources: (1) a main sequence star that is the "host," (2) a circumstellar disk centered on the host, (3) a PSF reference star, and (4) a self-luminous planetary companion.

A1–A2: source identifiers
A3–A4: the spectrum or color of a source, expressed as a spectral type in the Phoenix system or as the effective temperature (T_{eff}) of a blackbody (BB)
A5–A6: the apparent Vega magnitude of the source in K band. Note that, for now, the value of the brightness of the reference star must be identical to the value for the host star. Otherwise the ETC will give unphysical negative SNRs
A7–A8: the shape of each source, point or extended. If extended—referring now to the disk—*A8* gives the standard deviations (A+, A–) of an equivalent dual-Gaussian distribution
A9–A11: the X and Y offsets of a source from (0,0), and the rotation-in-place of the source (not meaningful for point sources)

The information on the host and reference stars comes from a catalog or outside research.

The X-Y offsets and PA value are arbitrary and purely notional.

<table>
<caption>Table B. Calculations</caption>
<tr><th colspan="2">Calculations</th><th colspan="3">Background</th><th colspan="2">Setup</th><th colspan="5">Detector</th></tr>
<tr><th>Calculation #</th><th>Sources</th><th>RA/Dec</th><th>Level</th><th>Date</th><th>Coronagraph</th><th>Filter</th><th>Subarray</th><th>Pattern</th><th>Groups</th><th>Integrations</th><th>Exposures</th></tr>
<tr><td>1</td><td>1, 3, 4</td><td>0/0</td><td>low</td><td>any</td><td>FQPM</td><td>F1065C</td><td>M1065</td><td>fast</td><td>10</td><td>60</td><td>10</td></tr>
<tr><td>2</td><td>1, 2, 3</td><td colspan="10">″</td></tr>
<tr><td>B1</td><td>B2</td><td>B3</td><td>B4</td><td>B5</td><td>B6</td><td>B7</td><td>B8</td><td>B9</td><td>B10</td><td>B11</td><td>B12</td></tr>
</table>

Tables B and C set up the "scenes" of sources for each calculation—here are two of them—and specifies the instrumental and observational parameters and procedures.

B1: calculation identifier
B2: sources included in the scene
B3–B5: zodiacal light foreground (ignored)
B6–B7: instrument setup (selected coronagraph type and filter)
B8: detector subarray
B9–B12: detector readout pattern and numbers of groups, integrations, and exposures

Table C. Strategies

Strategy								
Observation			Extraction					
Scene rotation	PSF sub source	PSF subtraction	SNR source	Contrast azimuth	Aperture rad	Contrast separation	Sky annulus	
							Inner	Outer
0	3	optimal	4	45°	0.3″	1″	0.45″	0.7″
″			2	″				
C1	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*	*C8*	*C9*

C1: "scene rotation" is an angle theta that:

- rotates the position of a point source by theta
- rotates the position and orientation of an extended sources (although generally they are centered at 0 0)

C2: select the reference source, selecting a source identifier from *A1*. Here, with only the RDI PSF strategy available, we must choose source #3
C3: only "optimal" PSF subtraction is currently available
C4: select which companion source is being observed (disk or planet)
C5: "contrast azimuth" is

1. The azimuthal direction along which the contrast vs separation figure is produced
2. The azimuthal direction used for the scalar calculation of contrast in the text form ETC report

C6: radius of the virtual photometric aperture, which is centered on the position of the SNR source
C7: "contrast separation" is the radial separation used for the scalar calculation of contrast in the text form ETC report
C8–C9: specify the annular, virtual photometric aperture, which collects stray light from around the SNR source, preparing for its subtraction in post-processing

Table D. Parameters and results

Quantity	Computation 1	Computation 2	
Instrument filter/disperser	f1065c/null		*D1*
Extraction aperture position (arcsec)	[–1.00, –2.00]	[0.00, 0.00]	*D2*
Wavelength of interest used to calculate scalar values (microns)	10.55		*D3*
Size of extraction aperture (arcsec)	0.3		*D4*
Total time required for strategy (seconds)	2880.00		*D5*
Total exposure time (seconds)	1440.00		*D6*
Extracted flux (e^-/sec)	285.24	101.25	*D7*
Standard deviation in extracted flux (e^-/sec)	7.48	13.54	*D8*
Extracted signal-to-noise ratio	38.13	7.48	*D9*
Input background surface brightness (MJy/sr)	20.71		*D10*
Total background flux in extraction aperture (e^-/sec)	1419.98	11894.21	*D11*
Total sky background flux in extraction aperture (e^-/sec)	909.99	909.20	*D12*
Fraction of total background flux due to signal from scene	0.36	0.92	*D13*
Average number of cosmic rays per ramp	3.7×10^{-4}		*D14*
Radius at which contrast is measured (arcsec). Same as *C7*	1.0		*D15*
Azimuth at which contrast is measured (degrees). Same as *C5*	45.0		*D16*
Contrast	see Figure 3		*D17*

Table D gives the values of parameters and results summarized in the **Reports** pane of the **Computations** tab.

Discussion

The ETC output plots show no evidence of saturation for these computations.

The results of computations 1 and 2—planet and disk—show a reasonable job of detecting both the planet and disk, with SNR = 38 and SNR = 7, respectively, in 1,440 s exposure time. See Figures 1 and 2 for the two-dimensional images on the detector.

Figure 1. Detector image for computation 1 (planetary companion)

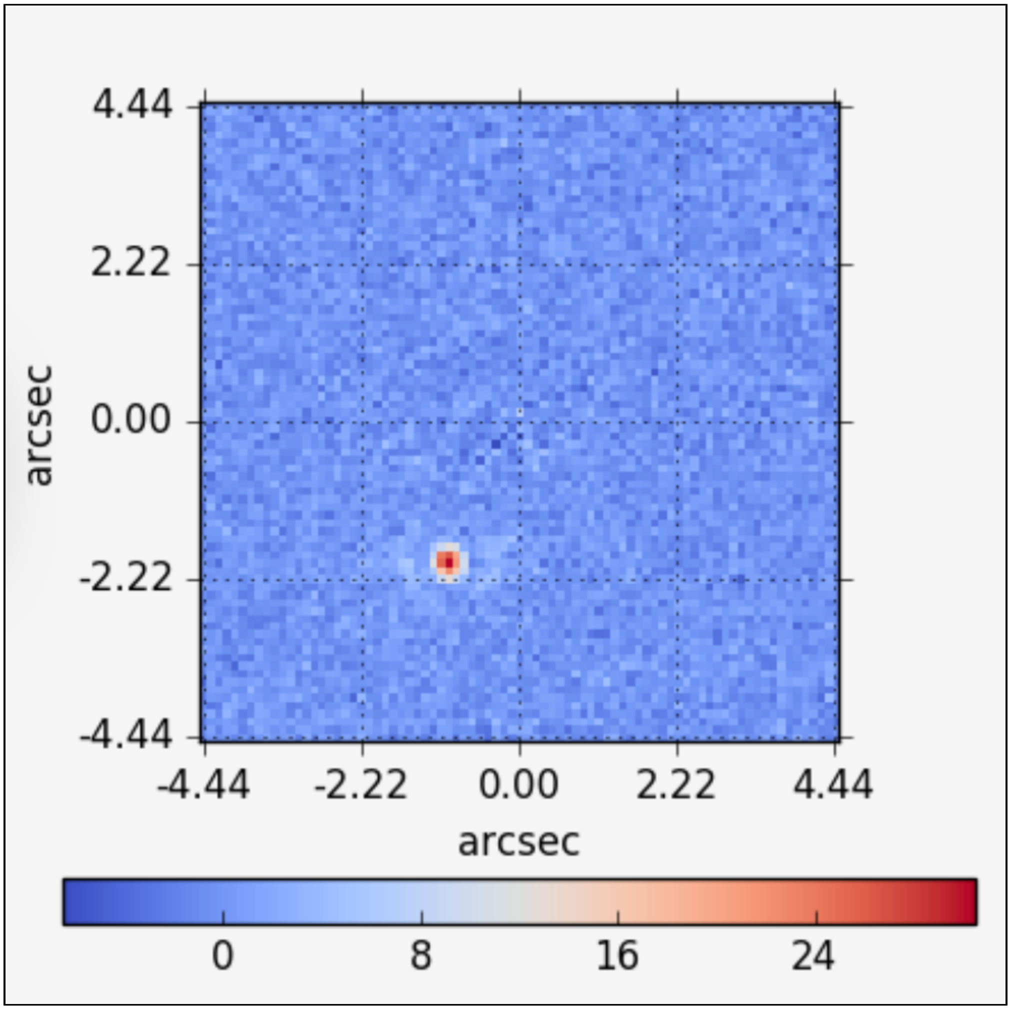


Figure 2. Detector image for computation 2 (circumstellar disk)

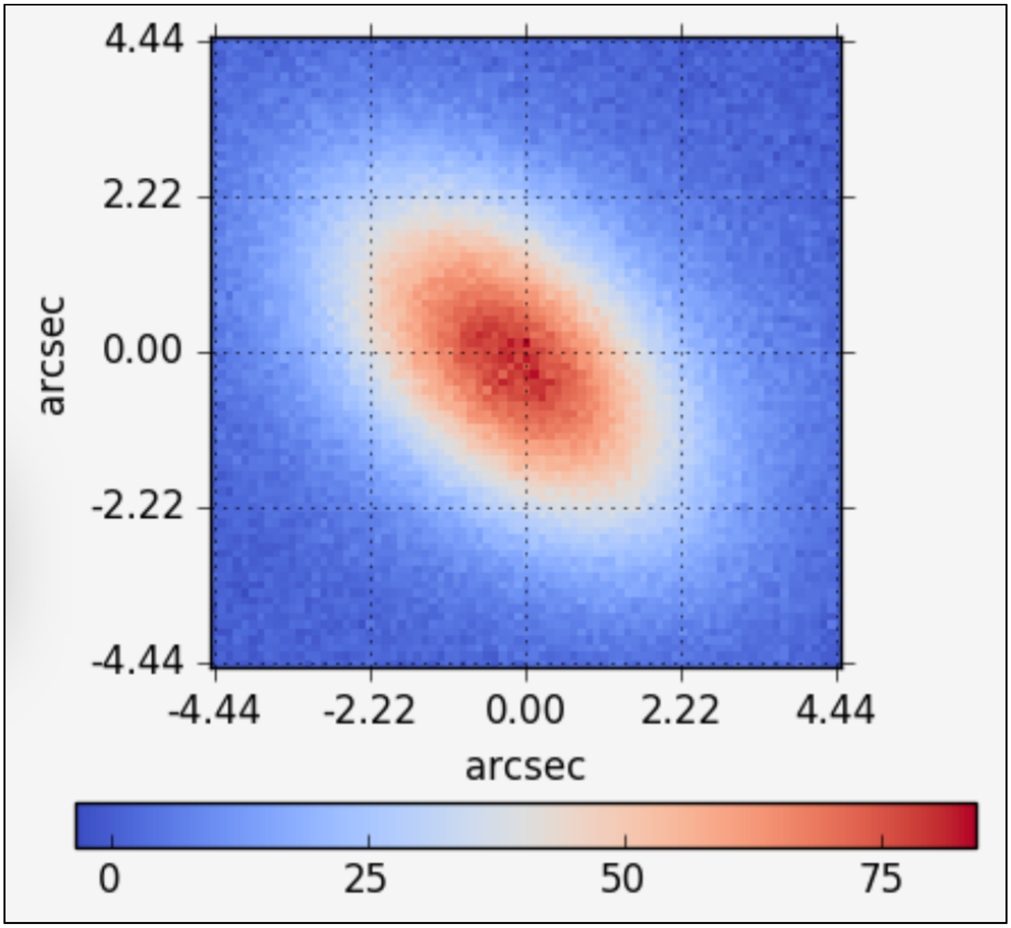
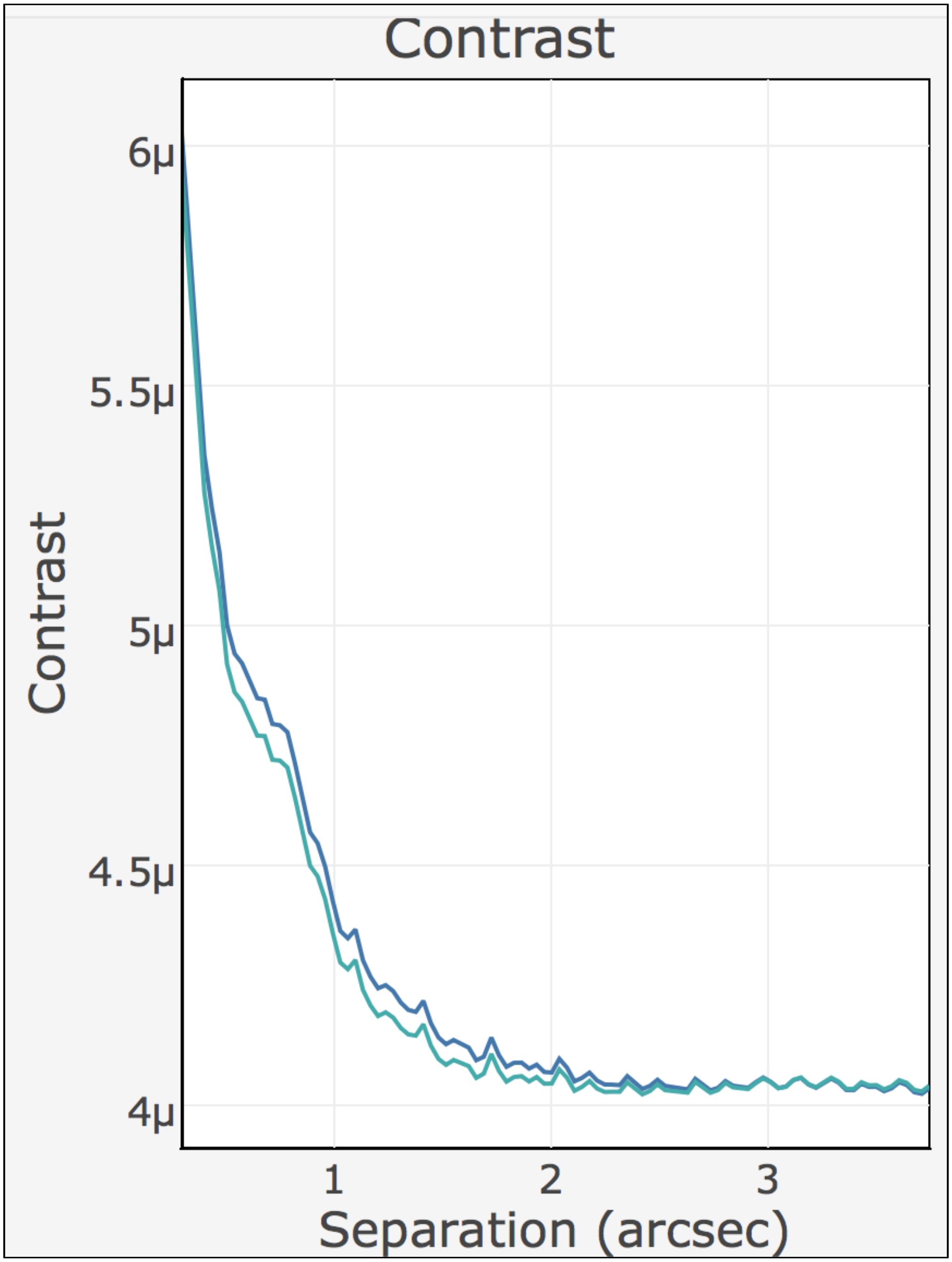


Figure 3 shows the contrast curves for computations 1 and 2, as a function of apparent separation and averaged over azimuth.

Figure 3. Contrast plots for computations 1 (blue) and 2 (green)



The symbol stands for 10^{-6} (dimensionless).

Published	18 May 2017
Latest updates	

	• 16 Mar 2018 To reflect changes in the ETC v1.2.2 patch release (PSF subtraction options)

HCI APT Instructions

Several procedures should be followed for entering valid JWST high-contrast imaging (HCI) observations, including correctly specifying coronagraphic sequences and linking PSF reference stars to science observations in the Astronomer's Proposal Tool (APT).

On this page

Main articles: HCI APT Coronagraphic Sequence Examples, MIRI Coronagraphic Imaging APT Template, NIRCam Coronagraphic Imaging APT Template, NIRISS Aperture Masking Interferometry Template APT Guide
See also: MIRI and NIRCam Coronagraphy of the Beta Pictoris Debris Disk, NIRISS AMI Science Use Case

This article provides a general walk-through of planning high-contrast imaging (HCI) observations in APT. Significant contrast improvements can be achieved when a PSF is subtracted from the star or object of interest to reveal its surroundings. Detailed, step-by-step instructions for specific coronagraphic modes are provided in these observation template articles: MIRI Coronagraphic Imaging APT Template, NIRCam Coronagraphic Imaging APT Template, and NIRISS Aperture Masking Interferometry APT Template.

The template for each coronagraphic observation has sections for entering information on a variety of important topics, including target acquisition, exposure times, special requirements for linking observations, PSF reference star observations, and, if needed for your science case, full frame astrometric images.

Science targets and PSF reference stars must be observed back-to-back—organized into coronagraphic sequences—in order to minimize changes in the PSF between exposures. You are encouraged to use one of the target visibility tools to verify that all targets in a sequence are simultaneously visible. Also, if specific position angles are required for your targets, the availability of the needed angles should be verified ahead of time with the Coronagraphic Visibility Tool.

Strictly speaking, the only restriction on science targets and PSF reference targets is they be schedulable at the same time. However, for purposes of efficiency and practicality, the closer together they are on the sky, the better. For PSF reference stars, as a guideline, try to find a reference target that is within about 20° of your science target. Larger separations are possible, but slew times get longer and thermal changes in the JWST optics may occur that could make it more difficult to match the reference PSF to your science observations. See HCI PSF Reference Stars for details.

Before starting to work in APT, as outlined below, it's assumed that you have used the JWST ETC to determine the exposure information for each target and type of observation, including target acquisition (TA), science, and PSF reference star exposures. See HCI ETC Instructions for information on gathering exposure specifications prior to entering observations into APT, and JWST Coronagraphic Observation Planning for an overview of the planning process.

Entering target information

Main article: APT Targets

In APT, coronagraphic targets are entered just like any other target. Nevertheless, you may find it very helpful to use designations in the ***Name in the Proposal*** * field (**Fixed Targets** form) to clearly indicate which targets are intended for science and which are PSF reference stars, as appropriate. These designations will show up in the pull-down menus in other parts of APT, to help you build up your coronagraphic sequences.

There is a comment box in the target entry form in APT where you can enter freehand information. If you have a large number of science targets and PSF stars to keep track of, you can enter information in the comment box, for tracking purposes.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Observations and sequences

Main article: APT Observations

Getting started on designing coronagraphic observations:

- For a given pair or set of targets to be observed, decide on the observation strategy and observation sequence that will be used.
- Define observation templates for each of the observations in a planned sequence.

Hint #1: collect all observations that pertain to a particular coronagraphic sequence into a single **Observation Folder.** Use additional folders for other sequences. This will help you organize your proposal.

Hint #2: each observation is specified in an observation template; create each of the observation templates in the sequence first, just specifying the instrument, template and target. Later, come back and fill in the details.

These steps will make it easier to make the various connections, such as developing the PSF reference observations, or adding the necessary special requirements to link the observations.

Ultimately, each sequence will be executed as a non-interruptible sequence. Therefore:

- place your observations in the desired order within the observation folder, and make sure the observation numbers occur in increasing order. You can use “drag and drop” in the APT tree editor to reorder observations if needed.

  > APT will execute the observations in a ***Sequence Observations ... Non-interruptible*** grouping in the order of increasing observation number. If you drag and drop the order of your observations in the APT tree editor, make sure the desired sequence of observations is still in increasing order of observation number. If it is not, edit the observation numbers so that ordering is achieved. (The observation number is an editable field in the observation template.) The numbers do not need to be sequential—only in increasing order within the sequence.

- Next, for each observation in your sequence, enter the exposure time information for TA, as well as images of the science target and PSF reference star. This information comes from your advance work in the Exposure Time Calculator (ETC). (See the individual “template” articles listed near the top of this article.)
  - Also, if NIRCam full frame astrometric (FFA) images are needed, indicate ***Yes*** in the **Astrometric Confirmation Image Parameters** template panel for this feature, and enter exposure information for these images.

- If any of your observations require the *small grid dithering* technique (SGD), make this selection in the observation template by choosing the appropriate ***Dither Type*** in the MIRI template or ***Dither Pattern*** in the NIRCam template. Note that the exposure time is increased by the number of dither points in the SGD pattern. Therefore, it is recommended that SGDs only be used when the highest quality PSF subtraction is required. Furthermore, it is envisioned that SGDs be used only on the PSF reference star, although using SGDs on science targets is not precluded.

Setting links between PSF reference observations and science observations

As previously discussed, the standard coronagraphic sequence requires both science and PSF reference star observations. While the relationships between reference and science observations should be clear in the APT sequences, such information also needs to be explicitly conveyed to the data processing system. This is done in the **PSF Reference Observations** panel in the APT coronagraphy templates, located at the bottom of the GUI (you may need to scroll down).

In the APT coronagraphy templates' **PSF Reference Observations** panel:

1. To specify that an observation is a PSF reference observation, click on the check box titled ***This is a PSF Reference Observation***. The rest of the panel will then collapse and no other action is needed.

> By JWST policy, PSF reference observations are designated as non-proprietary, even though the time is charged to the program. The reason for this policy is to serve the community's interests by building up, right from the outset, a library of coronagraphic PSFs, for various instruments and under varying conditions. Any exceptions to this policy must be justified in your proposal and agreed to by the appropriate time allocation committee (TAC) panel.

2. If the observation is a science target, the **PSF Reference Observations** box will show a list of the PSF observations. These PSF observations were previously flagged as such in their observation templates—for this to work, you should first flag all PSF observations in your sequence as decribed in (1).

   Each science observation must be associated with one or more PSF reference observations. Note that only PSF observations with coronagraphs/filters/occulters and subarrays matching a given science observation will appear in the list. In principle, science observations can appear in the list, and can serve as reference PSFs for other science observations, but this is a special case (see below).

Special case: coronagraphic surveys

The STScI Coronagraphic Working Group has identified two "survey" cases that may find utility in certain applications.

- The *shared-reference survey* allows the user to observe a set of science targets with a smaller number (one or more) of PSF reference star observations that can be applied to the entire group. This case is actually handled as described above, since the same PSF reference observation can be selected for the separate science targets, assuming they are all observed the same way and are included in the same observation sequence.

- The other case is the *self-referenced survey*, where a group of targets is observed, but it is not known *a priori* which targets/observations will be useful for science and which will be useful as PSF reference observations; the user just wants to observe the set of targets and decide later.

  > This is expected to be an extremely limited use case and explicit discussion and justification for its use must be made in your proposal's technical description. This mode is invoked by selecting the "Additional Justification" box in the **PSF Reference Observations** panel of the template.

  Even with the additional justification, the self-referenced survey still raises issues and concerns for initial data processing. The problem is that no PSF reference observations have been provided to the pipeline treatment of the science targets. To address the issue, APT will mark "errors" (red X's) on each observation in a self-referenced survey until one of the other science observations has been selected for use as the initial PSF reference observation. (Note that this amounts to little more than making a guess about a PSF reference observation. Nevertheless, this remedy will allow the data pipeline to at least make an initial PSF-subtracted data product.)

Assuming the TAC agrees with the justification, all targets will remain proprietary until such time that the data can be inspected by the user and a designation of "science" or "PSF reference" can be made. At that time, the PSF observations will be made non-proprietary and added to the PSF library.

Setting appropriate special requirements

Main article: APT Special Requirements

Adding Special Requirements in APT Video Tutorial

Setting the appropriate **special requirements** is a very important step for coronagraphic observations. At the very least, use the ***Sequence Observations ... Non-interruptible*** special requirement for observations that are part of a coronagraphic sequence to force the **Visit Planner** to look at the collective schedulability of the entire set (see below).

If a roll dither is required for the science target observations, the appropriate ***Aperture PA Offset ...*** special requirement must be placed on them. If you require another observation sequence at a larger offset (which will have to be at a different time), use the ***Aperture PA Offset ...*** special requirement to specify the desired angle. Hint: you should use the Coronagraphic Visibility Tool prior to your APT planning session to understand the range of angles available for your target, in order to avoid the disappointment of only discovering that the needed angles are impossible to observe when you run the APT Visit Planner.

The observation templates contain a major tab labeled **Special Requirements**, which provides access to the controls in APT for specifying the various special requirements. For some of the more complicated sequences involving multiple instruments, filters, or occulters, setting the special requirements can be tricky, and some iterations may be needed. Users should consult the examples of coronagraphic sequences and practice with the JWST APT coronagraphic sequence examples provided.

There is also a **Comments** tab in the observation template for each observation, next to the **Special Requirements** tab. Feel free to enter any relevant information there for future reference. Also note that each exposure specification line contains a box for entering a reference ETC workbook identifier (and calculation number). See the APT-ETC Connectivity article for more information.

Run the Visit Planner

Main article: APT Visit Planner

APT Visit Planner Video Tutorial

Once the observations for a given coronagraphic sequence have been fully specified and all APT errors resolved, you should run the APT **Visit Planner** (VP) on the entire observation folder holding the sequence. The VP can be run on individual observations, on observation folders, and/or on the entire set of proposed observations in a proposal. This process can take some time, depending on the size of the proposal. Since a sequence must be able to execute in its entirety, a check at the observation folder level will evaluate the schedulability of your sequence(s). This process should be straightforward if the visibilities have been checked ahead of time with the Coronagraphic Visibility Tool. Additional details—such as guide star availability—are checked by APT at this point.

Run Smart Accounting

Main article: APT Smart Accounting

Once the schedulability of your sequences has been verified and your entire proposal is in hand, run the **Smart Accounting** tool in APT. This tool identifies any excess major slews assumed by APT in the initial build-up of your observation sequences, and reduces the slews to the minimum needed. For example, APT assumes a major slew at the start of each new observation, by default. A set of observations within a non-interruptible sequence will obviously only need one major slew at the beginning of the sequence. **Smart Accounting** will catch and correct this, thus reducing your reported overheads.

APT tip: duplicating a sequence

If your program involves executing a similar pattern of observations for a number of targets, consider fleshing out the observation sequence for one pairing of science target and PSF reference star. Then, use the duplication functionality in APT to create additional sequences.

Assuming you have placed your observation sequence in a separate observation folder, highlight the folder you wish to duplicate in the APT tree editor in the left sidebar. The top APT bar shows pull-down menus for **File**, **Edit**, **Tools**, etc. From the **Edit** pull-down menu, select **Duplicate** (or **MultipleDuplicate** if more than one copy is desired) and the entire folder will be duplicated. Then, just edit the targets and exposure information as necessary for the actual targets in each observation sequence. This same shortcut can be used to duplicate individual observations instead of entire folders, if desired.

When using the duplication functionality, however, users should review each copied sequence carefully for unintended consequences. There may be any number of subtleties that you might want to change between sequences—blindly copying is not recommended without careful checking.

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Latest updates	

HCI Small Grid Dithers

Small grid dithering (SGD), in JWST coronagraphic imaging, uses the fine steering mirror (FSM) to make very small offsets between exposures. The multiple datasets produced by this optional technique, at the cost of additional observing time, may be used in post-processing to produce higher fidelity reference PSF subtractions.

On this page

Main article: NIRCam Small Grid Dithers
See also: MIRI Coronagraphic Imaging Target Acquisition, NIRCam Coronagraphic Imaging Target Acquisition

Target acquisition (TA) is an important factor that contributes to contrast performance in high-contrast imaging applications and typically depends on the specific instrument. For JWST, coronagraphic TAs rely on measuring the target's image centroid at a position away from the focal plane mask, then performing a small angle maneuver (SAM) to place the target behind a selected coronagraphic mask. Therefore, the accuracy of the TA is directly limited by the SAM accuracy, which is expected to be ~6–8 mas per axis (1-sigma radial) (see JWST Pointing Performance table for details).

For JWST high-contrast imaging, it is standard procedure to subtract a scaled image of an occulted point spread function (PSF) reference star to remove the speckles that remain in an occulted science target observation. However, the accuracy with which a science target and a subsequent PSF reference target can be placed behind an occulter is limited by the accuracy of the target acquisition procedure. Since the placement of a science target behind a given occulter may be slightly different from the placement of the PSF reference target, speckles in these observations may be slightly different, thus compromising the quality of the PSF reference subtraction from the science target observation.

In cases requiring the highest quality PSF matching, a technique called *small grid dithering (SGD)* can be invoked. The technique uses the fine steering mirror (FSM) to make a number of very small (5–20 mas) offsets of the target in a grid pattern around the nominal TA position, with an observation executed at each step, thus creating a mini library of PSFs obtained at the same epoch as the science observation. Post-processing of the ensemble of observations can be used to model a more precise speckle pattern to use for the subtraction, at the expense of the additional observational overheads. An excellent article by LaJoie et al. (2016) is available for those who need to know the details of the technique, where it can be most effectively used, and the tradeoffs involved. A technical report by Soummer et al. (2014) also provides more information.

Since the purpose of using SGD is to obtain an improved reference PSF to subtract from the science observation, it is anticipated that most users will only apply SGD to the PSF reference target, and even then only in cases where the highest quality PSF subtractions are required for the science. Using the SGD technique on a science target is not disallowed, but you will need to explain in your proposal why you think it is beneficial for your use case.

Specifying SGDs in APT

Main articles: MIRI Coronagraphic Imaging APT Template, NIRCam Coronagraphic Imaging APT Template

The expected use case for SGDs will be to (1) take the science observation(s), then (2) use an SGD dither pattern to obtain a set of slightly offset exposures on the PSF reference star. The ensemble of PSF star SGD exposures covers the expected region of possible misalignments from the science observation TA.

The SGD technique is expected to have the most benefit for MIRI 4QPM observations, owing to the requirement of very precise and accurate target placement relative to the apex of the mask. However, simulations have shown significant benefit for all MIRI and NIRCam coronagraphic modes (LaJoie et al. 2016).

MIRI and NIRCam instrument teams have created a set of pre-defined SGD options that can be selected in the appropriate APT observation template, using the pull-down menu for specifying dithers. Table 1 shows the available options for each mode, including the dither name used in APT.

Table 1. SGD Dither option names in APT

MIRI	
Coronagraph/filter	**APT dither type SGD options**
4QPM/F1065C *	*5-POINT-SMALL-GRID*; *9-POINT-SMALL-GRID*
4QPM/F1140C	*5-POINT-SMALL-GRID*; *9-POINT-SMALL-GRID*
4QPM/F1550C	*5-POINT-SMALL-GRID*; *9-POINT-SMALL-GRID*
LYOT/F2300C	*5-POINT-SMALL-GRID*; *9-POINT-SMALL-GRID*
NIRCam	
Coronagraphic mask	**APT dither pattern SGD options**
MASKSWB (wedge)	*3-POINT-BAR*; *5-POINT-BAR*
MASKLWB (wedge)	*3-POINT-BAR*; *5-POINT-BAR*
MASK210R	*5-POINT-BOX*; *5-POINT-DIAMOND*; *9-POINT-CIRCLE*

MASK335R	***5-POINT-BOX***; ***5-POINT-DIAMOND***; ***9-POINT-CIRCLE***
MASK430R	***5-POINT-BOX***; ***5-POINT-DIAMOND***; ***9-POINT-CIRCLE***

From this table, it should be clear that use of SGD comes with a price: depending on the grid chosen, the number of grid points (and hence observations) of the PSF reference star can be as high as 9 instead of one. The good news is that the FSM offsets are tiny compared with an FGS guider pixel, and so no reacquisition of the guide star is needed. The FSM motions themselves take relatively little time, so it is mainly the additional observation time that is required. Because of this efficiency hit, you should only select the SGD technique in cases where the highest suppression of target star light is needed, but in those cases, significant improvements can be garnered (LaJoie et al. 2016).

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Use of SGD data in the data processing

For observational sequences that include SGD data on the reference star, there are 2 possible processing algorithms to derive an improved PSF reference model for subtracting the residuals in the science image. They are KLIP (Karhunen-Lo`eve image projection) and LOCI (locally optimized combination of images). Initially, the pipeline will use the KLIP algorithm as part of standard processing. These algorithms use the small variations in the PSF speckle pattern from each SGD step to produce a model PSF that best matches the speckle pattern in the science target observation.

For details, refer to the publications by Lafreniere et al. (2007) and Soummer, Pueyo & Larkin (2012).

References

Lafrenière, D., et al., 2007, *ApJ*, 660, 770
A New Algorithm for Point-spread Function Subtraction in High-Contrast Imaging: A demonstration with Angular Differential Imaging

LaJoie, C-P, et al. 2016, *SPIE* 9904 Space Telescopes and Instrumentation: Optical, Infrared, and Millimeter Wave
Small-grid dithers for the JWST coronagraphs

Soummer, R., Pueyo, L. Larkin, J., 2012, *ApJL*, 755, L28
Detection and Characterization of Exoplanets and Disks Using Projections on Karhunen-Loeve Eigenimages

Soummer, R., et al., 2014, *SPIE* 9143 JWST-STScI-004142
Small-Grid Dithering Strategy for Improved Coronagraphic Performance with JWST

Published	27 Sep 2017
Latest updates	• 23 Dec 2019 Minor corrections • 16 Nov 2017 Added references and updated text

HCI Coronagraphic Sequences

JWST coronagraphic observations are normally executed together to minimize point spread function changes in science and PSF reference star observations.

On this page

See also: HCI APT Coronagraphic Sequence Examples
See also: Example Science Programs on NIRISS AMI and MIRI and NIRCam Coronagraphy

Most applications of high-contrast imaging require careful subtraction of diffracted light from the bright point source, the "host" source, in order to see the science targets that are the nearby faint "companion" sources. Recognizing the importance of optical stability, the STScI Coronagraphy Working Group has recommended that coronagraphic observations be grouped into sequences, to ensure they execute together in time. The goal is to minimize changes in the optics that might alter the point spread function (PSF). This goal leads to the concept of *coronagraphic sequences.* Details of these sequences will depend on the science goals of your program, including whether single or multiple filters/coronagraphs are needed, and whether small or large offsets in position angle are called for. Some details and examples are provided below.

There are aspects and options of coronagraphic observations—such as target acquisitions (TAs), full frame astrometric (FFA), and small grid dithers—that are specified within each observation template, but are not included explicitly in this article, which concentrates on organizing at the observation level.

For an example of an APT program that demonstrates the functionality of coronagraphic sequences, see HCI APT Coronagraphic Sequence Examples, which includes instructions on downloading an accompanying demonstration proposal available in APT.

The standard coronagraphic sequence

The *standard coronagraphic sequence* comprises 3 observations for each science target:

1. Observation of the science target in one spacecraft orientation
2. Second observation of the science target in a different spacecraft orientation (e.g., 10° roll)
3. Observation of a PSF reference star (to enable improved PSF subtraction in data processing)

The standard sequence uses a ***Sequence Observations ... Non-interruptible*** * APT special requirement to ensure the observations execute together and in the order shown, and to minimize possible thermal variations differentially affecting the acquired PSFs. The goal is to obtain the lowest limiting contrast by minimizing the opportunity for changes in the JWST wavefront between the 3 observations. The obvious inference from this is that the science target and PSF reference target must be schedulable in the same visibility windows. Visibility can be verified using one of the Target Visibility tools.

In the standard sequence, the 2 observations of the science target are referred to as a *roll dither*, which is done to mitigate hot pixels. Removal of hot pixels may be important if you are looking for point-like companions, but less important if you are looking at extended structure. The roll dither strategy is recommended as the default. The 10° value shown above is provisional, and assumes that the observation is scheduled at a time when the whole observatory can roll ±5° from its nominal position angle. In practice, the allowed offset from nominal varies from ±3.5° (7° total) to ±7° (14° total), as a function of solar elongation (longitude of the sun) at the time of the observation. Thus, forcing the roll offset toward the upper end of the range becomes very restrictive to scheduling because the windows of time where larger roll offsets can be accommodated get very small. (See JWST Position Angles, Ranges, and Offsets for more information.)

The PSF reference star observation is used to calibrate wavefront errors and other uncertainties in the TA process, and to support PSF subtraction in pipeline data processing. According to STScI policy, PSF reference star observations are non-proprietary; any exceptions must be justified in the technical description in your proposal. The goals of this policy are to facilitate the community's deeper understanding of the coronagraphic PSFs and to build a library of PSFs for all to use.

This standard sequence—or a derivative of it, as described below for other cases—is recommended for all coronagraphic programs. If you want to depart from this strategy, you must provide an explanation in the technical justification section of your proposal.

A single filter-occulter observation sequence

Here is a specific example of the standard 3-observation coronagraphic sequence using MIRI with a 4QPM coronagraphic mask and the F1065 filter:

1. Science target, MIRI, 4QPM, F1065
2. Science target, MIRI, 4QPM, F1065, 10° roll
3. Reference PSF target, MIRI, 4QPM, F1065

The 10° roll between observations 1 and 2 is the "roll dither," calling for 2 observations of the science target with a 10° position angle offset between them. Note that a roll dither is not performed on the reference star because, in most cases, it would not significantly improve results. Nevertheless, the user has the option of adding a roll dither to the reference observation as well, but at a cost in efficiency, because a 10° roll counts as a 10° slew of the observatory, even though the target remains the same.

In APT, the relative roll angle between the 2 science observations is specified using an ***Aperture PA Offset ...*** APT special requirement, which specifies the desired angle between the 2 science observations (e.g., +10° or –10°, in our example). The sign specifies the direction of the roll (see JWST Position Angles, Ranges, and Offsets). At a sufficiently large separation from the bright host star, the two roll-dithered science images can be differenced in post-observation processing to directly obtain a PSF subtraction. However, it is assumed that in most cases the goal is to detect structure around the host; therefore, a separate PSF reference observation is needed for PSF subtraction.

The 3 observations in the standard sequence are also linked in APT using the ***Sequence Observations ... Non-interruptible*** special requirement to ensure that they are executed in order.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Standard sequence implementation for multiple filters and occulters

The on-orbit stability of JWST is not yet known. As a consequence, the current policy is conservative, sometimes requiring many science and PSF reference star exposures in the same time frame. If implemented strictly, this strategy can result in inefficient scheduling.

For example, consider the use of coronagraphy to characterize the atmosphere of a known exoplanet using multiple filters. If the rules are strictly applied, the result is multiple standard coronagraphic sequences as outlined above, one for each choice of filter and occulter. To identify alternative strategies, a study was conducted by STScI to quantify the overheads associated with 2 possible observing strategies:

1. An *optimal wavefront stability* strategy, where standard sequences are consecutive in each filter to minimize the chance of any wavefront changes. This strategy increases the number of slews and rolls for the telescope.

2. An *optimal efficiency* strategy, where observations for a given target are organized—in each filter and occulter—to minimize the number of rolls and slews. This strategy increases the time between an observation of a target in a given filter and the corresponding reference PSF star observation in the same filter, but it results in more efficient use of the observatory.

The detailed study found that the optimal wavefront stability approach can require up to several hours more overhead per science target, depending on the number of filters and occulters being used. Hence, the optimal efficiency strategy is recommended, unless on-orbit operations reveals PSF variability on short times scales.

Building a coronagraphic sequence with multiple filters

Using the optimal efficiency strategy, here is how a user could implement multiple filters-occulters in a standard sequence. The following non-interruptible sequence of 6 observations is an example:

1. Science target, MIRI, 4QPM, F1065
2. Science target, MIRI, 4QPM, F1140
3. Science target, MIRI, 4QPM, F1065, 10° roll
4. Science target, MIRI, 4QPM, F1140, 10° roll
5. Reference PSF target, MIRI, 4QPM, F1065
6. Reference PSF target, MIRI, 4QPM, F1140

This example involves 2 MIRI filters, but if NIRCam were the instrument, more filters could also be added to such a sequence.

This choice of ordering the observations—changing the filters-occulters before changing the target—minimizes slew overheads.

Using the APT **Special Requirement** tab, the user should link multi-filter observations with the ***Sequence Observations ... Non-interruptible*** special requirement in the same way as for the single filter case.

Linking too many observations together into a sequence can make the total execution time long, to the point that the observations cannot be scheduled. Therefore, you should seek to strike a balance between efficiency and the pragmatic aspects of scheduling observatory activities.

You may find it instructive to inspect the reports that are generated by running **Smart Accounting** in APT. These files provide a more detailed breakdown of where various overheads are being charged and will help you understand the tradeoffs in efficiency for the different models. See the articles on the APT Visit Planner and APT Smart Accounting for more information.

Alternate sequences for other science cases

Larger roll offset case

Depending on the science case, it may be necessary to obtain a larger roll offset on the science target than can be obtained in a single pair of roll-dithered observations. For example, the occulter in a given coronagraph may block part of the scene that the observer wants to see, and the ~10° roll is not sufficient. In this case, the only option is to break the ***Sequence Observations ... Non-interruptible*** requirement and schedule an observation at another time, when the larger position angle change can be accommodated.

In this case, you should structure 2 coronagraphic sequences, which are then linked together with special requirements in APT to accomplish the science. Here is a specific example:

1. Science target, MIRI, 4QPM, F1065, initial PA
2. Reference PSF target, MIRI, 4QPM, F1065, initial PA
   (Obs 1 and 2 ***Sequence Observations ... Non-interruptible***
3. Science target, MIRI, 4QPM, F1065, PA offset by 30°
4. Reference PSF target, MIRI, 4QPM, F1065, PA offset by 30°
   (Obs 3 and 4 ***Sequence Observations ... Non-interruptible***)

For this scenario, you have the option of whether or not to include the ~10° roll dither in the individual sequences or simply schedule 2 pairs of science and PSF reference star observations, as shown above. The Coronagraphic Visibility Tool can be used to assess the availability of multiple position angles, and estimate what the time separation will be. It is expected that each sequence will contain an observation of a relevant PSF reference star, since the PSF will likely change between the 2 epochs. This information can then be used with the special requirements in APT to request the needed observations. See HCI APT Instructions for details.

Shared reference survey case

If a set of science targets are clustered on the sky in close proximity, it may be possible to economize by observing more than one science target in sequence before observing one or more PSF reference targets. This is called the *shared reference* case, because it breaks the pairing of individual science PSF observations in the normal coronagraphic sequence. An example might be a grouping of stars in a star forming region:

1. Science target #1, MIRI, 4QPM, F1065
2. Science target #2, MIRI, 4QPM, F1065
3. Science target #3, MIRI, 4QPM, F1065
4. Science target #4, MIRI, 4QPM, F1065
5. Science target #5, MIRI, 4QPM, F1065
6. PSF Reference target, MIRI, 4QPM, F1065

All 6 targets need to schedulable at the same time, and the ***Sequence Observations ... Non-interruptible*** special requirement would be placed on this entire set. The single PSF reference observation would get used for all 5 science targets. Some users may wish to schedule 2 PSF reference targets in order to guarantee at least one good PSF observation, if the characteristics are uncertain. Or the observation of the PSF reference star could be scheduled in the middle of the sequence, at the user's discretion. The point is, there is no one-to-one pairing of science and PSF reference observations as is done in the standard sequence.

Self-referenced survey case

The *self-referenced* survey case is a slight variation on the shared reference case. Here, the user decides to observe a set of targets not knowing which may show surrounding structure and which may not. The assumption is that some targets will be for science, but others—the ones not showing surrounding structure—will be used for PSF reference observations. Unfortunately, the question of which are which cannot be determined until after the observations are obtained. So for instance:

1. Science target #1, MIRI, 4QPM, F1065
2. Science target #2, MIRI, 4QPM, F1065
3. Science target #3, MIRI, 4QPM, F1065
4. Science target #4, MIRI, 4QPM, F1065
5. Science target #5, MIRI, 4QPM, F1065
6. Science target #6, MIRI, 4QPM, F1065

All 6 targets need to schedulable at the same time, and the ***Sequence ... Non-interruptible*** special requirement would be placed on this entire set. Since this is a special case, with no explicit PSF reference observations, 2 things need to happen: you need to carefully explain your assumptions in the technical justification portion of your proposal, and a box to this effect must be checked in APT. You also still need to select one of the targets to use as an initial PSF observation, to be used by the data processing system in its initial processing. See HCI APT Instructions for details.

Use of the small grid dithering technique

Main article: HCI Small Grid Dithers
See also: NIRCam Small Grid Dithers

The target acquisition accuracy with JWST cannot guarantee the same precise alignment of science targets and PSF reference targets on the coronagraphic occulters. For cases where the highest accuracy of PSF subtractions is desired, users can choose to apply a strategy of small grid dithers (SGDs).

SGDs can mitigate possible subpixel coronagraph misalignments between science and reference images. This strategy utilizes a defined set of subpixel dithered exposures to optimize coronagraphic PSF subtraction, which occurs in subsequent data processing. SGDs provide increased speckle diversity, which can be used to reconstruct an optimized, synthetic, reference PSF using one of the advanced PSF subtraction algorithms (Lafrenière et al. 2007; Soummer et al. 2012). While SGDs can be selected for observations of either a science target or a PSF reference star, it is envisioned that most users will apply it only to the PSF reference observation.

The SGD's subpixel dithers are executed with the fine steering mirror (FSM) under fine guidance. They are accurate to ~2–3 mas (1-σ/axis). Because they are executed using the FSM, their overhead is small. Nevertheless, the requested observation time increases as the number of dither points in the selected SGD pattern. The allowed (pre-defined) SGDs are readily available for MIRI and NIRCam by selecting the appropriate dither pattern in the relevant coronagraphic imaging template in APT. Simulations indicate that performance gains using the SGD strategy, compared to the standard undithered scenario, range from a factor of 2 for NIRCam to more than a factor of 10 for the MIRI 4QPM coronagraphs.

Details can be found in Lajoie et al. 2016.

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Published	18 May 2017
Latest updates	

HCI APT Coronagraphic Sequence Examples

Examples of how to specify JWST coronagraphic sequences, one for MIRI and one for NIRCam, are available in the Astronomer's Proposal Tool (APT).

On this page

See also: High Contrast Imaging Overview

Getting started

In APT, the **File → JWST Demonstration Proposals*** option provides 2 coronagraphy example programs: **MIRI Coronagraphic Example** and **NIRCam Coronagraphy Example**. These 2 examples show how the "MIRI Coronagraphic Imaging" and "NIRCam Coronagraphic Imaging" APT templates, respectively, are filled out.

A standard coronagraphic sequence involves a set of linked observations; these simple examples demonstrate the process by showing the appropriate special requirements needed for the linking. More complicated combinations using multiple filters and/or coronagraphs are also possible. Also, there are more complex ways of specifying PSF reference star observations than shown in these simple examples below. Refer to the HCI Roadmap (Stage 3 section) for details.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

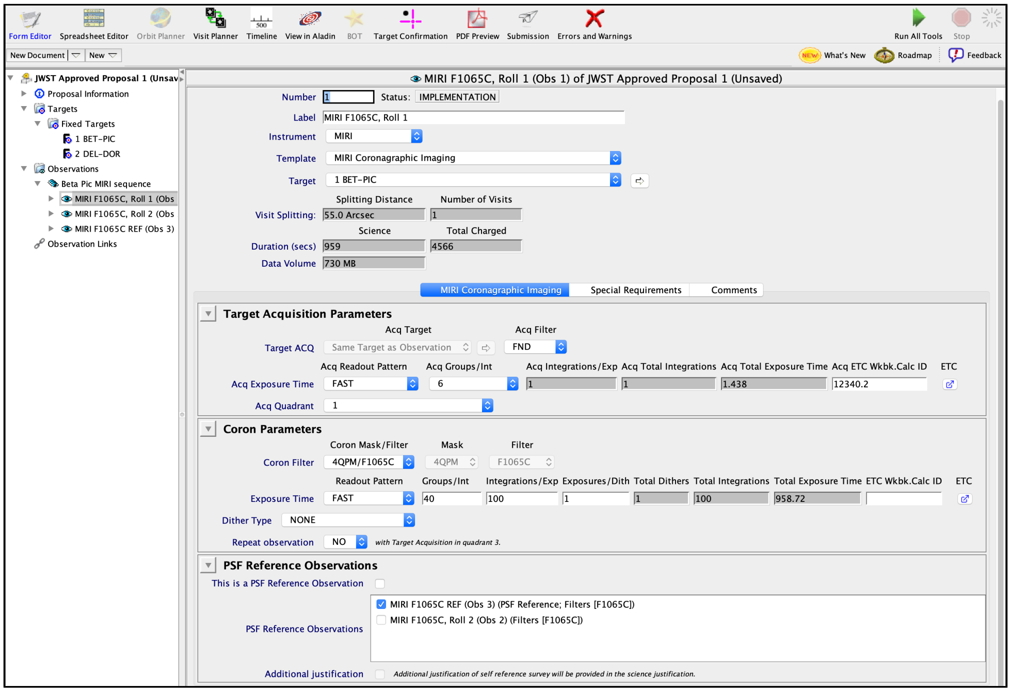
A MIRI example

The **MIRI Coronagraphy Example** can be loaded and viewed in APT as you walk through the example below. See MIRI Coronagraphic Imaging and related articles for detailed information about coronagraphy with MIRI.

There are 2 targets in this example: BET-PIC (the science target) and DEL-DOR (the PSF reference star). A standard coronagraphic sequence involves 2 observations of the science target and at least one observation of the PSF reference star, all linked together in a non-interruptible sequence. (This is done to minimize thermal or other changes that could cause the PSF to vary significantly.)

These observations have already been added to the APT MIRI example. After loading the example into APT, select the **Observations** folder in the left tree menu to see the filled out template information in the active GUI window, as shown in Figure 1. Note the template panels labeled **Target Acquisition Parameters**, **Coron Parameters**, and **PSF Reference Observations,** which will be further described below.

Figure 1. The APT GUI for a MIRI coronagraphic sequence



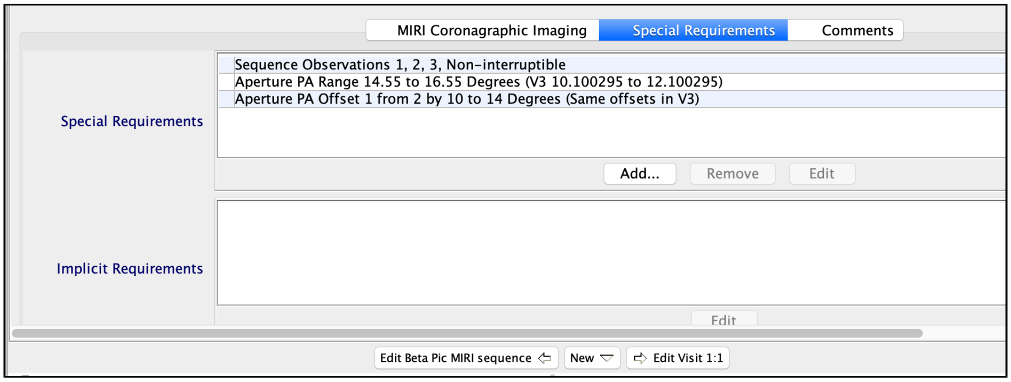
The appearance of the APT GUI for a simple MIRI coronagraphic sequence. In the tree editor at left, observations 1 and 2 are both on the science target, and observation 3 is of the PSF reference star. In the active GUI window, one sees template sections for the target acquisition, the coronagraphic exposure specifications, and the PSF reference star assignment section.

Special requirements

The science target is observed twice using a single MIRI 4QPM/filter combination. The initial science observation has an allowed roll angle range. (This is only necessary if there is known structure around the target, say a disk or a known planet, and the target needs to be positioned to avoid structures in the instrument field of view, in this case, the 4QPM quadrants boundaries.) The second science target observation has a roll angle offset relative to the first one, called a *roll dither*[2].

Figure 2 shows the special requirements that have been set to control this sequence.

Figure 2. Special requirements set for Observation 1

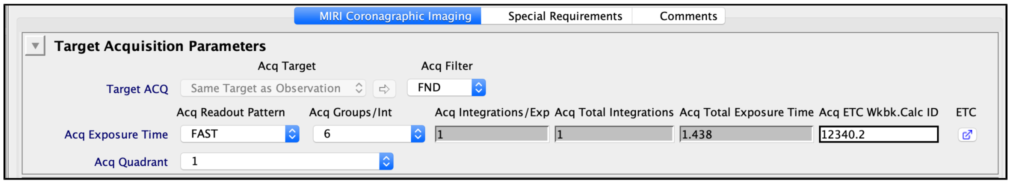


Clicking on the Special Requirements tab in this example of the APT MIRI coronagraphy template shows special requirements for the first observation. The aperture position angle is set to a fairly narrow 2° range, and an offset angle range of 10°–14° is set between observations 1 and 2. Finally, a non-interruptible sequence requirement is placed on the 3 observations, meaning that the science and reference star observations need to be schedulable at the same time (this can be checked in the APT Visit Planner).

Target acquisition parameters

Target acquisition (TA) parameters are shown in Figure 3. Legal (but unverified) values have been entered. In reality, you will need to assess the proper TA parameters for each target using the Exposure Time Calculator to ensure a successful observation. *This has not been done for this example.* An important option is to cross-reference the ETC workbook and/or calculation you used using the box at right. This can help you reconstruct your assumptions at a later time. See the APT-ETC Connectivity article for details.

Figure 3. Target acquisition parameters for the MIRI 4QPM case.



The MIRI target acquisition parameters section of the template is shown. The Acq Quadrant selection allows the user to avoid having a persistence spot in the quadrant where a possible source is expected to be. See MIRI Coronagraphic Target Acquisition for details.

Coronagraph parameters

The **Coron Parameters** block (see Figure 1) of the template is where the science exposure parameters are specified. These parameters should be set based on calculations performed with the Exposure Time Calculator, after selecting the parameters appropriate for the MIRI coronagraph.

PSF reference star observation

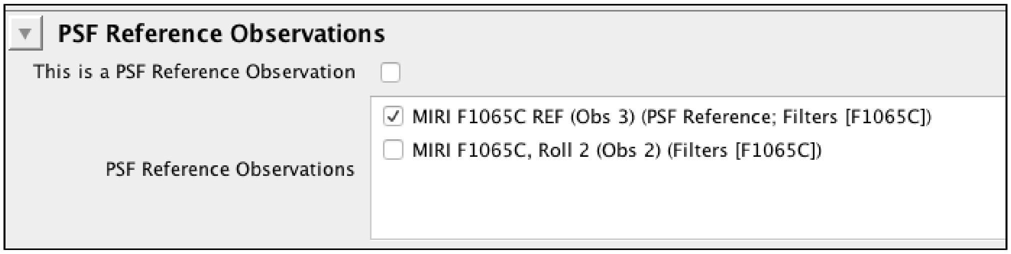
Finally, even though the SEQ NON-INT special requirement has grouped the observations together, information must be provided to the Data Management System (DMS) on how to connect the PSF reference star observation to each of the science observations. The **PSF Reference Observations** section, at the bottom of the template, is used for this purpose. Note that in APT, you may have to scroll down to see that block. For Observation 3 (the PSF reference star observation), simply select the appropriate check box:

Figure 4. Setting the PSF reference star observation for DMS

After selecting the check box to indicate this is a PSF reference observation, the unneeded portion of the PSF Reference Observations block goes away.

Then, for each of the science observations, this reference observation needs to be selected from the pick list provided, as shown in Figure 5.

Figure 5. Selecting the PSF reference star observation for a science observation, to be passed to DMS



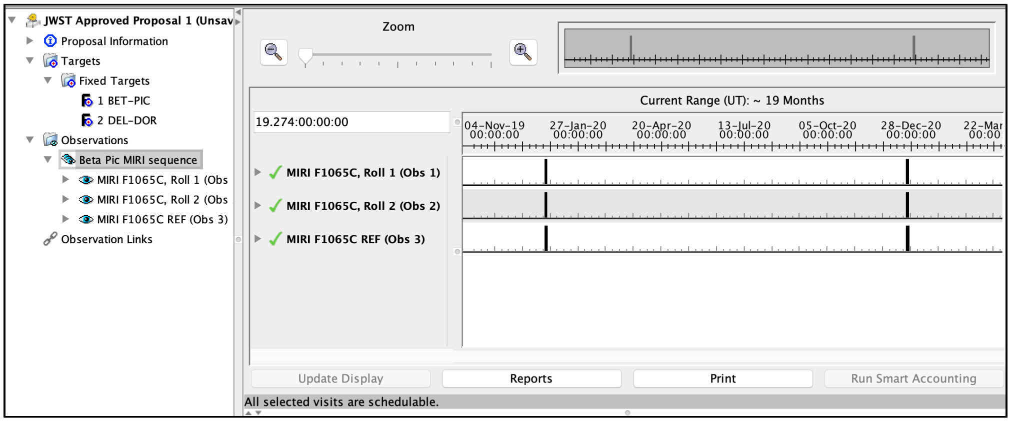
After selecting the check box as shown, a legal PSF reference observation has been selected and any red error X's should go away.

Visit Planner

When all observations in the defined coronagraphic sequence have been completely specified, you can run the Visit Planner (VP) to check schedulability. For the defined sequence to be schedulable, both of the 2 science observations and the PSF reference observation must be observable without interruption. APT will check this, as well as check for available guide stars and other constraints affecting angles and visibilities.

Figure 6 shows the VP display after selecting the observation folder containing the sequence and running the **Visit Planner**. If you have opened the example program in APT, it may show yellow caution signs by each observation. Simply click the red ***Update Display*** button and in a few seconds, green checks should appear, meaning not only is the visibility good for both targets at the same time, but guide stars are also available for all 3 observations as specified. Any time the parameters in the observation template are changed, a new run of the VP will be needed. (Try it!)

Figure 6. A Successful Visit Planner run.



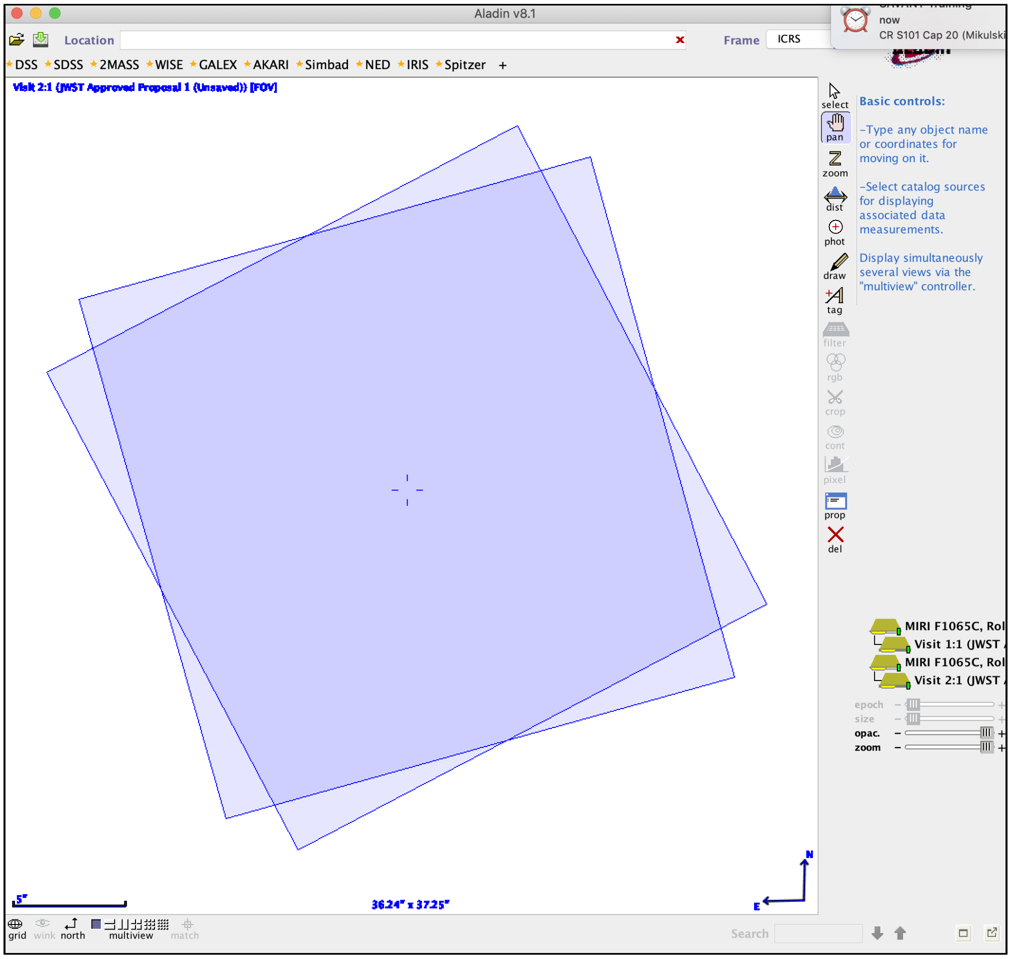
The observation folder containing the sequence is selected and the Visit Planner has been run, returning "all green" check marks, thus confirming schedulability. Note the very narrow windows in time, however, caused by the constrained aperture PA requested in the Special Requirements panel. These are highly constrained observations.

In Figure 6, although the sequence is schedulable, note the very narrow windows in time, thus making the scheduling of this sequence very constrained. This highlights the fact that users should only constrain the requested angles when necessary to support their science goals and even when an angular constraint is placed, the larger the range that can be allowed the better (from the standpoint of allowing scheduling flexibility). As an exercise, the user can try editing the special requirement that sets the allowed range of angles on the first observation and re-run the **Visit Planner** to see how the allowed time window changes.

Aladin

While not required, viewing the observations in Aladin can be a useful sanity check to confirm that that the angle had been selected properly and the roll dither had been specified as intended. In Figure 7, we selected the 2 science observations (that is, in the form editor, select Observation 1, then shift-select Observation 2, which should highlight both observations, then choose **View in Aladin** from the top tool bar in the APT GUI). Since we allowed a range of 10°–14° for the offset, Aladin shows the mean, which is a 12° offset, in the display.

Figure 7. The Aladin display after selecting the two science observations



The Aladin display after selecting the 2 science observations. (Select one, then shift-click the second one; Aladin will display both.) This shows both the selected absolute orientation and the offset specified between the 2 observations. In this example, the Digital Sky Survey (DSS) image was not displayed because the brightness of the target star makes it difficult to see the instrument fields of view.

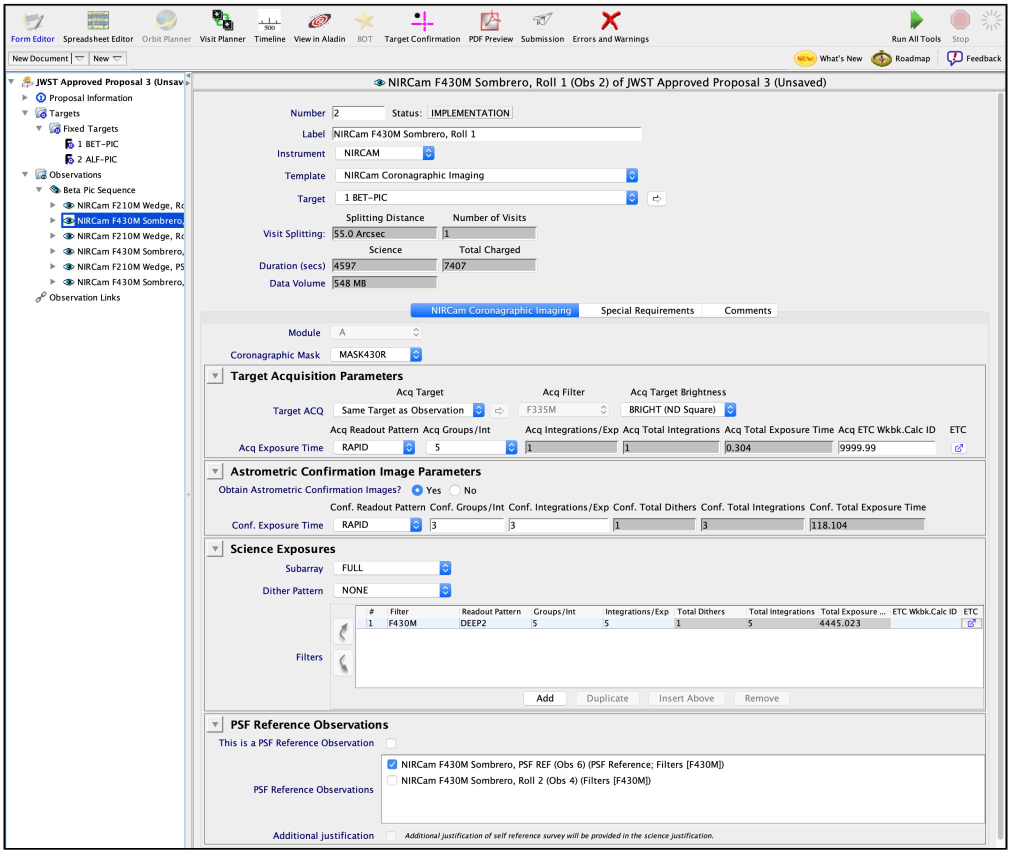
[2] Roll dithers are limited by JWST observing constraints to be <14°. See the JWST Dithering Overview.

A NIRCam example

The **NIRCam Coronagraphy Example** demonstration in APT can be loaded and viewed as you walk through the example below. Refer to the NIRCam Coronagraphy and related support pages for detailed information.

The example proposal contains 2 targets, BET-PIC (which represents the science target) and ALF-PIC (which represents the PSF reference star). In this example, we step up the complexity only slightly from the previous MIRI example by having the sequence contain observations with 2 coronagraphs/filters instead of one. In this case, all the observations are done at the initial position angle (roll 1) before moving to the offset roll dither position angle (roll 2). Of course, a single observation in each setup is used on the PSF reference star, so they are put together at the end of the sequence. Hence, this sequence contains a total of 6 observations instead of 3, all of which must be schedulable together in order to be valid.

Figure 8. The APT GUI for NIRCam observations using two coronagraphic/filter sequences, showing the Observation 2 template

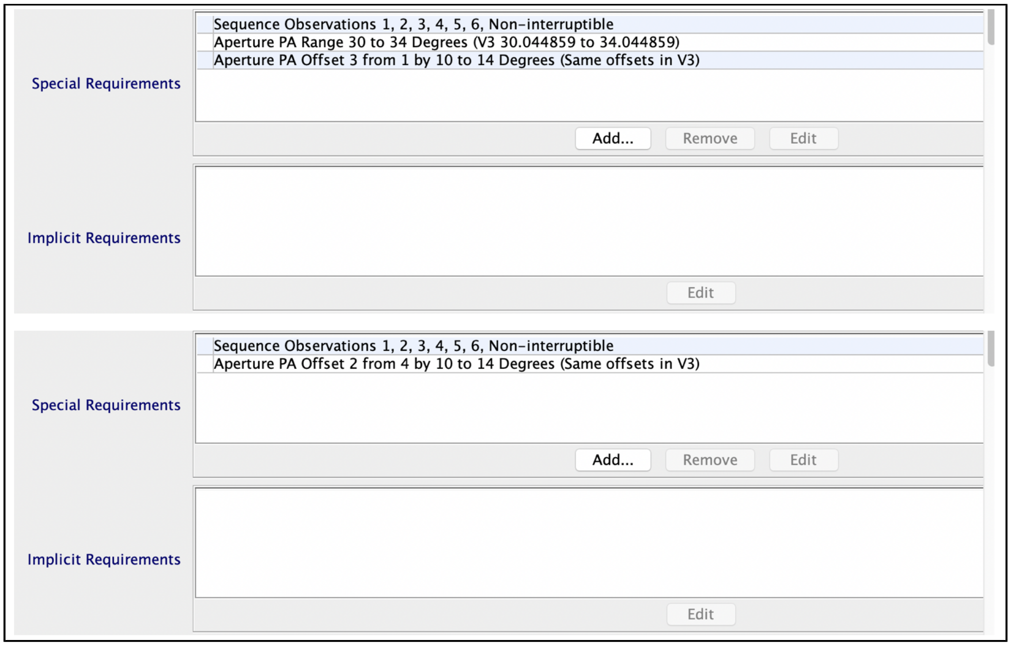


The APT GUI for a NIRCam coronagraphic observation. This template has blocks for Target Acquisition Parameters, Science Exposures, and PSF Reference Observations selections (similar to the MIRI template) but also has a section for specifying parameters for an optional Astrometric Confirmation Image, if desired.

Special requirements

First notice the observation order: observations with the 2 different coronagraph/filter combinations are done at roll 1 prior to the roll dither. Then, both of the observations are repeated after the roll dither. Finally, the PSF reference star is observed in both coronagraph/filter configurations but at a single roll angle. Figure 9 shows the Special Requirements for this example. Setting the special requirements in this case is a bit different from the MIRI case above, but notice all 6 observations are linked in the sequence, so they will execute together. Of course, this means that the PSF reference star must be observable at the same time as the science target.

Figure 9. The special requirements for Observations 1 (top) and 2 (bottom)



An absolute aperture position angle restriction is set, and then the desired relative aperture PA ranges between the pairs of observations with the same configuration is set (e.g., obs. 1 & 3, and obs. 2 &4). The "Sequence...Non-interruptible" means the entire set of observations will by executed back-to-back, and hence at the same absolute orientation.

In this example, as with MIRI above, we have assumed that the aperture PA needs to be constrained, and we have specified a range from 30°–34°. The offset in PA is set between observations 1 and 3, that is, two observations with the same configuration (F210M Wedge). The "Sequence...Non-interruptible" special requirement ensures the *two different configurations* execute together and are hence aligned.

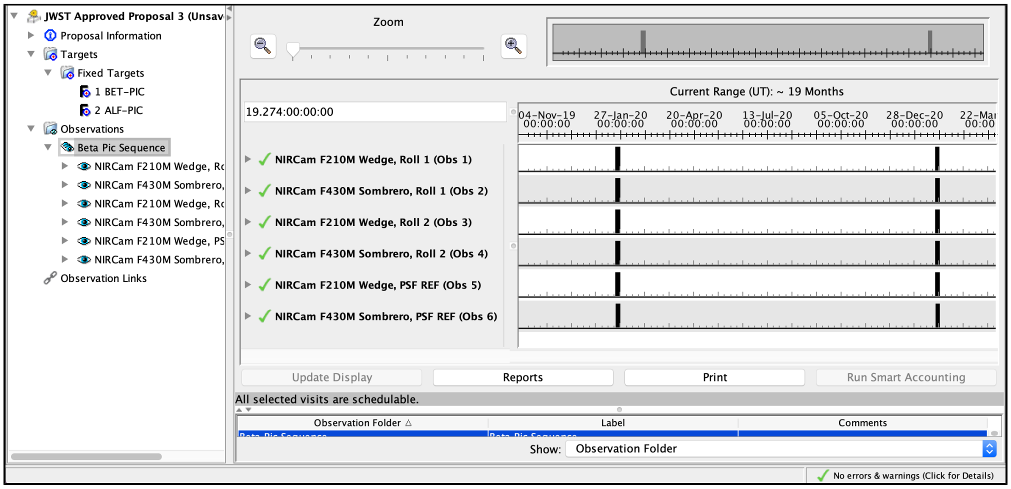
⚠ The "SEQUENCE ... NON-INTERRUPTIBLE" special requirement indicates that the specified set of observations will be done in "increasing observation number" order. In the example, the observations are shown in order of 1 to 6 in the tree editor (left sidebar). However, for general editing in APT, users are allowed to drag and drop observations in the tree editor. *If a user reorders the observations in a sequence using this method, it does not change the execution order, which is done via the observation number.* Hence, users should check that their desired order for the sequence is consistent with the ordering on the listed observation numbers.

The specification of PSF reference observations and their proper attachment to each of the science observations proceeds exactly as outlined in the MIRI example.

Visit Planner

As shown in Figure 10, even with a sequence of 6 observations, the **Visit Planner** has been able to verify that there is a time when all 6 observations can be scheduled together. Again, as with the MIRI example above, the fairly narrow range of allowed absolute PA placed on observation 1 results in a rather small window of schedulability, so this type of restriction should only be placed when necessary for the science.

Figure 10. A successful Visit Planner run for the 6-observation sequence

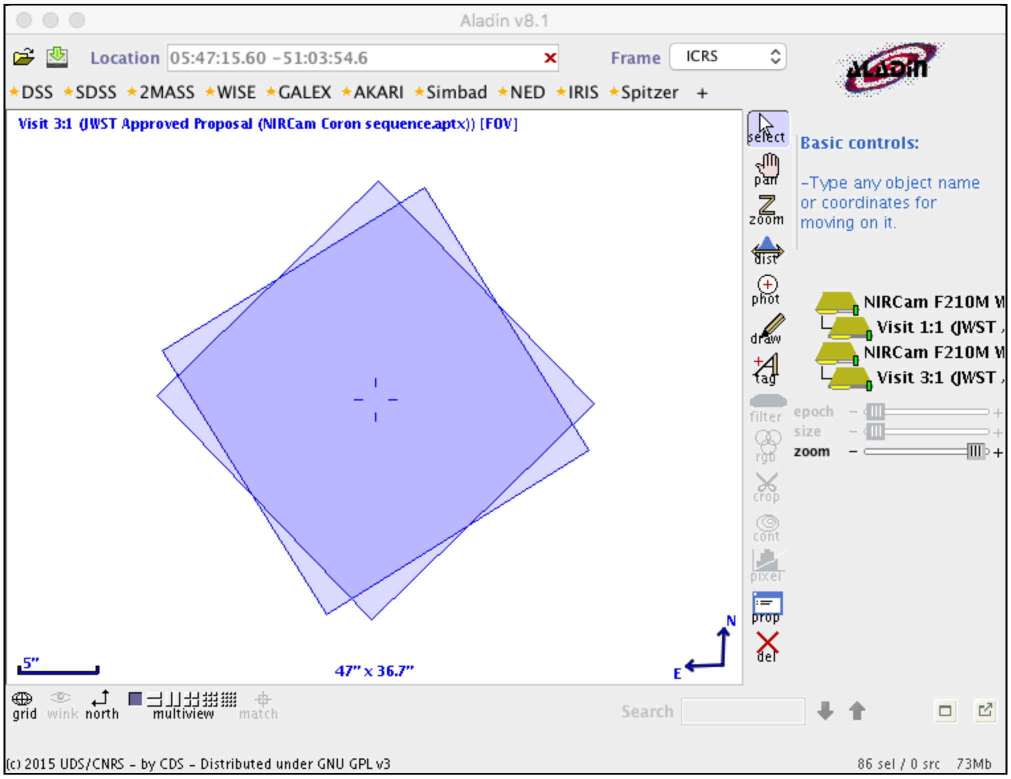


A successful VP run for NIRCam, demonstrating schedulability despite the setting of the angular offset special requirements needed in this example.

Aladin

Finally, if you wish to perform a sanity check on the angular offset between the 2 rolls on the science target, you can select the relevant observations in the tree editor and click **View in Aladin**, as shown in Figure 11.

Figure 11. This Aladin view confirms the desired roll offset between observations 1 and 3



This Aladin view confirms the desired roll offset between observations 1 and 3. Note that only the small field of view relevant to the NIRCam coronagraph is shown rather than the full NIRCam imaging field of view.

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HCI PSF Reference Stars

JWST high-contrast imaging (HCI) often requires the observation of a nearby, unresolved reference star with similar spectro-photometric properties to the target of interest, to ensure effective PSF subtraction.

On this page

Main articles: NIRCam Coronagraphic PSF Estimation, NIRCam Coronagraphic Imaging Recommended Strategies, NIRISS AMI Recommended Strategies
See also: MIRI Coronagraphy of GJ 758 b, NIRCam and MIRI Coronagraphy of the Beta Pictoris Debris Disk, NIRISS AMI Science Use Case

The baseline strategy for high-contrast imaging (HCI) with JWST includes the observation of a nearby star to generate an unresolved, high signal-to-noise (SNR) point spread function (PSF) to subtract from the science target, thereby reaching the highest possible contrast, with the goal of revealing faint astronomical signals surrounding the science target. This method is known as reference differential imaging (RDI).

Several factors can affect the quality of the RDI technique:

- the PSF reference star is not single or is resolved (e.g., binary or disk)
- the target acquisition (centering, in the case of a coronagraph) of the science target and PSF reference star differ (the PSF reference star is acquired at a different position and time)
- position or thermally-induced wavefront drifts of the observatory resulting in the PSF reference star being no longer exactly the same as when the science target was acquired
- the science target and PSF reference star differ in color or spectral energy distribution

The first factor can be addressed by selecting known good PSF reference stars, but this is not always trivial. The second factor can be addressed by using the small grid dither technique. The observer can minimize the impact of the latter two factors by (1) choosing a reference star in relative proximity to the science target (to mitigate thermal changes) and (2) by selecting a reference star that is spectro-photometrically similar to the science target. Choosing a nearby reference star also minimizes the telescope overheads (by reducing slew time). By including the science observation(s) and the PSF reference observation in a non-interruptible sequence, the visibility windows of the science and reference star must necessarily overlap at the time of the desired observation.

So how close in the spatial dimension must the science PSF star be to minimize thermal effects, and how close in spectral properties must they be for an acceptable match? There is no simple answer, but some guidelines may help:

Effect of spectral "mismatch"

See also: HCI Inner Working Angle

The spectral mismatch between a science target (hereafter “SCIENCE”) and its designated PSF reference star (hereafter “REFERENCE") has a stronger impact at shorter wavelengths and with wider filters. For a simple monochromatic case (narrowband filter in the continuum), when performing the PSF subtraction (SCIENCE − REFERENCE), one needs to account for the flux difference and photometrically rescale the REFERENCE. If the REFERENCE is fainter, the process of flux rescaling also scales the noise, and that is why it is recommended to use brighter REFERENCE(s) whenever possible.

If one thinks in terms of spectral energy distribution (SED) for both objects binned in spectral channels, the ideal photometric scaling factors can vary significantly from one spectral channel to the next. One can measure it empirically on the data but only in the spectral bandwidth of the filter. If it is a broadband filter, only an average scaling factor will be applied to the whole polychromatic image which can be thought of a superimposition of many PSFs at different wavelengths. The spectral mismatch between SCIENCE and REFERENCE will thus not only generate extra noise but allow possible under- and over-subtraction at various spatial locations of the PSF. Over-subtraction leads to negative fluxes and affects the estimation of the contrast and hence the detection limits. If one of the objects has strong emission features in its spectrum in the spectral bandwidth that is considered, the effect can be dramatic.

The Exposure Time Calculator (ETC) calculates the flux for each object through a given filter, accounting for the spectral type (or user-provided spectrum). However, the ETC considers the PSF profiles to be exactly the same and hence does not account for the loss in sensitivity due to under- and over-subtraction caused by a spectral mismatch.

This effect is assumed to be negligible above ~5 μm (hence for MIRI). Also, the effect will be obviously stronger closer to the center of the PSF and/or where the coronagraphic 3-D profile has structures (i.e., <10 λ/D). Further out, in the background-limited regime, the effect will be minor. At longer wavelengths, the background-limited regime takes over quickly from the speckle-limited regime where the effect can be substantial.

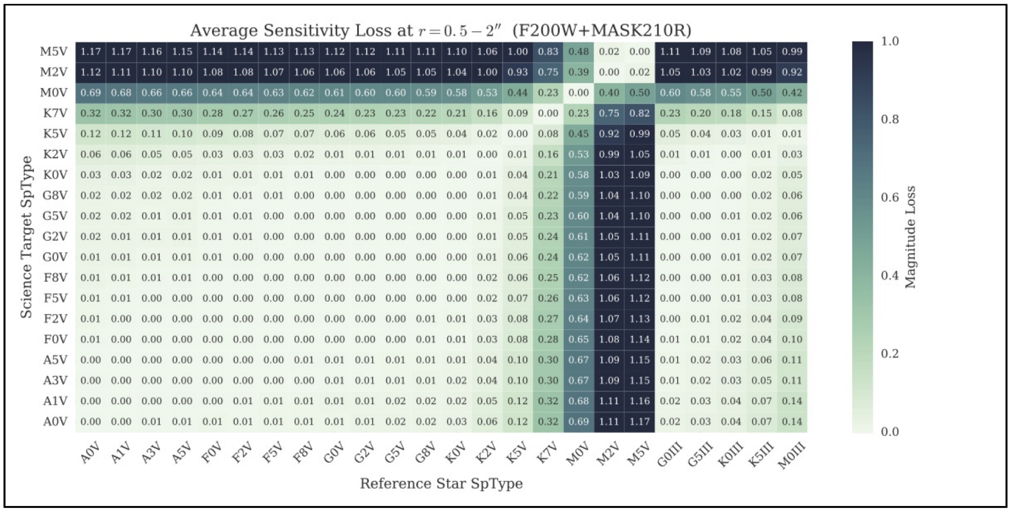
Effect for NIRCam coronagraphy

The NIRCam team has evaluated the effect of spectral mismatch on sensitivity for separations between 0.5” and 2” from a central object. These calculations were performed using pyNRC, a Python-based tool making use of WebbPSF. Figures 1–3 show the results for 3 of the most common filters (F200W, F322W2, and F444W) for NIRCam coronagraphic imaging with round occulting masks.

Note: these calculations only account for the effect of spectral mismatch between a science target (vertical axis) and a PSF reference (horizontal axis). They suppose that everything else is optimal (i.e. no thermal drift-induced wavefront errors, no misregistration). Therefore this loss of sensitivity should be thought of as the "best case scenario" if everything else is well mitigated thanks to good observing and PSF subtraction strategies. It is probably safe to assume these results are reliable beyond 1" separation, as inside this region other effects will dominate any spectral mismatch effects. Nevertheless, in many cases the loss of sensitivity due to spectral mismatch may be acceptable and constraints on the spectral type may be relaxed in favor of suitable reference stars that are brighter and/or closer on the sky.

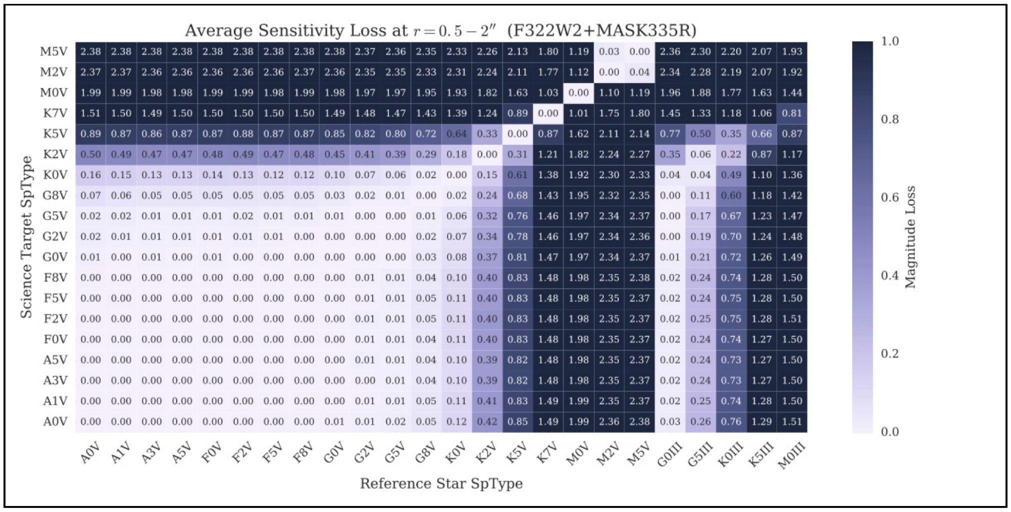
Web users may click on the figures for a larger view.

Figure 1. Estimated sensitivity losses due to spectral mismatch for NIRCam coronagraphy in F200W



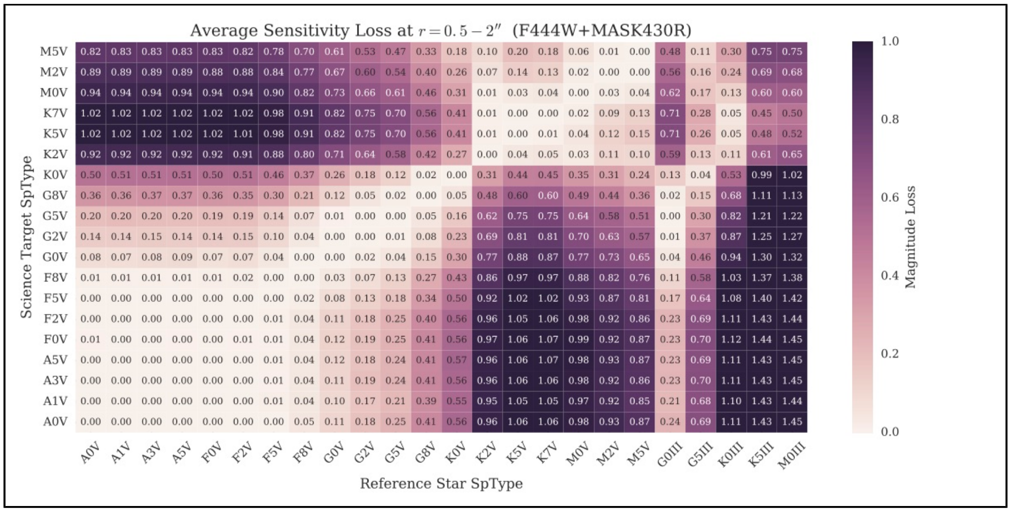
Estimated average sensitivity losses (in magnitudes) due to spectral mismatch between a science target (vertical axis) and a PSF reference (horizontal axis) for separations 0.5”–2” with NIRCam coronagraphy over the whole spectral bandwidth of the F200W filter and using the round occulting mask MASK210R. Other sources of sensitivity loss (including thermal drift and mis-registration) are not considered here.

Figure 2. Estimated sensitivity losses due to spectral mismatch for NIRCam coronagraphy in F322W2



Estimated average sensitivity losses as in Figure 1, but for F322W2 and the round occulting mask MASK335R.

Figure 3. Estimated sensitivity losses due to spectral mismatch for NIRCam coronagraphy in F444W



Estimated average sensitivity losses as in Figure 1, but for F444W and the round occulting mask MASK430R.

Selecting PSF reference stars with Simbad

Using Simbad's **Query by coordinates*** form, users can enter the coordinates of the science target and look exhaustively, to the catalogs' sensitivity limit, in a region surrounding the target of interest. From the returned table, one can sort by distance (in arcseconds), spectral type, magnitude and eventually narrow down the search, iteratively, to find the best suited PSF reference stars. Since JWST is mainly an infrared telescope, users should enable the search to include J, H, and K band magnitudes (that are most convenient for comparison with the science target); this is done prior to executing the query by clicking on the ***Output options*** button that opens the **Options and output parameters** form where these magnitudes can be selected at the ***Fluxes/Magnitudes*** parameter.

Using Simbad's **Query by criteria** form, users can search specific ranges of right ascension, declination, magnitude, and even spectral type. Here is an example query to search for a PSF reference star in the vicinity of Beta Pictoris with similar properties:

```
rah >= 04 & rah <= 07 & dec > -70 & dec < -40 & Kmag <= 4 & sptypes <= 'A9'
```

The returned results are:

```
Number of objects : 6

#|       identifier        |typ|  coord1 (ICRS,J2000/2000)   |Mag V |Mag K |  spec. type    |#bib|#not
-|-------------------------|---|---------------------------|------|------|---------------|----|----
1|* bet Pic                |*  |05 47 17.08769 -51 03 59.4412| 3.86 | 3.48 |A6V            |1149|   1
2|* del Dor                |*  |05 44 46.37811 -65 44 07.9011| 4.36 | 3.71 |A7V            |  50|   0
3|* alf Dor                |a2*|04 33 59.77719 -55 02 41.9243| 3.28 | 3.52 |B8IIIpSi       |  46|   0
4|* nu. Pup                |Ce*|06 37 45.67135 -43 11 45.3602| 3.17 | 3.39 |B8III          |  35|   0
```

```
5|* alf Car              |*  |06 23 57.10988 -52 41 44.3810|-0.74 |-1.35 |A9II            | 149|   0
6|* alf Pic              |PM*|06 48 11.45512 -61 56 29.0008| 3.30 | 2.570|A8VnkA6         |  67|   0
================================================================================
```

Notes:

- In order to get such output with Simbad, one needs to select the ***Return/display*** option.
- ***Mag K*** (as well as many other parameters) can be selected using the ***Output options*** page of Simbad, available from the top menu.
- The Python package Astroquery should allow users to perform similar Simbad and/or VizieR queries in a command line or batch manner.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Selecting PSF reference stars with SearchCal

The Jean-Marie Mariotti Center (JMMC) has created tools for the community including SearchCal, a GUI that allows users to select suitable, non-resolved calibrator targets matching various criteria. While SearchCal was designed for long-baseline optical/IR interferometry (hence the squared visibility criterion), it can easily be used to match JWST HCI needs. It offers a practical and graphical way to narrow down a search of PSF reference stars from a catalog of 2.5 million pre-selected stars (with computed and/or measured stellar diameters).

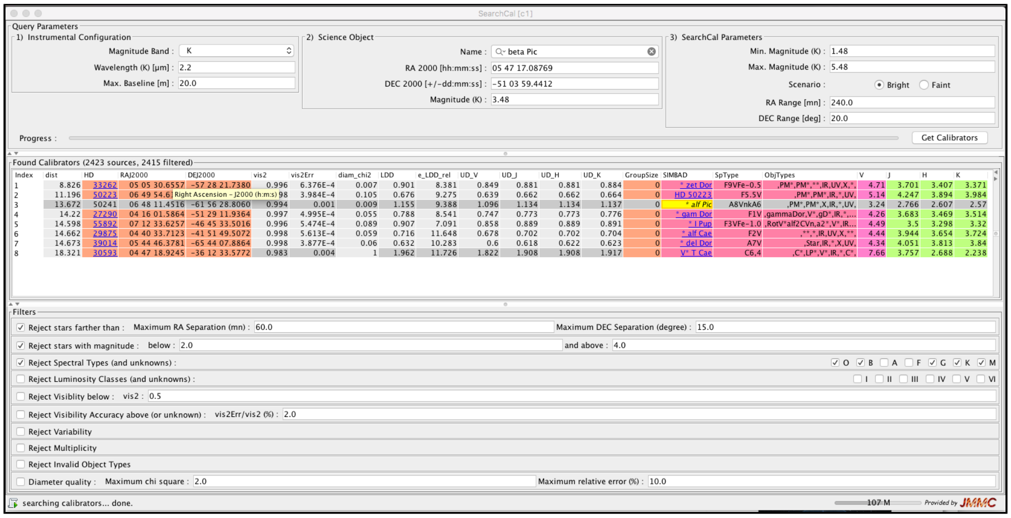
To use SearchCal for your JWST HCI needs:

- Query your science target in the ***Name*** field of the GUI (top, center)
- Select ***K*** as the ***Magnitude Band*** in the **Instrumental Configuration** box (top, left). The K band magnitude of the object will automatically be fetched from Simbad.
- Chose your ***Scenario*** in the **SearchCal Parameters** box (top, right):
    - ***Faint***: All 2.5 million stars from the catalog are browsed and returned in a circular patch with a maximum radius of 3,600 arcmin (60º).
    - ***Bright***: The research field is then a rectangular box, with a maximum size of 240.0 min (60º) in right ascension and 30.0º in declination, The stars are on average brighter and have a known spectral type. Since we care about the spectral type for the reasons explained in the section above, the ***Bright*** scenario is preferred as the first iteration, unless no suitable star is found.
- Click on the ***Get Calibrators*** button (top right corner below the **SearchCal Parameters** box); this will produce a list of objects in the **Found Calibrators** middle sub-panel
- Use the **Filters** (bottom sub-panel) to narrow down the search while focusing on the distance (***dist*** column to the left) and the spectral type (***SpType*** column) in the results listing. The most useful filters to enable for JWST HCI are:
    - ***Reject Invalid Object***

- ***Reject Multiplicity*** though in many cases, the possible additional component(s) will be too far away (>2") to affect the PSF subtraction
- ***Reject Spectral Types*** (too different from your science target)
- It can also be a good idea to select stars which are as bright as or brighter than your science target.

In some cases (away from the Galactic plane), the search will not return many stars. In that instance, you may want to relax some criteria and/or cross check with Simbad.

Figure 4. SearchCal query for a suitable PSF reference star for Beta Pictoris



Screen capture of a SearchCal query to look for a suitable PSF reference star for Beta Pictoris. In this case, Alpha Pictoris has previously been used as a PSF calibrator for many HST and ground-based programs to subtract from Beta Pictoris. SearchCal shows that Alpha Pic is indeed the closest (~13º apart) A-type star that is brighter than Beta Pic.

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HCI Supporting Technical Information

These articles provides additional details on high-contrast imaging.

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HCI Optics

High-contrast imaging (HCI) optics for 3 JWST instruments have been designed to suppress diffracted light from a source to make its fainter companions more observable.

On this page

Main articles: NIRCam Coronagraphic Imaging, MIRI Coronagraphic Imaging, NIRISS Aperture Masking Interferometry

Three JWST instruments offer various high-contrast imaging (HCI) optics to suppress diffracted light from the host and thereby make companion sources—both point and extended—more observable.

1. NIRCam coronagraphic imaging:
   - Five Lyot-type coronagraphs (3 round, 2 bars) are available.
   - All allowed NIRCam coronagraphic configurations are listed at the NIRCam Filters for Coronagraphy article.
   - NIRCam coronagraphs with round coronagraphic masks (occulters) work best in narrow and medium bands centered at 1.92, 3.23, and 4.35 µm.
   - Coronagraphs with bar-shaped occulters work best in narrow and medium bands in the ranges 1.7–2.2 µm and 2.4–5 µm.

2. MIRI coronagraphic imaging:
   - One Lyot-type coronagraph and three 4-quadrant phase mask coronagraphs (4QPMs) are available.
   - MIRI 4QPMs work only in narrow bands centered at 10.65, 11.40, and 15.50 µm.
   - MIRI's Lyot-type coronagraph works only in a broad band centered at 23 µm.

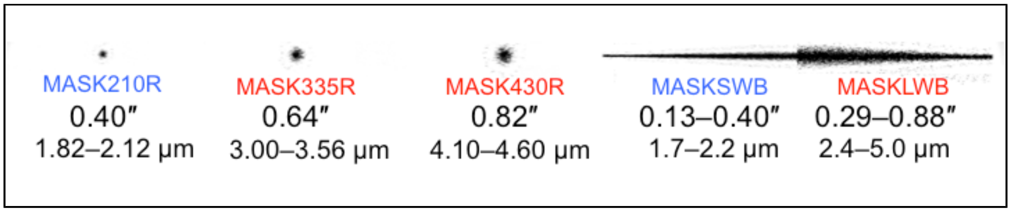
3. NIRISS aperture masking Interferometry: one aperture masking interferometer (75301597).
   - NIRISS/AMI works best with medium bands centered at 3.8, 4.3, and 4.8 µm.
   - NIRISS’s 65 mas pixels satisfy the Nyquist criterion at 4 µm and performance at shorter wavelengths is reduced. Nevertheless, because the wide filter centered at 2.77 µm spans a deep absorption feature of water, its use may be particularly relevant for exoplanetary research.

In addition, HCI can be carried out using basic imaging modes of the observatory (Rajan et al., 2015; Durcan, Janson, and Carson, 2016), as well as using IFU strategies similar to Konopacky et al. (2013). These modes are not yet covered in the documentation.

Lyot-type coronagraph

Main article: NIRCam Coronagraphic Occulting Masks and Lyot Stops
See also: NIRCam Filters for Coronagraphy

Figure 1. NIRCam Lyot-type coronagraph schematic and summary



First row: a schematic representation of the coronagraphic masks (occulters) in NIRCam's 5 Lyot-type coronagraphs.
Lower rows: the names of the masks, IWAs, and optimized wavelength range.
Blue: short-wavelength channel. Red: long-wavelength channel. (The focal-plane occulting mask for MIRI's Lyot-type coronagraph is shown at the lower right in Figure 2.)

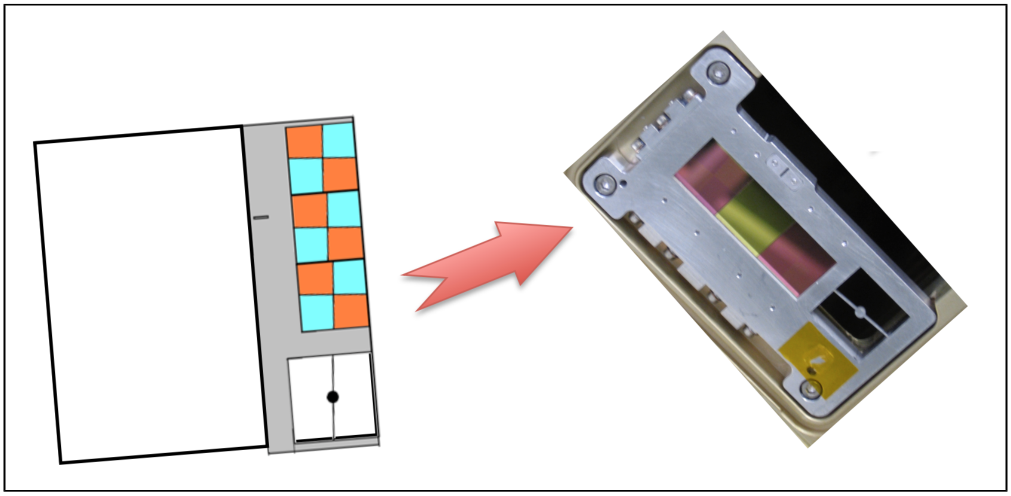
The HCI optics of Lyot-type coronagraphs are pairs of binary masks of different types: one occulter and one Lyot stop. The first mask—the occulter or "coronagraphic mask"—lies on the first focal plane of the imaging instrument, where it blocks light from the center of the host image, but allows any other light to pass. The effective radius of the occulter is the inner working angle (IWA), which is about as close to the host as one can work. The second mask—the Lyot stop—lies in the plane of the re-imaged pupil, where it blocks light from the host that has been diffracted at the edges of the primary mirror segments, the secondary mirror support structure, and the occulting mask itself. In other words, the Lyot stop suppresses the diffraction spikes and rings that commonly appear in direct images of bright stars. (The Webb PSF software may be used to get familiar with the detailed morphology of occulted coronagraph images.)

If the apparent separation between the feature of interest and the host is greater than the IWA, companion light passes the occulter, and—after losing a bit of light on the Lyot stop—the light from the feature of interest reaches the detector. On JWST, NIRCam has 5 sets of Lyot-type coronagraphic optics (3 with round and 2 with bar-shaped occulters), and MIRI has one Lyot-type coronagraph, with a round occulter. (See Figure 2.)

Four-quadrant phase-mask coronagraph (4QPMC)

Main article: MIRI Coronagraph Masks

Figure 2. MIRI coronagraphic masks



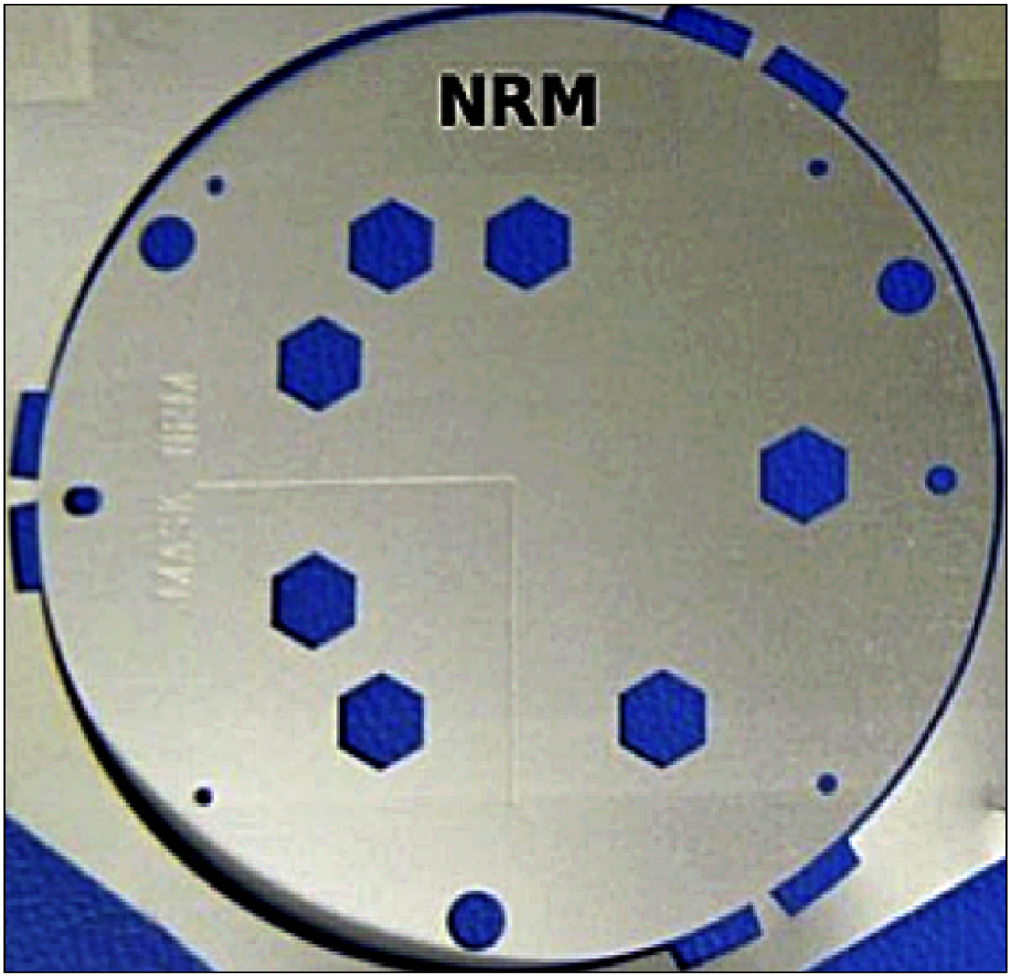
Left, in color, a schematic view of the MIRI imaging plane showing the 3 MIRI 4-quadrant phase masks (4QPMs) and in black&white, the MIRI Lyot-type coronagraph.
Right: the module containing the 4 MIRI coronagraphic masks (before final fabrication).

The HCI optics of 4QPMs are pairs of a phase mask on the focal plane and a Lyot occulting spot on the pupil plane. The phase mask, which is transparent at the appropriate wavelengths, imparts a 180° phase shift to light passing through 2 quadrants on the diagonal. Light from a source centered on the common point of the 4 quadrants interferes destructively. As in a Lyot-type coronagraph, the Lyot occulting spot attenuates light diffracted from the edges of the telescope aperture and support structures, in the pupil plane, and from phase and amplitude aberrations on the wavefront. The optical advantage of a 4QPM is a very small IWA in terms of λ/D (IWA = 1 λ/D at λ = 10–16 µm), which somewhat compensates for the lower, diffraction-limited, spatial resolution at MIRI's long wavelengths. The price paid is a strong sensitivity to optical aberrations and source misalignments.

Aperture masking interferometry (AMI)

Main article: NIRISS Non-Redundant Mask

Figure 3. NIRISS's non-redundant mask (NRM)



The NRM, prior to blackening. None of the 21 hole-to-hole vectors (baselines) are repeated.

The HCI optic of an AMI is a non-redundant mask (NRM) in the pupil plane. The mask is opaque except for holes, in the case of NIRISS/AMI, 7 holes. The number of unique (i.e., non-redundant) baselines between pairs of holes in the NIRISS/AMI NRM is N × (N − 1)/2, or 21, where N is the number of holes in the NRM. Each baseline creates a single fringe pattern at focus, and the 21 fringes interfere to create an interferogram, which is actually just a PSF, The PSF's fine structure is more than twice as sharp as the corresponding full aperture PSF, but with much wider wings.

An NRM interferogram possesses certain observables—closure phases and fringe amplitudes—that can be calibrated using a PSF reference observation to remove many instrumental effects. For higher contrast observations, the reference star is expected to be placed within a few to 10 mas of the target star when both are commanded to the center of the pixel. Such repeated placement is aimed at mitigating residual pixel-to-pixel variations that remain after flat fielding and other routine image calibrations are performed. These observables allow the fitting of basic models, such as binary or triple point sources, and simple extended structures. Binary point source flux ratios of up to about 10 stellar magnitudes should be achievable. The search space of an NRM extends inwards to a separation of $\lambda/2B$, where B is the hole-to-hole length of the longest baseline. For fitting binary models as well as for true imaging—that is, not using closure relations or model-fitting—the NRM on NIRISS has an inner working angle (IWA) of about 70 mas. Beyond half an arcsecond, NIRCam's coronagraphs provide better contrast.

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HCI Inner Working Angle

The JWST inner working angle (IWA) governs how close to the host the companion can be and still be observable.

On this page

Inner working angle (IWA)

Main articles: NIRCam Coronagraphic Imaging, MIRI Coronagraphic Imaging, NIRISS Aperture Masking Interferometry

The inner working angle (IWA) is approximately the smallest apparent separation (*s*) between host and companion sources at which the companion is detectable—if it is bright enough, of course.

The design specification is IWA = Nλ/D, where the nominal aperture diameter is D = 6.5 m, λ is a fiducial wavelength, and N = 6 for the NIRCam round occulters, N = 4 for the center of NIRCam bar occulters, N = 3.3 for MIRI Lyot-type coronagraph, and N = 1 for MIRI's 4QPMs and NIRISS's AMI.

For the coronagraphs, IWA is fixed and approximately equal to the 50% transmission radius of the coronagraphic mask (occulter). For NIRCam's bar occulters, Table 1 gives IWAs for the ends and the middle of the bar.

For MIRI's phase masks (4QPMs) and the NIRISS aperture masks (AMI), the nominal IWA = λ/D for the table's fiducial wavelengths.

Closer-in science (*s* < IWA) may be possible, but we caution observers that even if the throughput is not zero, it is increasingly reduced by the light lost on the coronagraphic mask, and the PSF of the companion is increasingly distorted by the same effect. Furthermore, the raw contrast $C_{raw}(s)$ will be increased (worsened) by the combination of reduced companion PSF and increased host PSF, at the same apparent separation *s*. These effects are likely to be very difficult to calibrate. Plots of the companion's estimated throughput versus *s* for relevant combinations of coronagraphic mask and filter, for both MIRI and NIRCam, can be found in Figures 1 and 2. PSFs computed by WebbPSF will show the expected distortion of the companion image based on current values of the aberrations in the JWST telescope optics.

Table 1. JWST nominal inner working angles (IWAs)

Instrument	Mask type	Mask name	fiducial λ (μm)	N	IWA

				(λ /D)	(arcsec)
NIRCam	round	***MASK210R***[*]	2.1	6	0.40"
		MASK335R	3.0		0.57"
		MASK430R	4.6		0.87"
	short-λ bar	***MASKSWB***	2.1	2	0.14"
				4	0.27"
				6	0.41"
	long-λ bar	***MASKLWB***	4.6	2	0.30"
				4	0.59"
				6	0.89"
MIRI	4-quadrant phase mask	***MASK1065***	10.65	1	0.33"
		MASK1140	11.40		0.36"
		MASK1550	15.50		0.49"
	Lyot	***MASKLYOT***	23	3.3	2.16"
NIRISS	non-redundant mask	***MASK_NRM***	2.77	1	0.089"
			3.8		0.12"
			4.3		0.14"
			4.8		0.15"

[1] Inner working angle for deepest contrast.

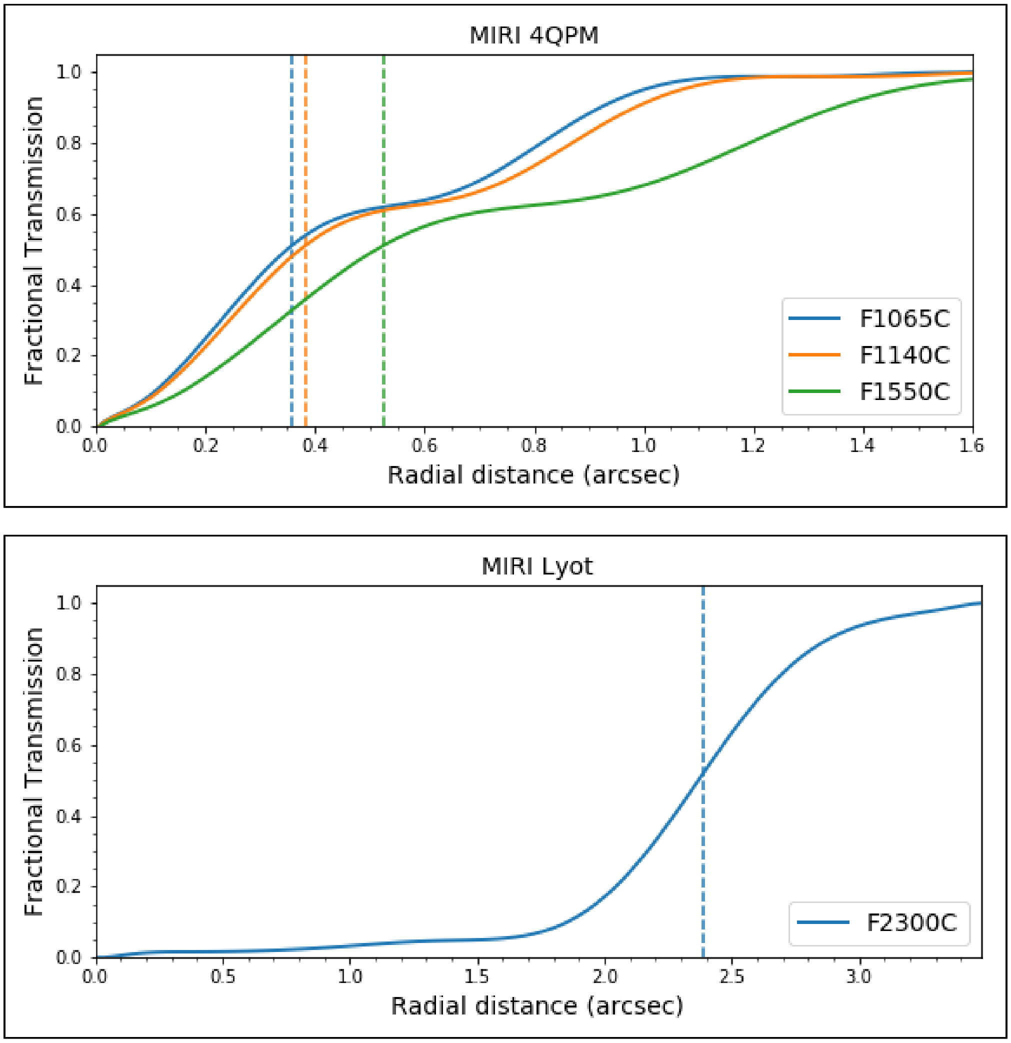
[*] ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

A variety of NIRCam filters are permitted for coronagraphy. For MIRI and NRISS, filters are available that match the fiducial wavelength.

MIRI: throughput vs. apparent separation for combinations of coronagraphic mask and filter

Main article: MIRI Coronagraph Masks

Figure 1. MIRI coronagraphic masks: throughput vs. apparent separation

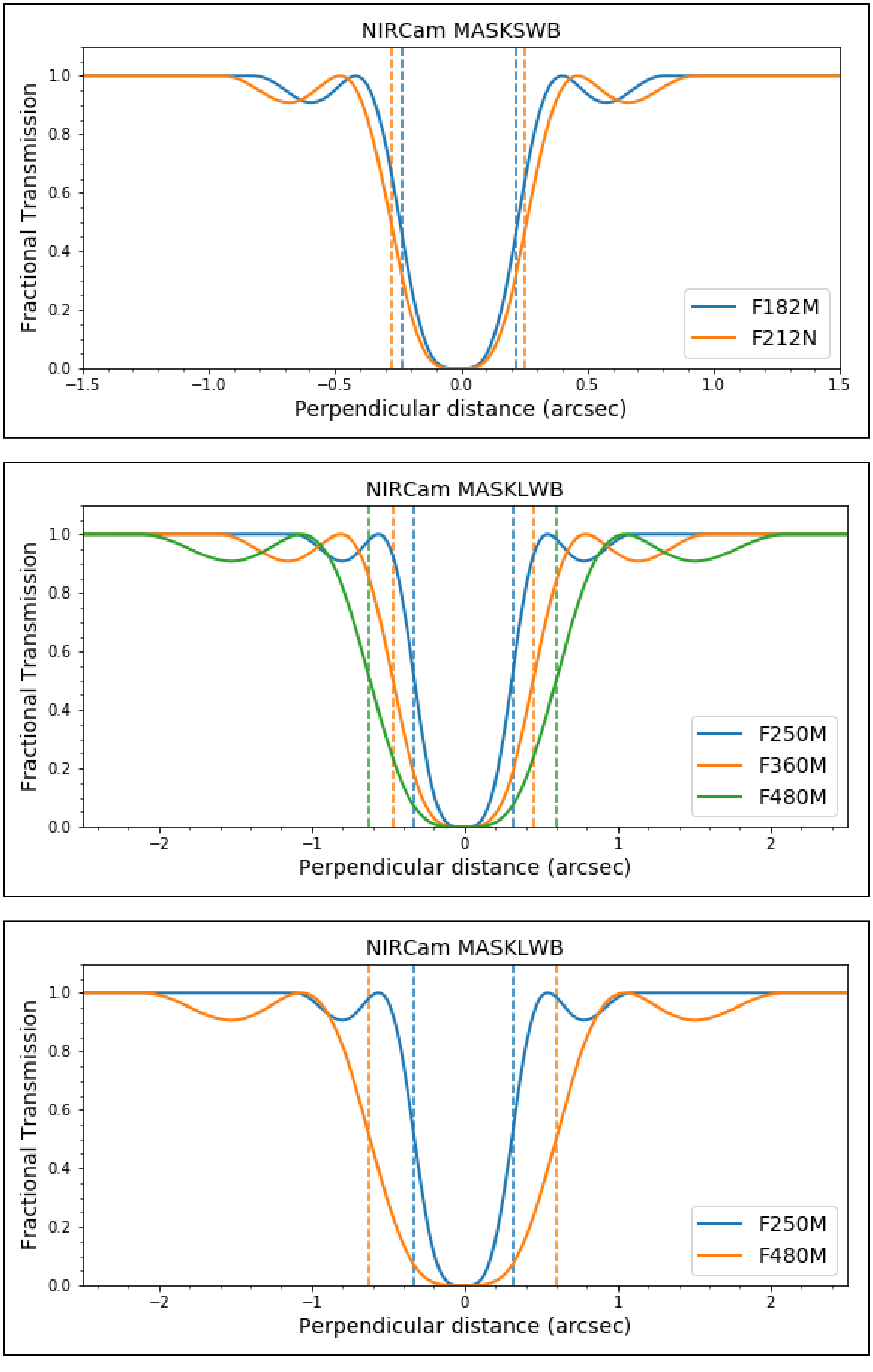


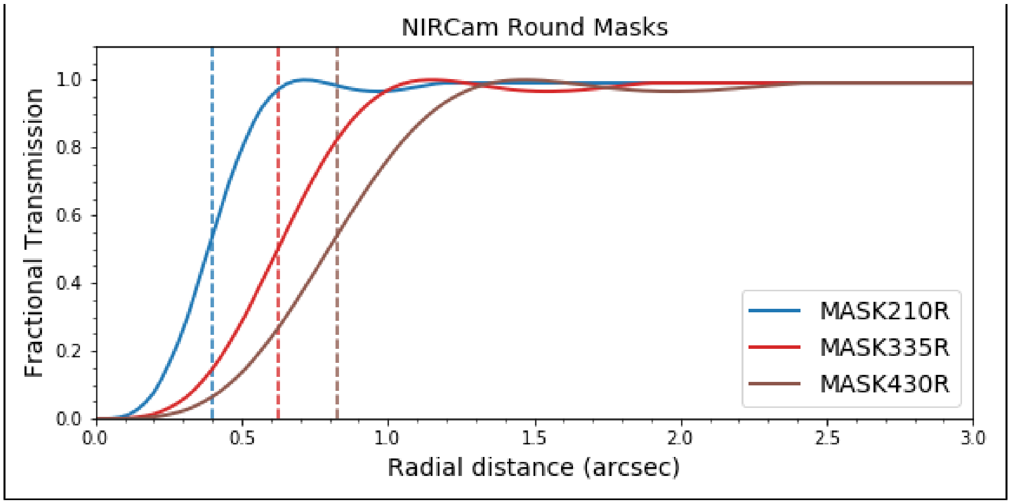
MIRI: throughput vs. apparent separation for combinations of coronagraphic mask and filter. The dashed lines show the apparent separations for 50% transmission.

NIRCam: throughput vs. apparent separation for combinations of coronagraphic mask and filter

Main articles: NIRCam Coronagraphic Occulting Masks and Lyot Stops, NIRCam Filters for Coronagraphy

Figure 2. NIRCam coronagraphic masks: throughput vs. apparent separation





NIRCam: throughput vs. apparent separation for combinations of coronagraphic mask and filter. The dashed lines show the apparent separations for 50% transmission.

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HCI Contrast Considerations

In JWST high-contrast imaging (HCI), the term *contrast* means the companion-to-host flux ratio.

> *Main articles: MIRI Coronagraphic Imaging, NIRCam Coronagraphic Imaging, NIRISS Aperture Masking Interferometry*

When developing an HCI investigation, the user's scientific goal is represented by an *operating point*, (s, C_{flux}), where

- s is the expected apparent separation between the companion and host, and
- $C_{flux} = flux_{companion}/flux_{host}$, the flux contrast between the companion and host.

This operating point is estimated to be feasible if $C_{flux} > C_{limit}(s)$, where $C_{limit}(s)$ is the *limiting contrast*.

$C_{limit}(s)$ is a function of many interrelated factors, and is, therefore, a challenge to estimate. In particular, $C_{limit}(s)$ depends on the instrumental configuration, the observing strategy, and the post-observation processing calibrations and processes. $C_{limit}(s)$ is especially sensitive to the step where a scaled reference PSF is subtracted from a science image. PSF subtraction is relied upon to extend the grasp of the investigation deep into the systematic noise (see Soummer et al.). In the absence of data, it is hard to say how well PSF subtraction will perform for JWST.

To be valid, the feasibility test $C_{flux} > C_{limit}(s)$ assumes that the planned observation has the same technical and procedural factors that produced the calibration of $C_{limit}(s)$.

To gain a better understanding of $C_{limit}(s)$, look more closely at the term "contrast" (C). Although C been widely adopted as a metric of HCI performance, its meaning is sometimes ambiguous in the context of where it appears. Therefore, the various possible meanings of "contrast" are disambiguated as follows:

1. C_{flux} is the term for the companion-to-host flux ratio. C_{flux} is a property of nature, independent of any instrumental or observational details or considerations.

2. $C_{PSF}(s)$ is the ratio of the PSF at separation s to its central value: $C_{PSF}(s) = PSF(s)/PSF(0)$. Here are other useful PSF ratios:
   a. $C_{JWST\_PSF}(s)$, the PSF ratio using the telescope PSF.
   b. $C_{centered\_PSF}(s)$, the PSF ratio using the instrument PSF. The numerator is the PSF when it is centered on the occulting mask and is evaluated at input values s > IWA.
   c. $C_{offset\_PSF}(s',s)$, which is the PSF ratio with the numerator equal to the PSF when it is offset from the center of the occulting mask by separation s', and the PSF is evaluated at an input value of s.

3. $C_{raw}(s) = C_{offset\_PSF}(0)/C_{centered\_PSF}(s)$ is the raw contrast, which is an intrinsic property of the instrument, independent of any natural or observational details or considerations, including noise and

integration time.

4. $C_{limit}(s)$ is limiting contrast, defined as the value of C_{flux}, for the minimum detectable companion. $C_{limit}(s)$ affirmatively *does* take into account any and all relevant technical and procedural factors, such as observational strategy, pointing and instrumental errors, detection threshold, and post-observation processing (especially the PSF-subtraction strategy). The detection threshold is related to the false alarm probability under the assumption that the residual errors after PSF subtraction are normally distributed.

5. $C_{ideal}(s)$ is a floor for the limiting contrast $C_{limit}(s)$, because it makes certain optimistic, simplifying assumptions. For example, $C_{ideal}(s)$ may assume that pointing errors are zero or that photometric noise is ideal, with photon-counting noise dominating.

6. $G_{contrast}(s) = C_{ideal}(s)/C_{raw}(s)$ is the *contrast gain*. $G_{contrast}(s)$ is the factor by which the instrument and procedures of HCI must suppress the telescope PSF.

$Q(s) = C_{flux} \times C_{raw}(s)$ is an auxiliary metric sometimes used to gauge the systematic errors in $C_{raw}(s)$ due to aberrations and their speckles. $Q(s)$ is the wing-to-center surface brightness ratio of the host-companion pair of sources, which has been called the *instantaneous signal-to-noise ratio*. Q depends only on the instrument and on nature, but not on any observational factors, such as exposure time or strategy for PSF subtraction.

At the current time, few treatments of $C_{limit}(s)$ are available for the JWST HCI modes. For now, users must extrapolate $C_{limit}(s)$ from published treatments of $C_{limit}(s)$:

- HCI NIRCam Limiting Contrast
- HCI NIRISS Limiting Contrast
- HCI MIRI Limiting Contrast

References

Beichman, C. A., et al. 2010, *PASP*, 122:162
Imaging Young Giant Planets from Ground and Space

Boccaletti, A., et al. 2015, *PASP*, 127, 633
The Mid-Infrared Instrument for the James Webb Space Telescope, V: Predicted Performance of the MIRI Coronagraphs

Greenbaum, A.Z., Pueyo, L., Sivaramakrishnan et al. 2015, *ApJ*, 798, 68
An Image-Plane Algorithm for JWST's Non-Redundant Aperture Mask Data

Soummer, R., Pueyo, L., and Larkin, J., 2012, *ApJ* 755 , L28
Detection and Characterization of Exoplanets and Disks Using Projections on Karhunen-Loeve Eigenimages

Published	18 May 2017
Latest updates	

HCI MIRI Limiting Contrast

Treatment of limiting contrast (C_{limit}) is based on current information about telescope aberrations and the expected performance of JWST MIRI.

Main articles: MIRI Coronagraphic Imaging, MIRI Bright Source Limits
See also: MIRI Coronagraph Masks

Limiting contrast, $C_{limit}(s)$, is the companion-to-host flux ratio of the minimum detectable companion. It is the detection limit and the best that can be done.

The article HCI Contrast Considerations provides a general treatment of "contrast" (C), including $C_{limit}(s)$.

$C_{limit}(s)$ is a function of essentially everything related to high-contrast imaging (HCI): myriad eclectic technical factors and procedures, end-to-end. This treatment of $C_{limit}(s)$ for MIRI is based on Boccaletti et al. (2015).

Figure 1 shows the best available treatment of various contrasts for a MIRI 4QPM2 coronagraph, as adapted from Figure 10 (upper right) in Boccaletti et al. (2015).

The "technical factors" behind the curves include:

- 4QPM2 inner working angle (IWA), filter, and nominal wavelength (0.49", F1140C, 11.30 μm)
- Stellar distance and spectral type of host source (10 pc, M0V)
- Exposure time (3,600 s)
- Telescope area and transmission (25 m^2, 85%)
- Detector quantum efficiency and noise (80%, readout 20 e^- rms, 0.001 flat field stability)
- Lyot stop transmission (62% for 4QPM)
- A random positional error of 10 mas and a wavefront error of 10 nm between rolls
- Reference star subtraction strategy
- False alarm probability of 3×10^{-3} (3-sigma), which assumes normally distributed errors with zero mean after reference star subtraction
- Currently available estimates of JWST aberrations

Under those assumptions, Figure 1 shows the approximate minimum contrast ratio for 3-sigma detection of a faint companion near a bright host, as a function of their apparent separation s in arcseconds.

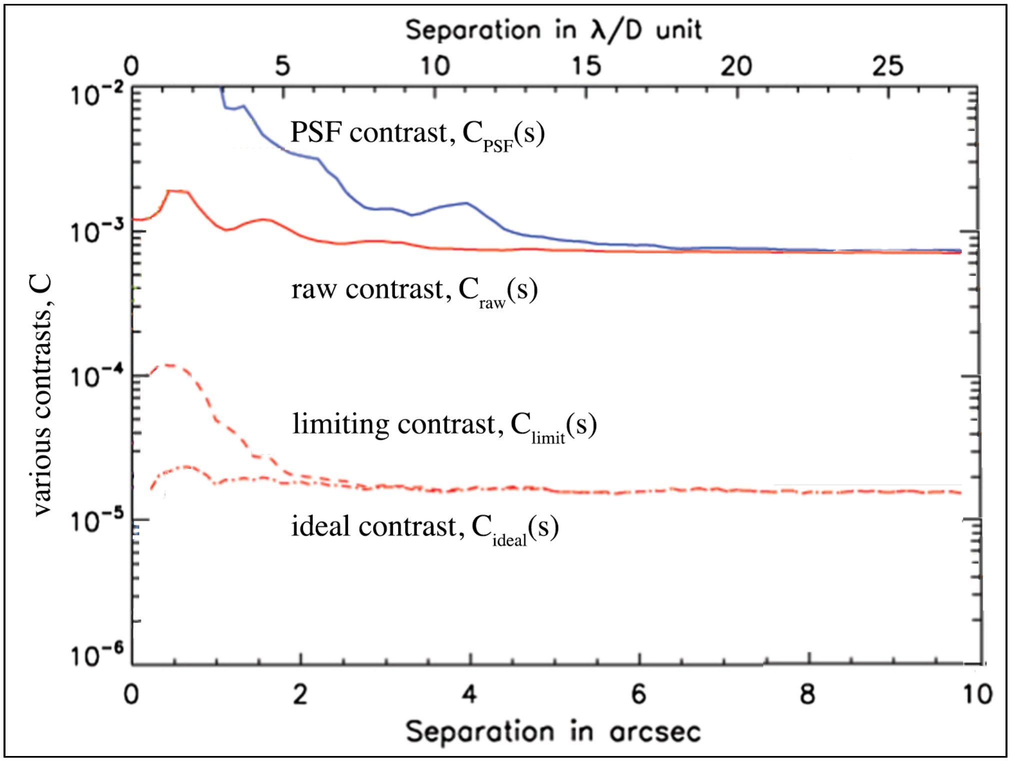
Boccaletti et al. (2015) also present variants of 3 particular technical assumptions: the 4QPM coronagraph (one of 3), filter, and the spectral type of the host source.

If the user's operating point (s, C_{flux}) lies above the red-dashed curve, that source is detectable under the technical and procedural assumptions of Boccaletti et al. (2015).

This is the best information on limiting coronagraphic performance for MIRI at the current time. In the future, with a better understanding of wavefront errors and other technical factors, or when users become interested in different combinations of technical factors, improved calculations of $C_{limit}(s)$ will be made available for MIRI coronagraphs.

Meanwhile, users may be able to obtain extrapolated estimates of $C_{limit}(s)$ using the Exposure Time Calculator (ETC) and other proposal tools.

Figure 1. MIRI limiting contrast example



Example of estimating limiting contrast for MIRI, adapted from Boccaletti et al. (2015), Figure 10, top-right panel, showing $C_{PSF}(s)$, $C_{raw}(s)$, $C_{limit}(s)$, and $C_{ideal}(s)$.

References

Boccaletti, A., et al. 2015, *PASP*, 127, 633
The Mid-Infrared Instrument for the James Webb Space Telescope, V: Predicted Performance of the MIRI Coronagraphs

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Latest updates	

HCI NIRCam Limiting Contrast

Treatment of limiting contrast (C_{limit}) is based on current information about telescope aberrations and the expected performance of JWST NIRCam.

Main articles: NIRCam Coronagraphic Imaging, NIRCam Bright Source Limits
See also: NIRCam Coronagraphic Occulting Masks and Lyot Stops, NIRCam Filters for Coronagraphy

Limiting contrast, $C_{limit}(s)$, is the companion-to-host flux ratio of the minimum detectable companion. It is the detection limit and the best that can be done.

The article HCI Contrast Considerations provides a general treatment of "contrast" (C), including $C_{limit}(s)$.

$C_{limit}(s)$ is a function of essentially everything related to high-contrast imaging (HCI): myriad eclectic technical factors and procedures, end-to-end. This treatment of $C_{limit}(s)$ for NIRCam is based on Beichman et al. (2010).

Figure 1 shows the best available treatment of $C_{limit}(s)$ for the 5 NIRCam coronagraphs. This graphic is adapted from Figure 6 in Beichman et al. (2010).

For the round occulting masks, the assumed filters are F210M, F335M, and F430M. For the bar-shaped masks, the filters are F210M and F430M.

The "technical factors" behind the curves in Figure 1 include:

- Images taken at roll angles differing by 10° and differenced in post-processing
- Random positional errors of 10 mas and and wavefront errors of 10 nm, introduced between rolls
- An adopted false alarm probability of 6×10^{-7} (5-sigma). (Normally distributed errors with zero mean are assumed after image differencing.)
- Currently available—and outdated— estimates of JWST aberrations are adopted

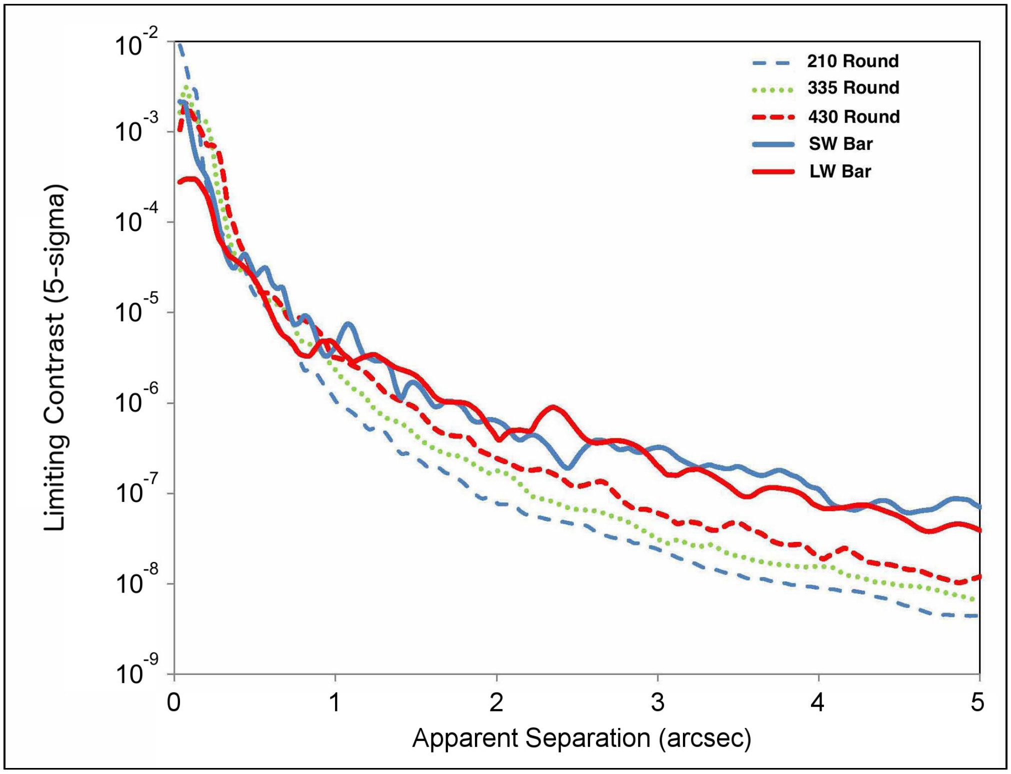
Figure 1 shows the estimated functions $C_{limit}(s)$ for the 5 NIRCam coronagraphs as a function of the apparent separation (s) in arcseconds.

The interpretation of these results is as follows: if the user's operating point (s, C_{flux}) lies above a color curve, that source is estimated to be detectable, but only under the same technical and procedural assumptions of Beichman et al. (2010).

This is the best information on limiting coronagraphic performance for NIRCam at the current time. In the future, with a better understanding of wavefront errors and other technical factors, or when users become interested in different combinations of technical factors, improved calculations of $C_{limit}(s)$ will be made available.

Meanwhile, users may be able to extrapolate estimates of $C_{limit}(s)$ using the Exposure Time Calculator (ETC) and other proposal tools.

Figure 1. NIRCam limiting contrast example



Example of estimating the imiting performance of NIRCam's 5 coronagraphs. Adapted from Beichman et al. (2010), Figure 6.

References

Beichman, C. A., et al. 2010, *PASP*, 122:162
Imaging Young Giant Planets from Ground and Space

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Latest updates	

HCI NIRISS Limiting Contrast

Treatment of limiting contrast (C_{limit}) is based on current information about telescope aberrations and the expected performance of JWST NIRISS AMI.

Main articles: NIRISS Aperture Masking Interferometry, NIRISS Bright Limits
See also: NIRISS Non-Redundant Mask

Limiting-contrast, $C_{limit}(s)$, is the companion-to-host flux ratio of the minimum detectable companion. It is the detection limit and the best that can be done.

The article HCI Contrast Considerations provides a general treatment of "contrast" (C), including $C_{limit}(s)$.

$C_{limit}(s)$ is a function of essentially everything related to high-contrast imaging (HCI): myriad eclectic technical factors and procedures, end-to-end. This treatment of $C_{limit}(s)$ for NIRISS AMI is based on Greenbaum et al. (2015).

Figure 1 shows the best available treatment of $C_{limit}(s)$ for the NIRISS AMI. This graphic is adapted from Figure 6 in Greenbaum et al. (2015).

The "technical factors" or assumptions behind the curves in Figure 1 include:

- Theoretical binary target
- Good flat field measurements with subpixel accuracy by precise positioning
- No variation of sensitivity within a pixel (intra-pixel sensitivity, or IPS)
- Negligible phase closure errors due to static piston in the pupil
- Companion-to-host flux ratio $C_{flux} = 10^{-2}$ (solid curves) and $C_{flux} = 10^{-3}$ (dashed curves)
- False alarm probability (unknown)
- Currently available estimates of JWST aberrations (outdated)
- Filters F277M and F430M

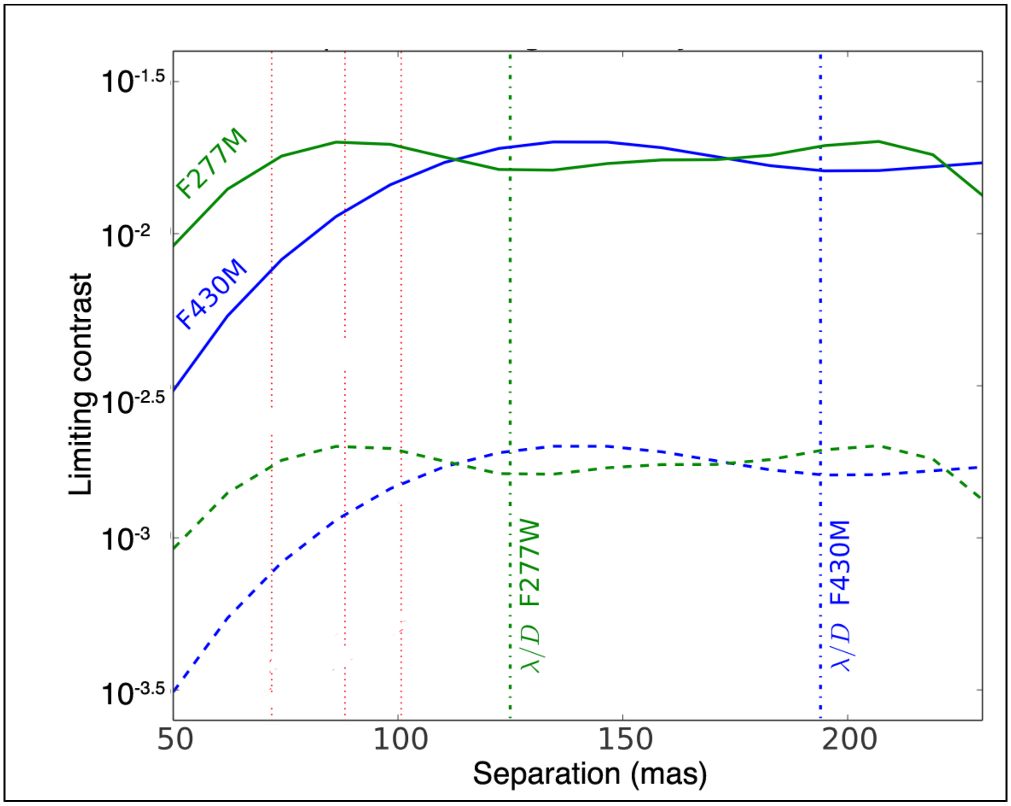
Under those assumptions, Figure 1 shows the estimated limiting contrast ratio for 5-sigma detection of a faint companion near a bright host as a function of their apparent separation *s* in mas.

If the user's operating point (s, C_{flux}) lies above a color curve, that source is detectable under the technical and procedural assumptions of Greenbaum et al. (2015).

This is the best information on limiting performance for NIRISS AMI at the current time. In the future, with a better understandings of wavefront errors and other technical factors, or when users become interested in different combinations of technical factors, improved calculations of $C_{limit}(s)$ will be made available.

Meanwhile, users may be able to extrapolate estimates of $C_{limit}(s)$ using the Exposure Time Calculator (ETC) and other proposal tools.

Figure 1. NIRISS AMI limiting contrast example



Example of estimating HCI limiting performance for NIRISS AMI. Adapted from Figure 16 in Greenbaum et al. (2015).

References

Greenbaum, A.Z., Pueyo, L., Sivaramakrishnan, A., et al. 2015, *ApJ*, 798, 68
An Image-Plane Algorithm for JWST's Non-Redundant Aperture Mask Data

Published	29 Nov 2017
Latest updates	• 26 Apr 2019 Updated links, including to the new imaging roadmap article. Simplified and clarified text.

JWST Integral Field Spectroscopy

JWST integral field spectroscopy (IFS) is the process of dissecting an astronomical scene into multiple spatial components and dispersing each component with a spectrograph in order to provide spatially resolved spectroscopic information.

On this page

Main article: MIRI Medium Resolution Spectroscopy, NIRSpec IFU Spectroscopy

Integral field units (IFUs) combine imaging and spectroscopic capabilities to acquire spatially resolved 2-dimensional spectroscopy in a single astronomical exposure. By dispersing the light from discrete spatial elements of the field of view, an image of the source is acquired at each wavelength, and (equivalently) a spectrum is captured at each spatial position (Figure 1). This provides a powerful dataset to study the characteristics of a wide variety of extended astronomical sources, including galaxies, nebulae and crowded stellar fields.

Figure 1. IFU slicer schematic

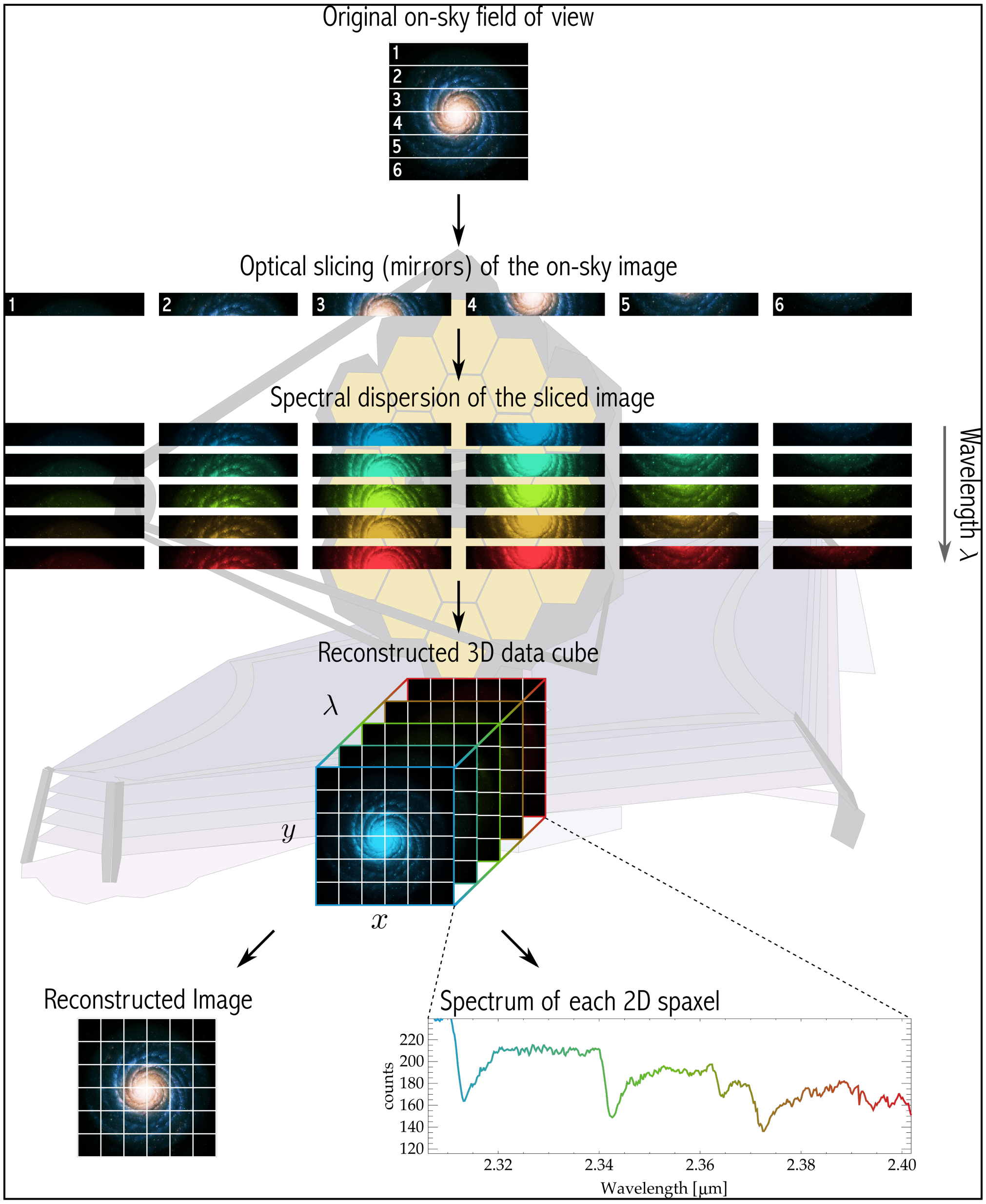


Figure 1 illustrates the basic principle of the JWST slicer-type integral field spectrograph. The telescope focal plane is sampled use an array of slicing mirrors, each of which then directs its light to a dispersive element to produce a long slit spectrum of each slice on a detector. Pipeline processing then reconstructs the dispersed spectra together into a 3-dimensional data cube consisting of images of the source at each wavelength (or correspondingly, a spectrum of the source in each spaxel).

The specialized optics in IFU instruments isolate the spatial segments of a spatial scene, format and align them onto the grating or prism in a spectrograph, and disperse the spectra from each position onto the detectors in a way so that data do not overlap (e.g., Figure 2). Specialized processing algorithms reformat the detector pixel data into 1-dimensional spectra of the individual optical samples of the astronomical scene (row-stacked spectra) and/or a data cube with 2 spatial dimensions and one spectral dimension. These 3-D data cubes can then be used to study spatially resolved spectroscopic quantities such as gas kinematics (derived from nebular emission lines), stellar kinematics (derived from absorption lines and stellar spectral templates), chemical composition, ionization profiles, and more.

Why use an Integral Field Unit (IFU)?

See also: IFU Terminology

Integral field units offer combined spatial and spectral information for an astronomical target; thought of another way, they provide a full spectrum for every spatial position in the field of view. This allows them to efficiently produce spatial maps of spectroscopic quantities such as kinematics and diagnostic line ratio strengths. Additionally, IFUs are not affected by traditional slit loss problems (any light lost from one optical element is recovered by the adjacent element), reduce the need for complicated target acquisition procedures (since objects do not need to be carefully centered within a single slit), and provide a better estimate of the extended background/foreground structures surrounding the astrophysical object of interest. IFUs thus provide extremely dense information coverage for a single object, typically at the cost of a relatively small field of view.

The IFUs aboard JWST are thus particularly useful for obtaining spectral maps of extended sources up to a few arcseconds in size (or larger, with mosaicing), or for obtaining spectra of point sources in which there is expected to be significant background emission which must be characterized and subtracted. Additionally, for mid-infrared wavelengths, the MIRI IFU is the only instrument capable of obtaining moderate resolution spectroscopy longward of 5 μm.

The JWST IFUs

Main articles: MIRI Medium Resolution Spectroscopy, NIRSpec IFU Spectroscopy

JWST has 2 IFUs: the MIRI medium resolution spectrometer (MRS) provides R ~ 1,500–3,500 spectroscopy from wavelengths of 5 to 28 μm over a contiguous field of view up to 7" × 8" in size, while NIRSpec provides R ~ 100, 1,000, and 2,700 spectroscopy from 0.6 to 5.3 μm over a contiguous field of view 3" × 3" in size. Details of the individual instruments are provided in the articles listed below.

- MIRI Medium Resolution Spectroscopy - An overview of the MIRI MRS
    - MIRI MRS Dithering - Detailed information on MRS dithering strategies
    - MIRI MRS Mosaics - Detailed information on MRS mosaicing strategies
    - MIRI MRS Dedicated Sky Observations - MRS background subtraction
    - MIRI MRS Target Acquisition - Target acquisition procedures for the MRS
    - MIRI MRS hardware
    - MIRI MRS APT Template
- NIRSpec IFU Spectroscopy
    - NIRSpec IFU Dither and Nod Patterns - Detailed information on dithering strategies
    - NIRSpec Integral Field Unit

- NIRSpec IFU Spectroscopy APT Template

Considerations for observing with the JWST IFUs

Main articles: NIRSpec IFU Dither and Nod Patterns, MIRI MRS Dithering, MIRI MRS Dedicated Sky Observations
See also: MIRI MRS Target Acquisition, NIRSpec Target Acquisition

Background observations

All astronomical scenes will contain signal from both the target of interest and background/foreground signal arising from zodiacal light, telescope thermal emission, or a variety of astrophysical sources. In many cases, it will be desirable to measure this signal so that it can be reliably removed from the spectra of the object of interest, especially longwards of 15 µm where telescope thermal emission dominates the background signal.

Traditional methods of dealing with background subtraction for IFS data have been two-fold, depending on the structure of the science target. For point source targets (or those that are small compared to the field of view), A /B style dithering is often performed to observe the target with 2 or more exposures widely spaced enough that each exposure can serve as the background for the other. This approach maximizes the on-source integration time of the telescope. For extended sources that fill an appreciable fraction of the field of view however, such simple in-scene dithering is insufficient to move the science target far enough on the detector. In such cases, a dedicated off-source background observation is typically obtained in order to provide a clean measurement of the background signal in a part of the sky known to be free of emission from the science target.

These different methods are reflected in the JWST Exposure Time Calculator as *nod-in-scene* (for point source targets) or *nod-off-scene* (for extended targets), as detailed in JWST ETC IFU Nod in Scene and IFU Nod off Scene Strategy.

Best practice procedures for both MIRI and NIRSpec background observations are currently under development and will be updated during commissioning.

Dithering

Since the JWST IFUs are spatially undersampled at most wavelengths, it is important to obtain dithered observations in order to optimize the image quality of the resulting data cubes. Detailed MIRI MRS and NIRSpec dither patterns have been designed that use sub-integer offsets to improve the sampling of the JWST point spread function. In addition to improving the spatial sampling (and corresponding image quality), dithering can also improve the spectral sampling of the IFUs, help mitigate the impact of bad pixels by sampling a source with redundant detector locations, and (in some cases) allow for measurement of the background signal in the IFU field of view.

PSF/LSF variations

In any integral field spectrograph, the size and shape of the spatial point spread function (PSF) and the spectral line spread function (LSF) (i.e., the spectral resolution) can change over the IFU's field of view. Any analyses working with these data should bear this in mind; estimates of the variability will become available during the commissioning and calibration process.

Target acquisition

The JWST IFUs can be used to observe both point sources (e.g., stars) and diffuse sources (e.g., nebulae). The absolute pointing accuracy of JWST is 0.1" (1 sigma, per axis) from the Fine Guidance Sensors; if more precise positioning of the object in the IFU field of view is required, either because the target is extended or its coordinates are uncertain, or it will be observed using large dithers or nods, then target acquisition should be performed using a bright point source. If the science target is diffuse, a nearby point source should be used for target acquisition instead.

Working with integral field data

Numerous tools and techniques have been developed for interacting with and visualizing IFS data; additional information will be added here as it becomes available.

- Color maps: Since a major product of IFS data is two-dimensional maps of astrophysical quantities, color is often used to convey information in such plots. Many commonly-available color maps (e.g., 'jet') can obscure genuine features in data and create perceived structures when none exist, in addition to being difficult to read for those with color blindness. Well-researched perceptually uniform alternatives include viridis, and the divergent RdBu options available in many modern plotting programs. Color lookup tables (e.g., for use with ds9) are available for both viridis and RdBu.
- Covariance: Since spectral data cubes are constructed from algorithms that reformat dispersed spectra, there is often significant covariance between adjacent spaxels in a data cube. There are a variety of methods that have been developed to account for this covariance in analyses of stacked spectra.
- Voronoi binning: This is a classic technique used to construct spatial binning regions of varying size and shape where the corresponding spectra reach fixed continuum signal to noise.
- Data cube construction: A variety of techniques exist to reformat pixel-level data into a convenient 3-D cube format, but the optimal method of constructing these cubes can vary depending on the science case.
- JWST analysis tools: These tools allow the user to work with IFU data products within the JWST software ecosystem.

Related Articles

Observing Strategies

MIRI MRS Recommended Strategies
NIRSpec Bright Spoilers and the IFU Recommended Strategies

Example Science Programs

NIRSpec IFU and MIRI MRS Observations of Cassiopeia A
MIRI MRS and NIRSpec IFU Observations of SN 1987A
MIRI MRS Spectroscopy of a Late M Star
NIRSpec IFU and Fixed Slit Observations of Near-Earth Asteroids

Additional resources

- IFS Wiki: A shared resource for historical background and tips/tricks for working with IFS data
- 3D Spectroscopy in Astronomy: An introductory text based on lectures at the Canary Island Winter School

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Latest updates	

IFU Roadmap

A roadmap to guide users, step-by-step, through the process of designing an observing program using either (or both) of the integral field units (IFUS) on JWST: MIRI Medium Resolution Spectrograph and the NIRSpec IFU.

For example programs that use this roadmap, please see the Cas A Example Science Program and the MRS Spectroscopy of a Late M Star Example Program.

Each step listed below is followed by a list of articles with additional details.

1. Pick one or both of the JWST IFU observing modes based on needed wavelength coverage.
   MIRI Medium Resolution Spectroscopy (MRS) (4.9–28.8 μm)
   NIRSpec IFU Spectroscopy (0.6–5.3 μm)

2. Pick wavelength setting(s).
   MIRI MRS: Select SHORT, MEDIUM, or LONG channel, or some combination thereof
   NIRSpec IFU: Select dispersers and filters, depending on needed wavelength coverage and resolving power

3. For MIRI MRS, determine whether you should choose simultaneous imaging with the MIRI Imager.
   MIRI MRS Simultaneous Imaging

4. Decide if you need to do a mosaic.
   JWST Mosaic Overview
   MIRI MRS Mosaics

5. Pick a dither pattern.
   MIRI MRS Dithering, MIRI MRS Recommended Strategies
   NIRSpec IFU Dither and Nod Patterns, NIRSpec Bright Spoilers and the IFU Recommended Strategies

6. Determine whether you need a dedicated background observation.
   MIRI MRS Dedicated Sky Observations
   NIRSpec Background Recommended Strategies

7. For NIRSpec IFU: Decide whether you need to obtain leakcal observations to mitigate the effects of light that leaks through the NIRSpec Micro-Shutter Assembly (MSA) shutters
   NIRSpec MSA Leakage Correction for IFU Observations, NIRSpec MSA Leakage Subtraction Recommended Strategies

8. Decide if you should do a target acquisition (TA)
   MIRI MRS Target Acquisition
   NIRSpec Target Acquisition, NIRSpec Target Acquisition Recommended Strategies

9. Calculate the required exposure time and detector readout parameters using the Exposure Time Calculator (ETC).
   JWST ETC IFU Nod in Scene and IFU Nod off Scene Strategy
   JWST ETC MIRI Target Acquisition
   JWST ETC NIRSpec Target Acquisition

10. Fill out the Astronomer's Proposal Tool (APT) for your observation
    MIRI MRS APT Template
    NIRSpec IFU Spectroscopy APT Template

Go to the Getting Started Guide to complete the steps for proposal submission.

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Latest updates	

IFU Terminology

Integral field spectroscopy, available in JWST's NIRSpec and MIRI instruments, has a variety of terms and acronyms in common use that may be confusing to those unfamiliar with the field.

On this page

Generic terminology

Main article: MIRI Medium Resolution Spectroscopy, NIRSpec IFU Spectroscopy

Many acronyms and naming conventions, shown in Table 1, are in general use across a variety of integral field spectrographs and are commonly adopted in the literature.

Table 1. General IFU acronyms and terms

Term	Description
Data cube	A 3-dimensional data product often produced using IFS data. Typically, this has 2 spatial dimensions (e.g., right ascension and declination) and one spectral dimension (wavelength). This may be produced from a single exposure or multiple dithered and/or mosaiced exposures. Generally such "cubes" are strictly more like long rectangular prisms with the wavelength axis containing substantially more elements than the spatial axes.
IFU	Integral field unit. This acronym refers to the physical hardware that breaks the focal plane up into multiple pieces prior to dispersal by a spectrograph. It can take the form of either a set of image slicers, a lenslet array, or an optical fiber bundle.
IFS	Integral field spectrograph, spectrometer, spectra, or spectroscopy. This acronym can have multiple meanings, either referring to the overall technique of integral field spectroscopy, the spectra obtained using such a technique, or the hardware system encompassing both the integral field unit and the spectrograph/spectrometer.
LSF	Line spread function. This is the characteristic shape of an unresolved spectral feature, i.e., the effective spectral resolution of the reconstructed data cube.
	A pixel refers to a physical detector pixel that is read out by some series of electronics. A spaxel

Pixel /Spaxel /Voxel	(spatial pixel) refers to a spatial element of a reconstructed data cube, while a voxel (volume pixel) refers to a volume element (spatial × spatial × spectral) of a data cube. Each spaxel in a data cube therefore has an associated spectrum composed of many voxels.
PSF	Point spread function. Typically (and somewhat loosely) refers to the spatial intensity profile of an unresolved point source either incident upon the slicer optics (i.e., the telescope PSF) or in the reconstructed data cube (i.e., the reconstructed PSF).
RSS	Row stacked spectra. A common data format for fiber-type IFUs that consists of a 2-dimensional array with each row in the array corresponding to the 1-D spectrum of a single fiber.
Slice	Multi-use term. This can either refer to an element of the slicing unit that chops up the focal plane (for slicer-type IFUs), or to an image at a single wavelength plane extracted from the reconstructed data cube.

JWST-specific terminology

JWST MIRI MRS

Table 2. IFU terms specific too MIRI MRS

Term	Description
Channel	The MRS has 4 channels that together cover the wavelength range 5–28 μm. Channels 1 and 2 share a detector, as do channels 3 and 4.
Band	Each MRS channel is divided into 3 wavelength ranges: SHORT(A), MEDIUM(B), and LONG(C). A single "unit" of wavelength coverage is therefore, e.g., band 1A (the A section of channel 1).

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JWST Multi-Object Spectroscopy

JWST multi-object spectroscopy (MOS) is used for simultaneous spectroscopy of multiple sources in a single exposure using NIRSpec's micro-shutter assembly (MSA). Observations are specified using the APT MOS spectroscopy template in APT.

On this page

What is MOS?

Main article: NIRSpec Multi-Object Spectroscopy

MOS is an efficient way to observe the spectra of an aggregate of sources that are within the field of view of an instrument at a single pointing. Most MOS instruments are wide field instruments with fields of view covering several square arcminutes up to a square degree. Typically, the source light exiting the telescope optics is focused onto the aperture plane of an instrument where the light passes through narrow slits or fiber optics and becomes dispersed by a refractive element like a prism or grating. The spectra are then imaged onto a detector. The data undergo rectification, registration, and extraction, as well as wavelength and flux calibration, typically using software designed specifically to handle multiplexed spectra.

MOS spectrographs

Over the past 15 years, the demand for astronomical MOS capabilities has expanded significantly. Today, most large 8–10 meter class ground-based observatories offer at least one MOS instrument option. Some employ configurable masks on sources in the FOV. Often, they are fiber-fed to get the light from the sources at different positions in the mask to the dispersive elements of the instrument.

Observation planning with these instruments typically involves the preparation of slit masks which are often milled out on-site prior to the observations. Most ground-based MOS instruments operate primarily at optical wavelengths shortward of J band. Additionally, there are large area IFU spectrographs (e.g., MUSE on the VLT), discussed in JWST Integral Field Spemctroscopy. For this article, discussion is limited to the general properties of more standard MOS instruments.

Near-infrared (NIR) spectroscopy is particularly well-suited to the study of high redshift galaxies whose important rest frame optical diagnostic emission lines are redshifted to the NIR. In galactic investigations, vibrational and rotational molecular lines in the NIR are indicative of the chemodynamical structure of stars of the Milky Way and can be used to study stellar radial velocities and abundances. The NIR spectra of young stars provide a means to enhance our understanding of star formation. However, the NIR wavelength regime also presents some challenges. NIR MOS spectroscopy from the ground, particularly from 3 to 5 μm, must contend with high background from the Earth's atmosphere. Atmospheric seeing from the ground can vary on the same timescales as the observation.

On JWST, the NIRSpec MSA is the primary instrument for MOS spectroscopy. The MSA planning tool (MPT) is used to plan MOS spectroscopy with NIRSpec.

Ground-based MOS compared with JWST MOS using the NIRSpec MSA

Main article: NIRSpec Micro-Shutter Assembly

Operating range

Main article: NIRSpec MOS Wavelength Ranges and Gaps
See also: NIRSpec Dispersers and Filters

JWST NIRSpec MSA's operating range is from 0.6 to 5.3 μm. From the ground, NIR spectroscopy is usually limited by the atmospheric absorption and OH (hydroxyl) emission. The MOSFIRE on Keck is its closest ground-based equivalent; it can operate over an extended range from 0.97 to 2.45 μm (into K band) compared to other ground-based MOS instruments which mostly stop before J band, at around 1 μm.

Apertures

In ground-based instruments, apertures are either slit masks or use fibers arranged into patterns on the sources in the field. For example, at Keck, the MOSFIRE instrument uses a precisely positionable slit mask that can be configured shortly before observations begin. Fiber-fed spectrographs have fibers that can be configured on source positions manually or automatically at the telescope.

The NIRSpec MSA on JWST uses a planning tool to create MSA configurations that are the equivalent of these slit masks.

Differences between ground- and space-based MOS spectroscopy, related to aperture considerations and angular resolution, are discussed below:

- The angular resolution of ground-based observations depends upon the seeing, which can vary during the exposures. In space, seeing is not an issue; the angular resolution remains stable and is primarily determined by the instrument optics.

- In ground-based MOS spectroscopy, the slits are precisely positionable. Conversely, the NIRSpec MSA is a fixed grid; therefore, not all MSA sources will be well-centered. As a result, slit losses will generally be greater compared to ground-based MOS spectroscopy. Accurate astrometry and pointing will allow for precise slit-loss corrections for point sources.

- A small percentage of MSA shutters have impediments: there are stuck shutters (open or closed), as well as shorted rows and columns. The MSA Planning Tool will help to plan around most of the problematic shutters. The tool uses an MSA shutter operability map that is expected to be monitored and updated frequently (about every 1 to 2 months). However it should be noted that there is a population of shutters that can become stuck closed or unstuck with each new movement of the magnet arm to configure the MSA. Only sources that happen to fall in a new undetected failed closed shutter would be impacted. On the other hand, a new failed open shutter can contaminate the spectrum of a source in the vicinity. However, the number of stuck open shutters is small and is expected be stable after launch. The planning tool will plan around these problematic shutters.

- The MSA suffers from light leakage between the shutter doors and the bars that support the doors. These leaks are discussed in detail in NIRSpec micro-shutter assembly. Typically this will not greatly affect target spectra unless there is broad scale nebular emission in the MSA field of view.

- The MSA shutters are very small—each shutter has an open area of approximately 0.20" × 0.46", surrounded by bars of width ~0.075" on all sides. Slits on ground-based instruments are typically larger, ~1", matched to the seeing conditions. The narrower slit widths in the MSA are afforded by NIRSpec's sensitivity and JWST's high angular resolution. These tiny tolerances highlight the need for greater astrometric accuracy for MSA observing, but especially *relative* astrometric accuracy. Target acquisition will remove the absolute astrometric uncertainty.

- Absolute astrometric correction for space-based operations will require target acquisition, which for NIRSpec MOS is done using reference stars across the MSA field of view at the start of a visit. Mask alignment strategies are similarly performed for ground-based MOS spectroscopy, but the accuracy requirement is less stringent because the slits are typically larger and the PSF wider.

Multiplexing

See Also: NIRSpec MOS Recommended Strategies

Multiplexing is the ability to observe a large number of targets in one exposure, at a given pointing. The multiplexing efficiency varies for MOS instruments, largely because the size of the field of view varies. The FOV of the NIRSpec MSA is smaller than for ground-based instruments, but JWST has high spatial resolution compared to seeing-limited ground-based MOS spectrographs. Since the JWST PSF is smaller, more spectra can be packed into a smaller distance in the cross-dispersion direction. In crowded fields, this provides an advantage over ground-based instruments.

Sensitivity and background

Main articles: NIRSpec Sensitivity, NIRSpec Bright Source Limits
See also: Components of the JWST Background, Background-limited JWST Observations, NIRSpec Background Recommended Strategies

At 3 to 5 μm, JWST will have a much lower background than ground-based spectrographs, as the thermal background is greatly reduced in space.

Ground-based instruments are subjected to atmospheric variability. The seeing from the ground limits the spatial resolution in the cross-dispersion direction, and can also lead to reduced spectral resolution if wider slits are required to avoid slit losses. Furthermore, seeing can vary on the same timescale as the observation itself. One component of background is the OH airglow spectrum, which is composed of many atmospheric emission lines in the NIR. Other sky lines are present as well. Often, scientific measurements are only possible between these sky lines, as they add noise and are sometimes difficult to accurately subtract. Space-based spectroscopy in the NIR is not affected by these atmospheric lines. Other types of the background are predominant in space, including zodiacal light and thermal emission from the telescope itself. But these are at a much lower level. The zodiacal emission will vary, but on much larger (seasonal) time scales with the orbital position of the telescope. A description of the background signal components at NIRSpec MOS wavelengths can be found at Components of the JWST Background.

For JWST, the dark current of its state-of-the-art detectors is low. Except for the PRISM, NIRSpec MSA observations are detector noise limited in low background environments and have high sensitivity in the NIR.

The ETC can be used to estimate the background and to obtain a good estimate of the expected signal to noise in the presence of the various background components. The background signal for JWST can reasonably be considered to be fixed for the duration of most observations.

Process differences

Main article: JWST Position Angles, Ranges, and Offsets
See Also: NIRSpec MOS Observing Process

A number of observing process differences exist between ground-based and JWST MOS observing, including position angle assignment, observation planning iterations, target acquisition, and pre-imaging:

- For ground-based MOS observing, the telescope orientation is usually not restricted during the cycle and the observer ultimately chooses a desired aperture position angle (APA), which is fixed only when the slit mask is completed. Because of the orbit of JWST, only certain ranges of telescope orientation and APA are available on any given date. Depending on the ecliptic latitude of a target, there may either be one long period when the target can be observed at a given position angle or two shorter periods during the cycle. Orientation angles are assigned operationally for MSA observations to provide scheduling flexibility on JWST.

- Observers are expected to use the MSA Planning Tool to design placeholder visits for proposal submission at a feasible user-selected APA. After APA assignment, detailed planning for program updates occur about 2 months before observations are executed, again using the MSA Planning Tool, but at the assigned aperture position angle. This is also when the most current knowledge of the evolving MSA shutter operability will be available to observers. The NIRSpec MOS Observing Process article describes this process in detail.

- As mentioned above, the most common target acquisition for this mode is done with reference stars, which must be in the correct brightness ranges (19.5–25.7 ABmag in the NIRSpec TA filters). Finding suitable point sources in these ranges may be challenging, and may require prior imaging.

- Pre-imaging will commonly be needed to support the increased astrometric accuracy of both the reference stars and the MSA targets. If pre-imaging is desired, the NIRCam pre-imaging observations must be specified completely at proposal submission. But the complete specification of the follow-up NIRSpec MOS observations, including reference stars, must wait for angle assignment, so there will be a second planning iteration that must happen. Other options for target acquisition in the MOS science template exist, and these are outlined in detail in NIRSpec Target Acquisition.

Dithering

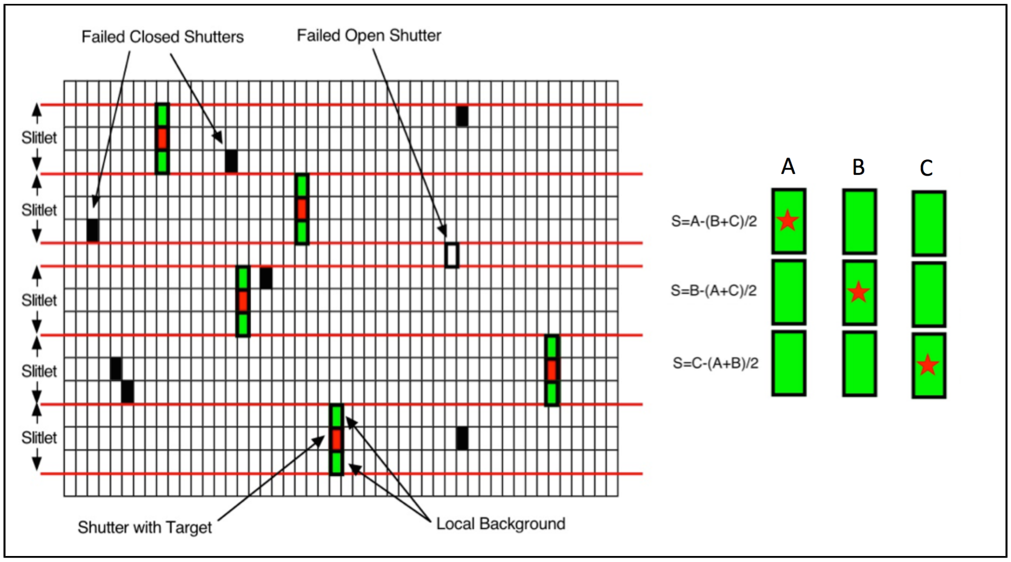
Main article: NIRSpec MOS Dither and Nod Patterns

Dithering and nodding along with the long (cross-dispersion) axis of the slit during an observation are useful in MOS spectroscopy to place the spectrum of each source onto different areas of the detector for better estimation of source and background signal and removal of detector artifacts. This strategy is particularly useful in ground-based infrared MOS observing, where it helps to obtain accurate source fluxes in the presence of high background. In instruments that have a marginal sampling, this strategy can improve the spatial sampling and can lead to more reliable estimates of the spectral line profile and spatial distribution of the emission.

The terminology of dithers and nods for JWST observations departs a little from the meaning of those terms in ground-based observing, where they can mean the same thing. For JWST, *dithering* means the telescope is moved to place sources in a different location on the MSA, requiring a reconfiguration of the MSA to observe the same targets. *Nodding*, or movement from one shutter to the next along the slilet in the MSA, does not require a new MSA configuration. Some distinctions between dithering and nodding for NIRSpec MOS and ground-based observing:

- Nodding is a common practice for all NIR instruments to measure and remove variable sky background.
- Nodding is used for background subtraction, while dithering is used for improved wavelength coverage (e.g., to provide measurements across a detector gap).
- Both nodding and dithering can be used to mitigate detector effects and improve data quality.
- Nodding in JWST "slitlets" moves the telescope over small separations (<1") from shutter to shutter; sources remain within the small slitlets. This is shown in Figure 1.
- Nodding distances for ground-based spectroscopy is specified by the user.
- The ground-based seeing-limited PSF requires larger nod offsets for sky background subtraction. Larger nod separations along the slit (>~2" typically) require longer slits and can impact the multiplexing efficiency. Since the slits are often customized to the targets, to perform nodding, the nods can be no larger than the smallest slit length.

Figure 1. Nodding in the MSA



A sketch of the MSA shutters (zoomed in) to illustrate target shutters (red) and associated local background shutters (green). The nodding technique combines the 3 exposures A, B, and C to produce background-subtracted target spectra, as indicated on the right.

Pre-imaging

> *Main articles: NIRSpec MOS Operations - Catalogs and Images, NIRSpec MOS Operations - Pre-Imaging Using NIRCam*

In general, MOS spectroscopy planning begins with a catalog of sources whose positions are known with enough accuracy to be able to place sources into slits. Typically, these positions are derived from imaging of the area of interest. When suitably accurate images are not available, the observer will need to obtain one from imaging instruments on the same or other telescopes.

JWST requires high astrometric accuracy catalogs (5–15 mas relative astrometry) to position the very small 0.2" wide shutters accurately onto science sources. Pre-imaging with NIRCam can provide this level of accuracy. Though pre-imaging is not required, it is desirable in many cases. Without this level of accuracy in the catalog, slit losses, and slit loss errors will result in increased data calibration uncertainties. Users may wish to propose for NIRCam pre-images in the same program as their NIRSpec MOS observations. For more details on pre-imaging with NIRCam, please read NIRSpec MOS Operations - Pre-Imaging Using NIRCam. JWST NIRSpec Observation Visualization Tool describes a tool to help with the planning of NIRCam pre-imaging.

NIRCam parallels

NIRCam parallels can be added to NIRSpec MOS observations. There is a one-to-one mapping between exposures of NIRspec and NIRCam, and there are extra overheads associated with the parallels because the instrument setups happen in series, not in parallel. Read JWST Parallel Observations for more details.

Data calibration considerations

Calibration of space-based and ground-based MOS spectroscopy pose different challenges, particularly in the robust estimation of the background, which is considerably higher and more variable for ground-based observing, and in slit loss correction, which must be done carefully for space-based MOS.

- 3 to 5 µm thermal IR spectroscopy is very difficult from the ground. The background is very high and photometric conditions can vary during the observation, making the slit loss correction more difficult. Conversely, assuming good positional astrometry, and since the PSF is stable (i.e., there is no atmospheric seeing), space-based photometry is more stable and more accurate.

- The background in ground-based instruments is measured between sky lines in J and H bands, from measurements made by nodding the target in the slit.

- Background estimation and subtraction in JWST: For point-like sources, the local background is estimated from background shutters in the slitlets, or from a combination of background shutters in nodded exposures. Alternatively, master background regions may be designated with the MSA Configuration Editor . Master background shutter spectra are co-added before subtraction from the source spectra. Background removal is described in CALWEBB_SPEC2.

- Aperture flux loss correction (i.e., slit loss correction) is less complicated from the ground for sources that may be moderately resolved in JWST, but are unresolved from the ground.

- The accuracy of wavelength calibration (and velocity measurements) depends on slit size, source centering, and the errors involved in calibrating the centering which depends on the pointing accuracy and slit losses. Wavelength calibration for NIRSpec is model-based. The data reduction pipeline wavelength assignment is expected to improve with on-orbit calibration. Wavecals are possible, but not recommended for most observations since they may cause persistence in subsequent spectroscopic observations. Off-centered sources will require a zero-point correction in the data reduction pipeline.

MOS Terminology

Table 1. MOS terminology

Term	Description
Band or bandpass	A range of wavelengths over which the instrument mode is operable. NIRSpec MOS bands are described in NIRSpec Multi-Object Spectroscopy.
Catalog	A list of candidates for observation. For NIRSpec MOS, the list should include TA reference stars and all other objects in the field for spectral contamination checking.

Contaminants	Sources whose spectra may inadvertently contaminate planned object spectra due to their proximity to planned sources or failed open shutters.
Dispersion	The quantity, in units of delta wavelength per pixel, that describes how the spectrum is sampled on the detector. NIRSpec MOS dispersion is plotted in NIRSpec Multi-Object Spectroscopy
Dithering	Moderate repositioning of the telescope between exposures to place the observed sources in a different location on the detector or detectors.
Filler candidates or secondaries	A subset of sources in the catalog with lower scientific priority than the primary candidates that can be used to increase the observing efficiency or multiplexing in an exposure.
FOV	Field of view of an instrument.
LSF	Line spread function, the characteristic shape of an unresolved spectral feature. The FWHM of the LSF defines the spectral resolution.
MSA	NIRSpec's micro-shutter assembly for performing MOS spectroscopy.
MSA configuration	The file which contains the planned MSA shutter status of the NIRSpec micro-shutter assembly. This file is used onboard the JWST telescope to instruct the instrument which shutters should be used to view sources at a given pointing/exposure.
Multiplexing	The efficiency with which the instrument can observe multiple sources at one pointing /exposure.
Nodding	Repositioning the telescope slightly between exposures to place the sources into different positions within the slit. Nodding is a specific type of dithering and it implies pairwise subtraction of exposures in pipeline processing.
Pixel	A pixel refers to a physical detector pixel that is read out by some series of electronics.
Pre-Imaging	The practice of obtaining imaging for improving source astrometry prior to spectroscopic observation. For JWST NIRSpec MOS spectroscopy, pre-imaging is done with NIRCam.
Primaries or primary candidates	These are the most important sources for observation defined by the observer. For many instruments including the NIRSpec MSA, weighting of the Primary candidates is also supported to help deliver these source spectra as products of the planning software.
PSF	Point Spread Function. Typically refers to the spatial intensity profile of an unresolved point source either incident upon the instrument optics (i.e., the telescope PSF), upon the aperture slit, or in the calibrated data.
Resolving power	A measure of the disperser's ability to separate spectral lines at an average wavelength. NIRSpec disperser resolving power is plotted in NIRSpec Dispersers and Filters.

Shutter	An element of the micro-shutter assembly (which contains nearly 1/4 of a million shutters) that can be configured open or closed on a source or background in the FOV. Several may be joined in the cross-dispersion direction to form a slitlet.
Slit	An aperture through which the filtered source signal is passed.
Slitlet	A slit in the MSA created from opening one or more adjacent shutters in the cross-dispersion direction.
Slit loss	The loss of light due to the slit size compared to the observed size of the source.
Slit mask	In many ground-based MOS spectrographs, a plate consisting of tiny holes or slits milled out to pass only the light from the sources of interest in the FOV.
Source centering	How close the source is from the center of a slit or shutter. This depends on the pointing accuracy of the catalog and the telescope with or without target acquisition. Source centering constraints are applied in the MSA Planning Tool.
Spectral resolution	The minimum separation in wavelengths that can be resolved by an instrument unambiguously. This quantity depends on both the resolving power of the disperser and the slit aperture of the instrument mode. See LSF.

Working with MOS data

Main article: NIRSpec Multi-Object Spectroscopy

Tools are available on the public github repository to help with the inspection and analysis of post-pipeline MOS data. Most are written in Python and require the installation of Astroconda. More information can be found in the JWST Analysis Tools article. Primarily intended for NIRSpec MOS data analysis are SpecViz and MOSViz. SpecViz is a tool for visualization and quick-look analysis of 1-D astronomical spectra. MOSViz is a quick-look analysis and visualization tool for multi-object spectroscopy (MOS). It is designed to work with pipeline output: spectra and associated images, or just with spectra. MOSViz is created to work with data from any telescope/instrument, but is built with the micro-shutter assembly (MSA) on the JWST/NIRSpec spectrograph in mind. As such, MOSViz has some features specific to NIRSpec data. User training workshops are offered periodically to help users become more expert at the use of the tools. See NIRSpec Training Webinars and Webcasts.

Example Science Programs

Multi-object spectroscopy is particularly well suited to a number of different science goals in the NIR. Some science use case examples include:

- measuring redshifts of distant galaxies for wide-area cosmological surveys

- measuring emission lines from galaxies, to obtain constraints on their physical conditions
- deep continuum spectroscopy of distant galaxies, covering feedback-sensitive outflow diagnostics in the rest-frame UV.
- Galactic star formation chemical abundances and stellar radial velocities

The science cases referenced below present some concrete examples that may help to understand the rationale behind observing strategies with the NIRSpec MSA. They include a rationale for different parameter choices in the MSA Planning Tool (MPT) in APT for the particular observing strategies used and other important observing considerations.

NIRSpec MOS Deep Extragalactic Survey

NIRISS WFSS with NIRCam Parallel Imaging of Galaxies in Lensing Clusters

NIRCam WFSS Deep Galaxy Observations

References

Wikipedia article on near-infrared spectroscopy

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Latest updates	

MOS Roadmap

A general guide to preparing JWST NIRSpec multi-object spectroscopy (MOS) observations.

On this page

Unlike most JWST observing modes, NIRSpec MOS science observations typically follow a *two-phase process*. This two-phase process is due to the very tiny shutters in the MSA and the need for precise target positioning in them. After proposal submission and acceptance, an aperture position angle (APA) (***Aperture PA*** * parameter in APT) assignment is made by STScI schedulers so that the NIRSpec MOS observations can be scheduled more efficiently and flexibly.

For most MOS science cases, observations are not specified directly in the Astronomers' Proposal Tool (APT) template in the same way as all other observing modes. The exceptions are long-slit observations or custom, manually-designed MSA configurations with the MOS and/or observations of moving targets, which will follow a modified process. Even in these exceptional cases, however, an APA assignment will often be required, demanding a two-phase approach. The MOS process is described in greater detail in the article NIRSpec MOS Observing Process.

In the first phase, for proposal submission, users will typically run the NIRSpec MSA Planning Tool (MPT) to create a set of *planning visit*s with placeholder pointings and MSA shutter configurations that will be representative of the pointing and configurations after an APA has been assigned. Provided the source density is representative, MPT can predict the number of targets to expect for each pointing for a given observing strategy. For proposal submission, it is also important to include any fully specified NIRCam pre-imaging observations that will be used to locate targets for NIRSpec follow-up. Timing links should be included, to ensure that the NIRCam pre-imaging is carried out before the NIRSpec observations, by a sufficient margin.

The second phase begins after APA assignment and after the NIRCam imaging is obtained (if any). Within a few months prior to the first MOS observing window, users will again run MPT, which will utilize the latest MSA shutter operability status, and the assigned APA**,** to design the final MOS observations that will specify the exact pointings and MSA configurations, and the expected targets that will be observed. This is called the *program submission* (a.k.a. *program update*). The reference stars used for MSA target acquisition must also be finalized in this submission.

The typical MOS observer will use MPT to create optimal plans for MOS observations that attempt to maximize the number of observed sources. In order to clarify the MOS planning process, a step-by-step roadmap for proposing NIRSpec MOS science is summarized below. Additionally, some useful MOS observational strategies are discussed in the MOS Recommended Strategies article.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Specific considerations

Catalogs

NIRSpec observations planned with MPT require planning catalogs. Catalogs produced from HST ACS or WFC3 imaging have sufficient relative accuracy for detailed MOS observation planning and program updates. The catalog should be as complete as possible, including not only sources of scientific interest, but all other sources in the field, to be able to identify potential contaminants. The relative astrometric accuracy of the catalog is important for target acquisition to put science sources in the tiny shutters. For example, a relative astrometric accuracy of 5 mas in the catalog is necessary to deliver a NIRSpec MSA target acquisition (***MSATA***) accuracy of 20 mas. Catalog accuracies of 5–10 mas are required for meaningful use of the centering constraint in MPT which can help to limit slit loss and wavelength calibration uncertainties. Catalogs are not necessary for long-slit observations using the Q4 field points.

NIRCam pre-imaging

NIRCam pre-imaging may be needed for MOS observations where imaging and catalogs are either non-existent or of insufficient astrometric accuracy to plan detailed MOS observations.

NIRCam parallels

Many science cases will benefit from the ability to observe NIRSpec MOS targets while simultaneously imaging nearby fields with NIRCam for future science exploration. NIRCam parallels can be added from the NIRSpec MOS APT template. A set of joint dithers can be added to improve the NIRCam pixel sampling. The MOS Recommended Strategies article discusses this and other useful strategies.

Moving targets

Consult the Moving Target Roadmap. MOS observations of moving targets must be specified directly in the MOS APT template at the observation level. Fill out the template directly, select a pre-designed custom config or the canned long slit, and select the correct science aperture (the Q4 field point should be used with the canned long slit).

Canned long slit and custom MSA configurations

A pseudo long slit is offered directly in the MOS APT template in the pull-down selector for the MSA configuration. Together with the mosaic capability in the template, it is possible to step sequentially across a large extended target and obtain spectroscopy through the long slit. Similarly, users can create a custom configuration with the Manual Planner that can be used in the MOS template together with dithers specified in the Manual Planner, or mosaics specified in the MOS template to step across a series of smaller extended targets over the MSA field of view.

NIRSpec MOS proposal roadmap

The following roadmap should be used by those who wish to submit a proposal for MOS observations. It follows from steps outlined in the Getting Started Guide article. The program update (second phase) follows a similar approach - in that case, observers will replan their MSA observations using an assigned aperture position angle (that will be populated for the user in APT) and also select reference stars for the MOS visits. Consult the NIRSpec MOS Observing Process for a details about this process.

This roadmap assumes the standard use of the MPT to define NIRSpec MOS observations using a catalog. Details specific to other more specialized cases using canned or custom MSA configurations are presented using the pull-down options shown in the roadmap at various steps. For an example program that uses the standard roadmap, please see the NIRSpec MOS Deep Extragalactic Survey article.

Each step listed below is followed by a list of articles with additional details.

Roadmap for MOS observations (for proposal submission)

1. Determine the range of feasible MOS observation aperture position angles (***Aperture PA***) for the area of interest.
   General Target Visibility Tool (GTVT)
   NIRSpec Observation Visualization Tool (NOVT)

2. An input source catalog is required for MOS observations of multiple distinct sources with the NIRSpec MSA. Obtain or create a source ***Catalog*** of sufficient accuracy.

   a. Determine whether HST imaging and source catalogs exist for your fields. If so, obtain one for later use with the MSA Planning Tool (MPT).
      Hubble Space Telescope Finder Images and Catalogs
      Hubble Source Catalog
      MAST
      Vizier

   b. If a catalog derived from HST imaging does not exist, then create a ***Catalog*** that spans an area of the sky in the field of interest to allow MPT to select optimal pointings. An area of 5' × 5' is suggested. For proposal submission you may use a simulated catalog or one created from observations with other telescopes.
      NIRSpec MOS Operations - Catalogs and Images
      MPT Catalogs - Examples

3. Decide on a target acquisition strategy. MOS programs prepared with MPT will use ***MSATA*** for target acquisition. However, ***MSATA*** doesn't have to be fully specified at proposal submission.
   NIRSpec Target Acquisition
   NIRSpec MSA Target Acquisition
   NIRSpec MOS Operations - Slit Losses

   For extended sources or moving targets, it is possible to define a MOS observation in the APT template directly. For those cases,

   NIRSpec Wide Aperture Target Acquisition
   NIRSpec Verify Only Target Position
   NIRSpec MOS Operations - Slit Losses

4. Optional NIRCam pre-imaging may be done if existing imaging and source catalogs for your fields of interest do not provide the required positional accuracy:

You should propose for NIRCam pre-imaging in the same proposal as your NIRSpec observations. NIRCam pre-imaging observations must be *fully defined* at the time of proposal submission.
NIRCam Pre-Imaging

- Pick desired wavelength setting(s) for NIRCam pre-imaging. It is sometimes desirable to use the F115W filter which is closely matched to the NIRSpec F110W TA filter, for example.
  NIRCam imaging: NIRCam Filters

- Determine which dithers and mosaic patterns to use with your NIRCam imaging.
  NIRSpec Observation Visualization Tool (NOVT)

- NIRCam imaging observations should be *fully defined* at the time of proposal submission, and should cover a sufficiently large field of view to allow for spectroscopic follow-up at *any* potential assigned ***Aperture PA***. An area of 5' × 5' is suggested.
  NIRCam Primary Dithers
  NIRCam Mosaics
  NIRCam Dithers and Mosaics
  NIRCam Imaging Recommended Strategies

- Determine the required exposure time and detector readout parameters for your NIRCam observation including target acquisition using the Exposure Time Calculator (ETC).
  JWST ETC New User Guide
  JWST ETC Workbooks Overview
  NIRCam Imaging Recommended Strategies
  JWST ETC Target Acquisition

- Complete the Astronomers Proposal Tool (APT) template for your NIRCam pre-imaging observation.
  NIRCam imaging template in APT

5. Pick desired wavelength setting(s) for MOS observations. Select dispersers and filters, depending on needed wavelength coverage and resolving power.
   NIRSpec Dispersers and Filters

6. Determine what dither strategy to use with your NIRSpec MPT-generated MOS observations. Nods and dither specifications can be added when designing an observation with the MPT Planner. (Alternatively, nods and dithers can be added using the Manual Planner for custom MOS observations described further down in the roadmap. The only options for dithering canned long slit observations is with the Manual Planner, or by using mosaicking.)
   NIRSpec Dithers and Nods
   NIRSpec Dithering Recommended Strategies

7. Before specifying your NIRSpec MOS observation, learn about recommended practices for dithering, background subtraction, MSA leakage, and general MOS recommendations.

NIRSpec MOS Recommended Strategies
NIRSpec Background Recommended Strategies
NIRSpec MSA Leakage Subtraction Recommended Strategies

JWST Moving Targets in APT
Moving Target Recommended Strategies

8. Determine the required exposure and detector readout parameters for your NIRSpec MOS observations including target acquisitions using the Exposure Time Calculator (ETC). Perform these calculations by bracketing the range of expected source brightnesses in the wavelength bands of interest, avoiding saturation of the brightest sources. ETC workbooks are provided for each instrument mode to illustrate parameter selection.
   NIRSpec Detector Recommended Strategies
   JWST ETC Target Acquisition

9. Create NIRSpec MOS observation plans in APT/MPT. Run the MSA Planning Tool (MPT) in the Astronomers Proposal Tool (APT) to create automatically-designed NIRSpec MOS observations with MPT. Navigate to MPT from the **Observation Folder** level in APT. Follow the articles under the MOS APT Template (**Catalogs**, **Planner**, and **Plans**, in that order) from the links shown below to walk through the creation and evaluation of a MOS Plan. An example science case is illustrated in the article NIRSpec MOS Deep Extragalactic Survey.
   NIRSpec Multi-Object Spectroscopy APT Template
   NIRSpec MSA Planning Tool, MPT
   NIRSpec MPT - Catalogs
   NIRSpec MPT - Planner
   NIRSpec MPT - Plans
   MOS APT Template Parameters

   OR create a MOS observation using the canned MSA Quad 4 long slit.

   - Fill out the Astronomers Proposal Tool (APT) for your NIRSpec MOS observation directly (and completely) at the observation level in APT. (Refer to step 13). The target should be one selected from the **Targets** folder—your moving or extended fixed target. ***WATA*** is the default TA strategy, but you may select a different TA option. The default ***Science Aperture*** is the ***Q4 field point***, which is used wth ***WATA***. Specify your exposure parameters, and be sure to select the ***Q4 Field Point 1 Long Slit*** configuration to center your target in the slit at the defined reference point for that aperture.
     MOS Custom Configuration Process

   - Optionally specify a mosaic. Canned long slit observations with the MSA can additionally make use of the mosaic option in APT to, for example, step the slit across the source in the dispersion direction. If you have a use case that requires mosaicking, you may specify the mosaic at the observations level in APT.
     APT Mosaic Planning

- Likewise, these observations may require an ***Aperture PA*** special requirement to limit the range of position angles. Be sure to add one, if necessary (refer to step 14).
- Continue from step 14.

OR create a MOS observation using custom MSA configurations.

- Determine one or more fixed pointings and an orientation (APA). If making a *custom* MOS observation using a ***Catalog***, first determine the exact pointing and orientation. It may be helpful to view an image of your target(s) in Aladin, and to overlay your catalog sources positions there. Custom MSA configurations will typically be considered placeholder observations (like those generated with MPT), unless there is a strong scientific justification for a fixed ***Aperture PA***. After an ***Aperture PA*** is assigned, observers will be able to re-plan their custom MOS observations for the program update.
  JWST APT Aladin Viewer
- Navigate to the **Manual Planner** in MPT, and create or ingest your custom MSA configurations at the fixed pointing(s) you determined. Continue to add exposure specifications using the same MSA configuration, or new MSA configurations, and include any offsets. Click ***Finish Plan*** when done.
  MOS Custom Configuration Process
  NIRSpec MPT - Manual Planner
- Evaluate the plan(s). These plans can be evaluated (and even merged together for making a single observation) in the **Plans** tab of MPT, like auto-generated MPT plans.
  NIRSpec MPT - Plans
- Create an Observation from the plan. Select a plan, and create a MOS observation from the manual plan (refer to step 11).
- Fill out Observation in APT. Fill out the Astronomers Proposal Tool (APT) for your NIRSpec MOS observation directly at the observation level in APT (refer to step 13). Be sure to select the correct manually-designed MSA configuration from the pull-down menu in the exposure specification table.
- Optionally specify a mosaic. Custom observations with the MSA may additionally make use of the ***mosaic*** option in APT to, for example, step the slit across the sources in the dispersion direction. If you have a use case that requires mosaicking, you may specify the mosaic at the observation level in APT.
  APT Mosaic Planning
- These observations may require an exact APA special requirement, ***Aperture PA***. Be sure to add one (refer to step 14).
- Continue from step 14.

10. The MPT should be run at several available APAs to check the variation in plan results and obtain more informed estimates of the observing time needed to execute the science. Multiplexing depends on a wide range of factors: the catalog density, extent, source distribution, the slit shape used, source centering constraints, etc. Multiplexing mostly does *not* depend on aperture position angles for catalogs distributed isotropically in angle. However, cases that involve a handful of highly weighted sources may be impacted by the selected angle. The user should test this in any case.
    NIRSpec MPT - Parameter Space

11. Create an MPT Observation. Once you have an MPT plan that you are happy with, click ***Create Observation*** from the **Plans** pane in MPT to populate the NIRSpec MOS mode observation template with pointings, MSA configurations and exposure parameters.
    NIRSpec MPT - Plans
    NIRSpec Multi-Object Spectroscopy APT Template

12. Note that MSA target acquisition (***MSATA***) reference alignment targets, called *reference stars*, and related TA parameters for the science observations cannot be defined at proposal submission because the execution ***Aperture PA*** isn't yet assigned. The selection of reference stars and MSATA parameters is done at the visit level, after the MOS observations are finalized. Leave this for later, in the detailed program update submission.

13. Fill out Observation in APT. Navigate to the observation level of your MOS observation in APT and continue to fill out the remaining elements of the MOS APT template, including the decision to add **Confirmation Images** to be able to locate targets in the slitlets in post-analysis.
    NIRSpec MOS Operations - Confirmation Images

14. Determine from viewing in Aladin, or with NOVT, whether an ***Aperture PA*** special requirement is needed. The NIRSpec MOS observation should ideally *not* have a specific ***Aperture PA*** special requirement added. However, some use cases may need such constraints. For scheduling flexibility, a minimum range of approximately 20°–30° is recommended. Observation planning using a catalog with MPT or a manually created plan uses an ***Aperture PA***, however this angle is not guaranteed for the observation, nor is it used downstream to plan or schedule the observation. However, the ***Aperture PA*** assigned by STScI will be enforced for program update submission.
    NIRSpec MOS Operations - Pre-Imaging Using NIRCam
    NIRSpec Observation Visualization Tool (NOVT)
    Aperture Position Angle Special Requirements
    APT Aladin Viewer

15. Timing special requirement needed when NIRCam pre-imaging is requested.

    When NIRCam pre-imaging is specified in the proposal,

    The MOS observation should have a ***Timing*** special requirement (specifically, an ***AFTER <observation link>***) added to ensure enough time is allowed between NIRCam pre-imaging and NIRSpec follow-up observations. The recommended minimum is 60 days, but 42 days is the absolute minimum, leaving only 2 weeks for the observing team to complete program updates. The NIRSpec Observation

Visualization Tool (NOVT) can be used to visualize and help plan the pre-imaging observations relative to the NIRSpec observation.

NIRSpec MOS Operations - Pre-Imaging Using NIRCam
Timing Special Requirements
NIRSpec MOS Observing Process
NIRSpec Observation Visualization Tool (NOVT)

16. Add optional NIRCam coordinated parallels, if desired. View the footprints of any NIRCam parallels in APT in the Aladin viewer using the ***FOV*** button and by highlighting the NIRSpec observation. Select ***single aperture*** if the view is too crowded. If the NIRCam parallels are specified with joint subpixel dither options, make sure the NIRSpec exposure time is appropriate. Some joint subpixel dither options will double or triple the number of NIRSpec dithers.
Coordinated Parallel Observations
Coordinated Parallels Custom Dithers
APT Aladin Viewer

17. The APT Visit Planner should be run to check the scheduling of the MOS visits created by the MPT.
APT Visit Planner

References

Karakla, D. et al. 2014, *Proc. SPIE* 9149
The NIRSpec MSA Planning Tool for multi-object spectroscopy with JWST

Published	02 Jun 2017
Latest updates	

A Comparison of MOS spectroscopy with the NIRSpec MSA and other JWST Instruments

JWST multi-object spectroscopy (MOS) with the NIRSpec micro-shutter assembly (MSA) is compared with the NIRISS wide field slitless spectroscopy (WFSS) mode, and the NIRCAM WFSS mode.

On this page

Comparing MOS spectroscopy in NIRSpec, NIRISS, and NIRCam

> *Main articles: NIRSpec Multi-Object Spectroscopy, NIRISS Wide Field Slitless Spectroscopy, NIRCam Wide Field Slitless Spectroscopy*

MOS is an efficient way to obtain the spectra of many sources all within the field of view (FOV) of an instrument at a single pointing. This can also be accomplished using a wide field slitless spectroscopy capability (WFSS) like that offered with the NIRISS and NIRCam instruments. To compare and contrast MOS spectroscopy and wide field slitless spectroscopy, this section will focus on these instrument capabilities as offered by JWST instruments.

Field of view and operating range

The field of view and wavelength coverage for each instrument mode are compared in Table 1. Here are some differences:

FOV:

- The field of view (FOV) of the NIRISS WFSS mode is smaller than that of the NIRspec MSA.
- For a single module in the NIRCam WFSS mode, the FOV is also smaller than that of the MSA.

Wavelength Coverage and Spectral Resolution:

- NIRISS WFSS operates over a shortened wavelength range from 0.8 to 2.2 μm with low spectral resolution (R ~ 150).
- The NIRCam WFSS mode operates over the range from 2.4 to 5 μm with moderate resolution (R ~ 1,600). The same instrument mode includes simultaneous short wavelength (SW; 0.6 to 2.3 μm) imaging over roughly the same field of view via a dichroic.
- NIRISS WFSS and NIRCam WFSS modes use grisms to disperse the spectra onto their respective detectors.
- The NIRSpec instrument uses a set of 3 high- or medium-resolution gratings to cover the entire operational wavelength range. Together with matched filters, a minimum of 3 exposures will cover the 1–5 μm range, and additional exposure can extend this coverage to 0.7 μm. NIRSpec MOS mode additionally offers a prism for low resolution spectroscopy.
- A common practice in the WFSS modes of both NIRISS and NIRCam is to couple the grism with a blocking filter to effectively shorten the spectrum on the detector and limit spectral overlap from other sources in the field, including the background.
- NIRSpec MOS with the MSA can obtain the entire range from 0.6 to 5.3 μm in the low-resolution PRISM in a single exposure with a much lower probability of contamination.

Spectral Contamination and Slit Losses

One clear advantage of MOS instruments with slit masks is that they can block out sources to prevent contamination by overlapping spectra. Masking out other sources of light allows greater efficiency and sensitivity for faint targets, which can be lost in slitless spectroscopy if they are contaminated by a bright, nearby object. Moreover, because slits block the background as well, MOS spectroscopy with slit masks can reach greater sensitivity than WFSS. Conversely, with WFSS, the dispersed background from areas even quite far from a target occupies the same detector area as the spectrum of the target, leading to added noise.

With NIRISS WFSS and NIRCam WFSS, the spectra of all targets may optionally be observed at 2 perpendicular angles in a single observation (requiring a second exposure) using 2 orthogonal grisms. Spectra taken this way are mapped to different locations on the detectors. Combining extracted spectra observed at both angles is useful for mitigating contamination (since a spectrum contaminated in one angle will hopefully be clean in the orthogonal angle). The strategy also helps with de-blending overlapping science spectra of nearby sources and can improve spectral sampling.

In WFSS modes for NIRISS and NIRCam, there are no slits, hence no slit losses. With the NIRSpec MSA, there are slit losses associated with the MSA bars. Since it is not possible to obtain perfect centering on each source in the fixed grid of the MSA shutters, slit losses will vary from target to target. For point sources, pipeline processing will correct for these losses, although the accuracy of the correction depends on the accuracy of the target acquisition. Alternatively, for extended targets, slit losses from the 0.2" wide MSA shutters can be significant and may be difficult to quantify in some cases.

Comparative Summary of Techniques

A summary of the advantages and disadvantages of each technique is shown in Table 1. The JWST Wide Field Slitless Spectroscopy article contains more detailed information about WFSS with JWST (both NIRISS and NIRCam instruments). APT Guides are available for each of the instrument modes:

NIRCam Wide Field Slitless Spectroscopy APT Template
NIRISS Wide Field Slitless Spectroscopy APT Template
NIRSpec Multi-Object Spectroscopy APT Template

Other articles have been written to describe science use cases in these instrument modes.

Table 1. Comparison of wide field slitless spectroscopy with NIRISS and NIRCam, and NIRspec MOS spectroscopy

	NIRSpec MSA	NIRISS WFSS	NIRCam WFSS
FOV	3.4' × 3.6'	2.2' × 2.2'	2.2' × 2.2' for one module, reduced by the filter choice 2.2' × 5.0' for two modules, reduced by the filter choice
Wavelength Range	0.6–5.3 µm (PRISM) in one exposure 0.7–1.89 µm (Band I), 2 filters /exposures required 1.66–3.17 µm (Band II) in one exposure 2.87–5.27 µm (Band III) in one exposure no imaging possible with NIRSpec	0.6–2.8 µm (several filters required to cover the range) 0.8–2.2 µm (several filters required to cover the range) Imaging possible in same observation	2.4–5.0 µm (several filters required to cover the range) Optional simultaneous shortwave imaging (0.6–2.3 µm)
Resolving Power	R ~ 100 (PRISM) R ~ 1,000 (Med-res gratings, Bands I–III) R ~ 2,700 (High-res gratings, Bands I–III)	R ~ 700 (0.6–2.8 µm) R ~ 150 (0.8–2.2 µm)	R ~ 1,600
Observable aperture	APA is assigned once observations are scheduled	Perpendicular APAs are	Perpendicular APAs are additionally possible in same observation

position angles 1		additionally possible in same observation	
Slit Losses	MSA fixed shutter size, vignetted by MSA bars	None	None
Dithering	Recommended to bridge the detector gap and sample point source spectra at several locations in a shutter and on the detector. The NIRSpec PSF is critically sampled at most wavelengths and undersampled at some.	Recommended because the NIRISS PSF is under-sampled.	Recommended to provide direct imaging of out-of-view sources, and to bridge detector gaps and module gaps.
Contamination and confusion by other sources	Only if contaminating sources occupy the same shutter	Unavoidable for most sources. Spectra of all sources across the field in dispersion direction may overlap	Unavoidable for most sources. Spectra of all sources across the field in dispersion direction will overlap
Background	Blocked by the MSA, with only a small amount of leakage, thereby achieving great sensitivity.	The entire background that passes through the blocking filter is dispersed, adding noise.	The entire background that passes through the blocking filter is dispersed, adding noise. The background of NIRCAM slitless observations is expected to have significant structure caused by the final shape of the pickup mirror illuminating the grism.

Table Note: The range of feasible angles for all instrument modes depends on the target pointing ecliptic latitude.

MOS and WFSS data

Figures 1 and 2 show examples of data for the WFSS modes in NIRISS and NIRCam, respectively. These figures are from a Newsletter article (Vol 30 Issue 2) by Dixon and Willott showing a field of simulated galaxies based on position derived from CLASH (Cluster Lensing and Supernova Survey with Hubble) data, and the WFSS spectral images produce by the NIRISS WFSS observing mode.

Figures 1 and 2. Simulated direct image and WFSS spectroscopy of the same field with NIRISS

Figure 1: Simulated direct image of the CLASH field (Postman et al. 2012). This color composite combines F090W, F150W, and F200W images. The crosshair near the bottom of the field marks the high-redshift galaxy discussed in the text. The dispersion directions of the two NIRISS grisms are aligned with the crosshairs.

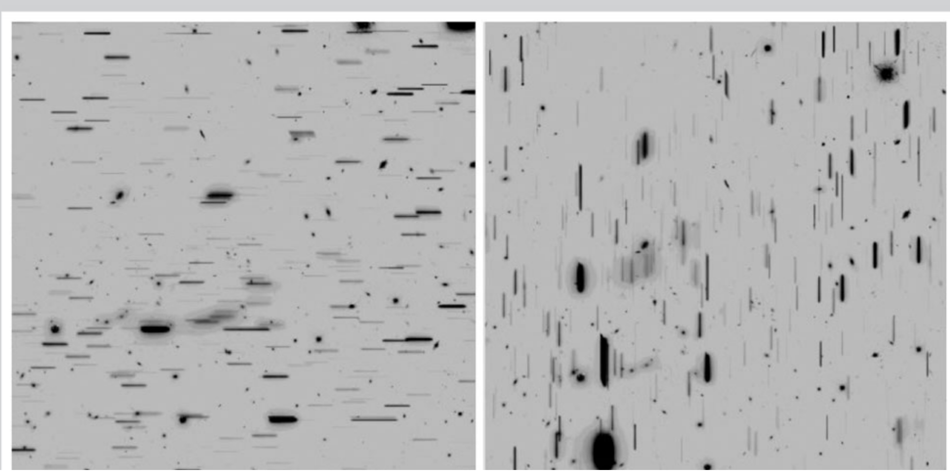
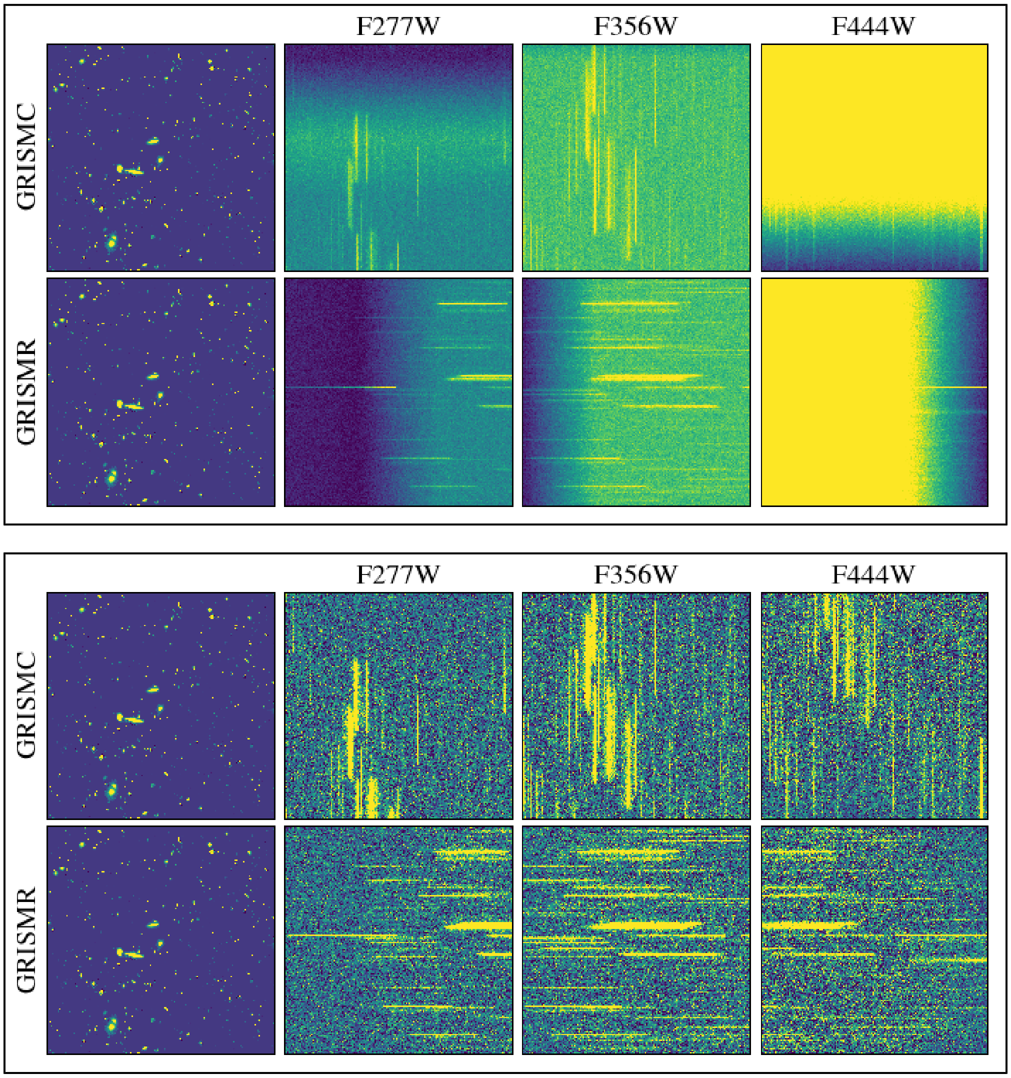


Figure 2: Simulated GR150R (*left*) and GR150C (*right*) images of the CLASH field through the F200W filter. GR150R disperses into rows on the detector, while GR150C disperses into columns.

A field of simulated galaxies based on a position derived from CLASH (Cluster Lensing and Supernova Survey with Hubble) data. Credit: Van Dixon and Chris Willott STScI Newsletter 2015 (Vol 30, Issue 2).

Figure 3 below is a view of simulated NIRCam Grism WFSS data with 2 cross-dispersed GRISMs.

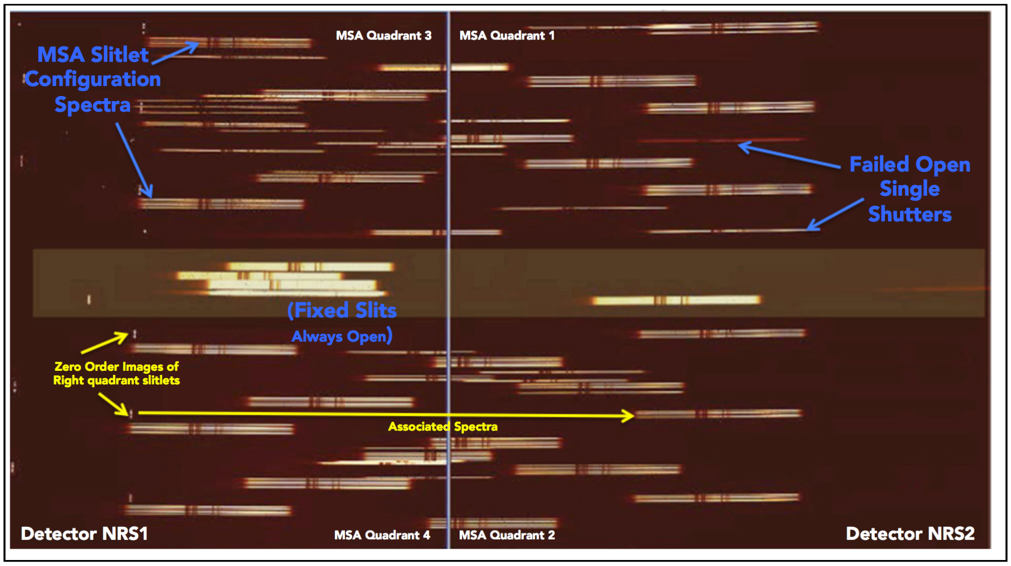
Figure 3. Simulation of NIRCam WFSS dispersed grism data using different cross filters



Simulated single-module NIRCam observations of a section of the GOODS-S ERS field. Top Panel: full simulations that include estimated dispersed grism backgrounds. Bottom Panel: Same as Top Panel but the backgrounds have been subtracted.

Figure 4 presents simulated NIRSpec MOS data with the R ~ 1,000 G140M grating for comparison with the data products above.

Figure 4. Pre-flight NIRSpec MOS slit data



NIRSpec MOS data acquired with a ground calibration test lamp using the R = 1000 G140M/F100LP short wavelength spectral configuration. The four MSA quadrant spectra are shown. This observation was acquired with a special 5-shutter calibration-only slitlet pattern that had 3 shutters open with 2 closed in-between them. ***About 100 micro-shutters were opened in all. Bright spectra near the vertical center are from the fixed slits, which are milled into the same mounting plate that contains the MSA. Fainter single-shutter spectra from individual failed open shutters can also be seen.***

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Latest updates	

JWST Time-Series Observations

JWST time-series observations provide a way to monitor time variable phenomena, with observations optimized for detecting faint variations in flux over short or long timescales.

On this page

Time-series observations (TSO) are carried out to monitor astrophysical sources that are time variable. A time-series observation is typically a long staring observation, optimized to detect and characterize faint temporal modulations in the source flux. Common examples are observations of stellar variability, eclipsing variables, brown dwarf variability, or exoplanet transits.

The lack of interference from Earth's atmosphere and the gravity free environment make a large space-based observatory, such as JWST, particularly suitable for this type of observations. Such observations place specific requirements on the observatory and the instrumentation to ensure the highest possible level of stability over lengthy exposures, as well as on the data processing environment.

This article describes how TSOs are performed using JWST: the instrumentation and modes that are available, user tools to prepare TSOs, the data processing infrastructure, and some guidelines for preparing successful TSOs.

Time-series observation with JWST

Several steps have been implemented to optimize JWST's instrument setup and data processing to provide the highly stable conditions needed for long duration staring at TSOs:

- dithering is disabled
- target acquisition is enabled (mandatory for some modes)
- exposures can take longer than 10,000 s
- high gain antenna moves are allowed during the exposure
- data are processed via a dedicated pipeline branch (CALTSO3); every integration is treated as an individual observation.

The TSO conditions are available to a number of modes across all 4 JWST instruments. Some of these have been designated as TSO-only modes; for others modes, a user can choose to flag observations as TSO via the Astronomer's Proposal Tool (APT).

Typical noise sources that affect the (spectro-) photometric precision in TSOs are described in this dedicated article.

Instrument modes for TSOs

Details about TSO-specific instrument modes are available in these articles:

- NIRISS Single Object Slitless Spectroscopy (SOSS)
- NIRCam Time-Series Imaging
- NIRCam Grism Time Series
- NIRSpec Bright Object Time-Series Spectroscopy (BOTS)
- MIRI Imaging TSOs
- MIRI Low Resolution Spectroscopy (LRS)
- MIRI Medium Resolution Spectroscopy (MRS)

These articles are dedicated instrument documentation pages for these modes, with detailed information on the instrument hardware and operations. Other modes may be used to measure time series of sources, but the conditions listed above will not be available. This section provides guidelines on the scientific applications of each TSO instrument/mode combination.

TSOs roadmaps

See the following article for guidelines and a roadmap for how to prepare your time-series observations with JWST.

Time-Series Observations Roadmap

TSOs example science programs

The following example science programs are available for time-series observations.

- NIRCam Time-Series Imaging of HAT-P-18 b
- NIRCam Grism Time-Series Observations of GJ 436b
- NIRISS SOSS Time-Series Observations of HAT-P-1
- NIRSpec BOTS Observations of WASP-79b

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Latest updates	06 Dec 2019

TSO Roadmap

A roadmap to guide users, step-by-step, through the process of designing an observing program using one of the dedicated time-series modes on board JWST.

On this page

For time-series observations (TSOs), we assume that the total length of the observation is driven by the duration of the transit, rotation, or variability period rather than the signal-to-noise requirement, and that these quantities are known from previous observations or from the literature. A useful reference source for this information, aside from published literature on your target, is the ExoMAST database.

The first step is to select the TSO mode that is most appropriate for your observation. The first choices to make here are

(a) imaging or spectroscopy
(b) near- or mid-infrared?

Table 1. A decision matrix for time-series imaging and spectroscopy observations

	Photometry	Spectroscopy
λ ≤ 5 μm	NIRCam time-series imaging	NIRCam time-series grism spectroscopy NIRISS single object slitless spectroscopy (SOSS) NIRSpec bright object time-series spectroscopy (BOTS)
λ ≥ 5 μm	MIRI imaging	MIRI low resolution slitless spectroscopy MIRI medium resolution spectroscopy

TSOs roadmap: imaging

1. Determine the required wavelength coverage: near-infrared or mid-infrared.
   The links in Table 1 provide more information about the wavelengths covered and filters provided by the imaging TSO modes.

2. By studying the sensitivity, saturation limit, and dynamic range of the relevant detectors, determine the required array configuration (full array or subarray)
   NIRCam Sensitivity, NIRCam Bright Source Limits, NIRCam Detector Subarrays
   MIRI Sensitivity, MIRI Bright Source Limits, MIRI Detector Subarrays

3. Choose the appropriate pupil optic and/or filter configuration
   NIRCam Pupil and Filter Wheels, NIRCam Filters
   MIRI Filters

4. Calculate the required exposure configuration using the JWST Exposure Time Calculator. Note that for TSOs each integration is treated as a separate image by the calibration pipeline; the purpose is to monitor the target over a period of time, *not* to co-add the integrations to increase the SNR. We therefore recommend that the ETC be used to model the SNR for a *single integration.* The number of integrations is then determined by the required length of the observation (e.g., based on the known transit duration). The ETC can also be run from its code engine, Pandeia.
   NIRCam Detector Readout Patterns
   MIRI Detector Readout Patterns
   Pandeia Tutorial

5. For NIRCam time-series imaging, use the Exposure Time Calculator (ETC) to determine the appropriate target acquisition strategy. For multi-epoch observations, target acquisition ensures that the target is placed in the same subpixel location for each epoch, which may be important to control for systematics such as intra-pixel responsivity variations. Note: target acquisition is *currently not available* for MIRI imaging.
   NIRCam Time-Series Imaging Target Acquisition, JWST ETC NIRCam Target Acquisition
   JWST Pointing Performance

6. Using the outcomes of steps 1 to 6, complete the Astronomer's Proposal Tool template using the appropriate NIRCam or MIRI template. Remember to check that the ***Time Series Observation***[*] and ***No Parallel*** special requirements are selected in the **Special Requirements** tab of the observation form in the proposal. The ***Time Series Observation*** special requirement disables the use of dithering and mosaicking, and allows a single exposure to run longer than 10,000 s. You will also need to specify the phase constraints and transit timing specifications in the Special Requirements section; without this information the observation cannot be successfully scheduled.
   NIRCam Time-Series APT Template
   MIRI Imaging APT Template
   APT Special Requirements

[*] ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

TSOs Roadmap: Spectroscopy

1. Determine the required wavelength coverage: near-infrared or mid-infrared.
   The links in Table 1 provide more information, in broad terms, about the wavelength coverage of the available spectroscopic TSO modes (near- vs. mid-infrared). For more details on the (instantaneous) wavelength coverage of each mode, check the instrument mode articles (listed below). Additional parameters to consider for selection between the near-IR modes are (1) sensitivity and saturation limits and (2) spectral resolving power. Table 2 gives a summary overview of the NIR modes; for spectroscopy beyond 5 µm, the MIRI low resolution spectrometer (LRS) and medium resolution spectrometer (MRS) are both available. Note that MIRI LRS with the slit cannot be used for TSOs —these observations always use the LRS slitless mode in the ***SLITLESSPRISM*** subarray.
   NIRCam Grism Time Series, NIRCam Sensitivity, NIRCam Bright Source Limits
   NIRISS Single Object Slitless Spectroscopy (SOSS), NIRISS Sensitivity, NIRISS Bright Limits
   NIRSpec Bright Object Time-Series Spectroscopy (BOTS), NIRSpec Sensitivity, NIRSpec Bright Source Limits
   MIRI Low Resolution Spectroscopy (LRS), MIRI Medium Resolution Spectroscopy (MRS), MIRI Sensitivity, MIRI Bright Source Limits

Table 2. Overview of near-infrared TSO spectroscopy modes

Mode	Disperser type	R	Subarray choices?	Readout pattern choices?	Target acquisition	Other
NIRCam grism time series	Grism	1,600	4	yes	yes	Spectroscopy in long wavelength channel only, accompanied by weak lens imaging in short wavelength channel
NIRISS SOSS	Grism	700	3	yes	yes	SOSS modes provides scientifically useful spectra in 2 orders
NIRSpec BOTS	Prism or grating	100, 1,000, 2,700	5	yes	yes (WATA)	Gratings are combined with filters to determine the instantaneous spectral coverage

Table 3. Overview of mid-infrared TSO spectroscopy modes

Mode	Disperser	R	Subarray	Readout	Target	Other

	type		choices?	pattern choices?	acquisition	
MIRI LRS	Double Prism	~100	no	no	yes	TSOs are only available in the slitless mode, which uses the ***SLITLESSPRISM*** subarray
MIRI MRS	Grating	~1, 500-3,500	no	yes	yes	A single exposure covers 1/3rd of the full wavelength range; full coverage of 4.9-28.8 µm would require 3 separate exposures. The MRS simultaneous imaging capability for MRS is disabled for TSOs.

2. Select an instrument observing mode. The recommended strategies articles are particularly valuable to help you choose between the near-IR modes.
NIRCam Time-Series Observation Recommended Strategies
NIRISS SOSS Recommended Strategies
NIRSpec BOTS Operations
MIRI LRS TSOs, MIRI MRS TSOs

3. Based on the target properties, determine the detector readout pattern and subarray configuration for the instrument mode. For MIRI TSOs, the readout pattern (***FAST***) and, for LRS, subarray (***SLITLESSPRISM***) are fixed.
NIRCam Detector Readout Patterns, NIRCam Detector Subarrays
NIRISS Detector Readout Patterns, NIRISS Detector Subarrays
NIRSpec Detector Readout Modes and Patterns, NIRSpec Detector Subarrays,
MIRI Detector Readout Patterns, MIRI Detector Subarrays

4. Calculate the required exposure configuration using the JWST Exposure Time Calculator. Note that in TSOs each integration is treated as a separate image; the purpose is to monitor the target over a period of time, *not* to co-add the integrations to increase the SNR. We therefore recommend that the ETC is used to model the SNR for a *single integration.* The number of integrations is then determined by the required length of the observation (e.g. based on the known transit duration). Note that the ETC can also be run from its code engine, Pandeia.
JWST ETC Pandeia Engine Tutorial
JWST ETC SOSS Spectral Extraction Strategy

5. Users are encouraged to use PandExo for more detailed modelling of spectroscopic exoplanet transit observations (Batalha et al.). PandExo is an exoplanet modelling tool built on Pandeia, the code engine for the ETC. While Pandeia can only model a stellar spectral energy distribution (SED), PandExo accepts as input a stellar SED, a planet spectrum, and the transit duration and provides, as output, the error obtained on your spectrum. You can also optimize the number of groups per integration. PandExo has good front-end plotting functions, as well as parallelized bash scripts for running multiple noise models at once. It provides improved noise computation for TSOs compared with the ETC.

6. Determine whether target acquisition is required, and use the ETC to determine the appropriate strategy. Target acquisition is highly recommended (for some modes, mandatory) for spectroscopic TSOs given the importance of target placement on the detector, particularly when data will be combined from different transit epochs.
   NIRCam Target Acquisition, JWST ETC NIRCam Target Acquisition
   NIRISS Target Acquisition, JWST ETC NIRISS Target Acquisition
   NIRSpec Target Acquisition Recommended Strategies, JWST ETC NIRSpec Target Acquisition
   MIRI Target Acquisition, JWST ETC MIRI Target Acquisition

7. Using the outcomes of steps 1 to 6, complete the Astronomer's Proposal Tool template using the appropriate template. Remember to check that the ***Time Series Observation*** and ***No Parallel*** special requirements are selected in the **Special Requirements** tab of the observation form in the proposal. The ***Time Series Observation*** special requirement disables the ability to use dithering and mosaicking, and allows a single exposure to run longer than 10,000 s. You will also need to specify the phase constraints and transit timing specifications in the Special Requirements section; without this information the observation cannot be successfully scheduled.
   NIRCam Grism Time-Series APT Template
   NIRISS Single-Object Slitless Spectroscopy APT Template
   NIRSpec Bright Object Time-Series APT Template
   MIRI LRS APT Template
   MIRI MRS APT Template
   APT Special Requirements

Go to the Getting Started Guide to complete the steps for proposal submission.

Example Science Programs

Example science programs that use this roadmap:

NIRCam Time-Series Imaging of HAT-P-18 b

NIRCam Grism Time-Series Observations of GJ 436b

NIRISS SOSS Time-Series Observations of HAT-P-1

NIRSpec BOTS Observations of WASP-79b

References

PandExo homepage

Batalha, N. E. et al. 2017, *PASP*, 129, 064501
PandExo: A Community Tool for Transiting Exoplanet Science with JWST & HST

Published	19 Jun 2019
Latest updates	13 Nov 2019 Minor updates

TSO Noise Sources

Determining the precision of time-series observations requires a thorough understanding of noise sources affecting the observations.

On this page

Detecting faint signal modulations in a time-series observation requires high precision (spectro-) photometric measurements. The highest achievable precision is to reach the photon noise floor of the observation, i.e., where the noise budget is dominated by the Poisson noise of the source and background.

Key to reaching the highest precision measurements is a thorough understanding of the noise sources affecting the observation, and the correlations between them. Sources of noise in any observation can be astrophysical or instrumental in nature. A faint exoplanet transit signal can, for example, be masked by flux variations from starspots or other types of stellar variability.

In this article, we give an overview of the noise sources arising from the spacecraft and instrumentation for time-series observations, and their expected temporal behavior.

The information presented here is based on pre-flight predictions of observatory, telescope and/or instrument behavior; or based on experience with other missions (e.g. Hubble, Spitzer). It is subject to significant uncertainty until in-flight data is available to study the various sources of systematic noise and their impact on the photometric precision achievable with JWST instrumentation.

Spacecraft noise sources

Main articles: JWST Pointing Performance, JWST Communications Subsystems, JWST Background Model
See also: Fine Guidance Sensor

Spacecraft pointing drifts and jitter

Pointing control and slewing of JWST is performed by the attitude control subsystem (ACS). Fine guiding additionally involves the Fine Guidance Sensor (FGS). Changes in the spacecraft pointing can cause the target to drift across the detector, causing correlated noise or discontinuities in the measured time series. Such motions can arise from a number of causes and over varying timescales. Pointing issues and their impact on time-series observations for other missions, such as Kepler and Spitzer, are provided in Beichman et al. (2014).

Once fine guiding has been established, the absolute pointing accuracy of JWST with respect to the celestial coordinate system will be determined by the astrometric accuracy of the Guide Star Catalog and the calibration of the JWST focal plane model. The spacecraft pointing accuracy is unlikely to be sufficient for high precision science observations; therefore, target acquisition is recommended (and in some cases, mandatory) for such observations. Where target acquisition is performed, the pointing accuracy is determined by the required slew distance, with smaller slews giving the highest accuracy. Latest information on pointing accuracy and stability are described in a dedicated page.

The effects of pointing drifts can be further compounded by undersampling of the PSF, uncorrected intra-pixel gain variations, and flat fielding residuals (see below).

High-gain antenna moves

The high gain antenna (HGA) is part of the JWST communications subsystem that manages the required two-way communication between the observatory and the ground. The HGA requires periodic pointing adjustments to maintain its attitude towards Earth. This repointing will take place every 10,000 s, which imposes a 10,000 s limit on regular (non-TSO) science exposures. This limitation is waived for TSO observations, to allow observers to monitor a transient event such as an exoplanet transit, continuously for a longer period of time. The repointing of the HGA will, in this case, be performed during a science exposure, resulting in a small but measurable pointing jitter.

Background

Many observations with JWST will be background limited, meaning that the noise will be dominated by the background emission, and not by photon noise from the target or detector read noise. The overall background seen by JWST instrumentation has contributions from several astrophysical and observatory sources; articles on the observatory background describe these sources in more detail. At wavelengths greater than 15 μm, the background seen by JWST is expected to be dominated by thermal emission from JWST itself.

Of particular importance for TSO is the variability of the thermal background over the duration of a typical observation. An exoplanet transit observation may last several hours. A full phase curve reconstruction could perhaps span a full day. We don't currently (i.e., prior to launch) have a detailed understanding of the time variability of the observatory background—measurements during commissioning will provide data on this issue. Modeling suggests that the thermal constant of the mirrors is long (over days), and the thermal constant of the sunshield is short (over minutes). Note that the JWST Exposure Time Calculator assumes a constant background.

See the JWST Background Model article for more detailed information.

Instrumental noise sources

> *Main articles: NIRISS Detector Performance, NIRCam Detector Performance, MIRI Detector Performance, NIRSpec Detector Performance*
> *See also: NIRCam Persistence*

Detector gain variations

The near-infrared and mid-infrared detectors onboard JWST are all subject to inter-pixel gain variations, i.e., small pixel-to-pixel differences in the digital numbers generated per electron by the detector electronics. Gain variations are typically a few percent in magnitude for JWST's IR detectors. Such gain variations are traditionally measured and calibrated using a detector flat field. They are multiplicative in nature, and the effect is therefore corrected by division by the flat field.

Uncertainty in the flat field measurement, or changes in pixel gain over time, can leave residual flat field noise in the reduced data.

Intra-pixel gain variations

More challenging than pixel-to-pixel gain variations are changes in pixel responsivity or quantum efficiency across the pixel area, the so-called intra-pixel gain variations. This issue is compounded when the point spread function (PSF) of the instrument is undersampled by the detector pixels. Ingalls et al. (2012) describe the effect in detail for the IRAC instrument on board the Spitzer Space Telescope, where this was found to be the dominant source of correlated noise. Various methods for correcting this effect can be found in the literature, e.g., Ballard et al. (2010), Stevenson et al. (2011), Krick et al. (2016). We do not expect this issue to affect the JWST instruments to the same extent as previous IR missions since a number of factors will aid to mitigate their effect:

- Improved pointing stability of the telescope
- Better sampling of the PSF
- Higher precision astrometry and proper motion information on guide stars
- Improved detector technology

More detailed measurements will be made during commissioning.

Persistence

Persistence is a memory effect in the instrument detectors, leaving a weak positive image that decays exponentially over time. The strength of the image is related to the brightness of the source that illuminated the detector. The physical mechanism causing persistence is thought to be the trapping of a small number of photoelectrons in the detector substrate, which are then released over time after the illumination has ceased (Regan et. al. 2012). This slow release manifests as a weak latent image that decays with time.

Because the effect depends on the previous illumination of the detector, it is hard to characterize and correct in a given observation. The impact on precision photometric measurements is most severe when observing a very faint target in the same detector region that previously held a very bright source. It will pose less of a problem for lengthy continuous observations of bright targets at a fixed detector location. Because TSO observations are predominantly targeting bright objects—to maximize SNR over time—many TSO observations are expected to monitor the generation of persistence over time.

Whilst the impact of persistence on JWST time-series observations will depend on the observing mode, the target brightness and the observing strategy, detector modeling and testing will help define mitigation strategies or pipeline correction steps. Leisenring et al. (2016) provide detailed study results for the NIRCam detectors. Analysis of the effect for the MIRI detectors has shown multiple time decay constants, which makes characterization challenging; based on testing experience, the time between visits (timescales of minutes) should allow for any persistent images to decay to <1% of their initial levels. However the effect will require further characterisation after launch.

Further background on the physical nature and predicted extent of this effect on JWST instruments, as well as HST WFC3, are provided in the references below.

References

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ADS Arxiv

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ADS Arxiv

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ADS Arxiv

Published	04 Oct 2017
Latest updates	06 Dec 2019

TSO Saturation

The optimal number of groups and integrations for time-series observations are defined by instrument-specific strategies & signal limits — the so-called *saturation* limits.

On this page

When preparing time-series observations (TSOs), the concept of *saturation* is one of the central ones when trying to optimize the number of groups and integrations. This, in turn, helps define not only which targets are actually feasible scientific cases with the instruments onboard JWST, but also strategies to optimize the efficiency of the observations (i.e., the photon-collecting time).

In this article, we give an overview of the concept of saturation in the context of JWST for TSOs: what it means, how important it is for the different instruments and strategies to cope with its impact for scientific observations.

⚠ The information presented here is based on pre-flight predictions of observatory, telescope and/or instrument behavior; or based on experience with other missions (e.g. Hubble, Spitzer). It is subject to significant uncertainty until in-flight data is available to study the various sources of systematic noise and their impact on the photometric precision achievable with JWST instrumentation.

What is Saturation?

See also: JWST Exposure Time Calculator, NIRISS Bright Limits, NIRCam Bright Source Limits, NIRSpec Bright Source Limits, MIRI Bright Source Limits

Saturation in the JWST context

The strict physical definition of *saturation* for a pixel in a detector is related to its full well capacity: the signal level at which any additional photon reaching a given pixel can no longer be counted. For JWST, proposers will get information on saturation from the Exposure Time Calculator - the tool they are expected to use to optimize the groups and integrations of observations.

Interestingly, the Exposure Time Calculator - unless stated otherwise - **does *not* use the above definition of saturation**. Although the full well capacity of the pixels has been directly measured for all the detectors onboard JWST, there is at this (pre-launch) stage still some uncertainty on the overall throughput of the observatory and therefore on the flux arriving at the instrument detectors for a given astrophysical source. On top of this, the Exposure Time Calculator considers a single representative limit flux value for all the pixels, and therefore, the defined maximum signal level has to be chosen wisely. Because of this, the *saturation* in the JWST Exposure Time Calculator is really a **signal limit set to ensure that data can be adequately calibrated** and thus represents our best pre-launch knowledge of the observatory limits. Depending on the instrument, this is around ~70% to ~80% of the detectors' full well capacity for TSOs.

For the Cycle 1 Call for Proposals, it is expected that users use this signal limit as a guide and follow the instrument-specific guidelines to interpret those limits. These will be much better characterized during the JWST commissioning phase.

Comparison to other saturation definitions

Definitions of saturation or signal limits in other space-based instruments like, e.g., the Hubble Space Telescope's (HST) Wide Field Camera 3 (WFC3) or Spitzer's Infrared Array Camera (IRAC), have defined observational strategies for TSOs in the past. The detectors used by WFC3 and IRAC are similar to the ones used by JWST's near-infrared instruments and MIRI, respectively; but the detectors on board JWST have benefited from more recent technology development. Users should therefore be cautious when translating their HST or Spitzer experience to JWST. Here we compare how the concept of saturation differs between these generations of instruments.

For HST/WFC3, a commonly adopted definition of saturation involved measuring each pixel's deviation from linear behavior: when the non-linearity correction for a pixel is above 5%, the pixel is considered "saturated" (Hilbert 2008; signals above this limit are simply not corrected for non-linearities in HST/WFC3 data per contractual specifications). Initial considerations for planning observations with HST/WFC3 for TSOs (typically for transit spectroscopy) suggested some observations could benefit from targeting counts much lower than this saturation level to avoid the non-linear regimes of the detector (McCullough & MacKenty, 2012). However, recent methods for dealing with lightcurve systematics (which come mainly from persistence/charge trapping; see e.g., Stevenson & Eck 2019 and references therein) have mostly lifted this constraint for HST/WFC3. Observations targeting around ~70% of the "saturation" level were still able to deliver (differential) high-precision spectrophotometry during TSOs at the highest fluences (Stevenson & Fowler, 2019). This suggests that near photon-limited precision is achievable even in possible non-linear regimes of the detector for that instrument configuration. Spitzer/IRAC uses the "traditional" definition of saturation (i.e., the signal level at which full well is achieved). Recommended signal limits are also based on the level of non-linearity of the detector: correction at the 1% level is only possible up to ~90% of full well, after which the signals cannot be linearized.

Translating the above HST and Spitzer experience to JWST is, however, not straightforward. If the same saturation definition for HST/WFC3 was applied to the analogous JWST near-infrared detectors (i.e., the ones used by the NIRCam, NIRISS and NIRSpec instruments), they would cut the dynamical range of the detectors by about 75%, as the JWST detectors present higher non-linear responses. Similarly, the same statement applies to the MIRI detectors when compared to the Spitzer/IRAC ones. Ground-testing and new calibration methods, however, should allow for non-linearity corrections which are more precise than the ones performed for Spitzer

/IRAC and HST/WFC3 (see, e.g., the case for NIRCam; Canipe et al. 2017). This suggests that the limitation for most TSOs — at least for differential measurements — will not be the instrument non-linearity behavior, but most likely various other sources of systematic noise. The contributions of various systematics for TSOs will also be different between JWST and its predecessors, as they depend on numerous design and performance parameters, such as pixel scale and sampling, pointing stability, and flat field stability.

Testing these complex and often correlated issues in a physically representative way is exceptionally challenging on the ground due to the required measurement precision. Full characterization can only be performed once JWST is in orbit.

Target signal limits for TSOs

General recommendations

Given the uncertainties related to ground-testing of the instruments onboard JWST, defining tight signal limits to target during proposal preparation is hard to do for the Cycle 1 Call for Proposals. **For proposals that can afford it, targeting from 50% saturation (in the JWST context, see above) up to the saturation limit should be on the safe side**, with the former being perhaps the safest choice for Cycle 1. Note that in most cases, this range of signal limits won't have an impact on the precision but only on the observation efficiency (i.e., the photon-collecting time).

When defining a number of groups per integration considering these signal limits, it is important to be aware as well that, due to the non-destructive reading of the JWST detectors, the JWST Pipeline can flag and disregard saturated groups, allowing users to use the remaining groups in the ramp to construct the final ramp. This adds an additional level of freedom in that if a number of groups saturate during the ramp, this does not imply the whole integration is lost. This is useful, e.g., for MIRI observations, where saturating in the last group can actually be helpful.

Users are encouraged to check the instrument-specific strategies that have been written by the instrument teams, to which we link to below.

TSOs of very bright targets

If the observations being planned with JWST involve a bright object which is at the limit of what is observable with the observatory according to the signal limits defined by the Exposure Time Calculator, it might be wise to first revise the observational strategy being proposed and be absolutely sure that there is no other possible mode to observe the target in order to lower the maximum fluence attained by the observations. For example:

1. If performing spectrophotometry: is it possible to use an **instrument mode with a higher resolving power**? This might help to spread the light of the object in more pixels.
2. Is it possible to use **smaller subarrays**? These can help decrease the read times.
3. Is it possible to use a **faster readout mode** for the detector?

4. Is **saturation happening in the spectral region of interest**? If not, mild saturation might be an option; note, however, charge diffusion can occur for neighboring pixels (see, e.g., Plazas et al. 2018).

In general, if after revising all these points the target still saturates (i.e., the object achieves saturation in less than 3 groups), then observations could possibly enter a regime of risk in which the quality of the to-be-acquired data is uncertain, and recommendations to follow are strongly instrument-specific. Guidelines for these cases are provided in the instrument-specific pages, which are linked below so users can explore options in this direction.

Instrument-specific recommendations

Below we link to the recommended strategies relevant for TSOs of each of the instruments onboard JWST. These contain important information that must be reviewed by proposers when deciding to use a given instrument during proposal planning and submission.

- MIRI TSO Recommended Strategies
- NIRISS SOSS Recommended Strategies
- NIRCam TSO Recommended Strategies
- NIRSpec Detector Recommended Strategies

References

Canipe A., Robberto M., Hilbert B. 2017, JWST-STScI-005167, SM-12
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Laboratory Measurements of the Brighter-fatter Effect in an H2RG Infrared Detector

Spitzer: IRAC Instrument Handbook

Stevenson K. B. and Eck W. 2019, Instrument Science Report WFC3 2019-13
Pre-Flashing WFC3/IR Time Series, Spatial Scan Observations

Stevenson K. B. and Fowler J. 2019, Instrument Science Report WFC3 2019-12
Analyzing Eight Years of Transiting Exoplanet Observations Using WFC3's Spatial Scan Monitor

JWST Moving Target Observations

JWST can track and observe planets, satellites, and nearly all comets and asteroids more than 1 AU from the Sun.

On this page

JWST offers the capabilities necessary for observing Solar System (moving) targets, with high sensitivity and spatial resolution, through imaging as well as low and medium resolution spectroscopy, from 0.6 to 28.5 μm. The observatory will be in a solar orbit near Earth's L2 point, so scheduling will be more flexible and efficient compared to HST (which is in a low Earth orbit). JWST's thermal design only allows Solar System targets to be observed near quadrature; observations at opposition are not feasible.

Solar System observations with JWST

An overview of JWST's Solar System capabilities, as well as exploration of some possible science applications can be found in Milam et al. (2016) and Norwood et al. (2016). The following list includes links to flyers on some potential science investigations:

- General: Overview of JWST's capabilities for observations of Solar System targets
- Solar System GTO & ERS programs: Details of all Guaranteed Time Observations (GTO) and Early Release Science (ERS) programs targeting Solar System objects
- Asteroids & near-Earth objects (NEOs): Surface composition, thermal properties
- Giant planets: Vertical and horizontal cloud structures, global circulation, chemistry and composition, thermodynamics
- Giant planet satellites: Volcanic activity on Io, satellite atmospheres, plume activity on Europa and Enceladus, irregular satellites
- Trans-Neptunian Objects (TNOs): Surface composition, diameter/albedo, colors, binarity
- Mars: Atmospheric composition, evolution of dust storms and clouds
- Occultations: Minor bodies, rings, mutual events, serendipitous occultations

- Rings and small satellites: Discovery and characterization, transient phenomena (ring arcs and spokes), composition
- Titan: Atmospheric composition, clouds and hazes, surface temperature, surface changes
- Comets: Dust, gas, nuclei, observability

More detailed examinations of 10 science areas, and a summary of JWST capabilities and operations for moving targets, can be found in a January 2016 special issue of PASP.

Example APT files and ETC workbooks

GTO & ERS

APT files from the Guaranteed Time Observations (GTO) programs are currently available at the Guaranteed Time Observations webpage.

APT files from the Early Release Science (ERS) programs are currently available at the Early Release Science webpage.

APT files can also be downloaded from APT using the tool's main menu: **File → Retrieve from STScI → Retrieve using Proposal ID**, then enter the proposal ID in the pop-up box, and click ***OK***. Proposal IDs for the Solar System GTO and ERS programs can be found at the links above and on the GTO & ERS 2-page flyer.

JWST Demonstration proposals

An example APT file for observations of Solar System objects can be found in the APT tool, from the main menu under **File → JWST Demonstration Proposals → Solar System Example**. This example file includes observations of minor bodies, comets, satellites, and giant planets using the instruments and modes most suitable for Solar System programs.

ETC sample workbook and example science program

The Exposure Time Calculator (ETC) provides a **Solar System Sample Workbook**[*] and an example science program that can be retrieved from the Available Workbooks page (see JWST ETC Using the Sample Workbooks for additional information on how to retrieve these workbooks). These example workbooks provide users with a starting point for creating sources and calculations for planning Solar System observations.

The example science program, NIRSpec IFU and Fixed Slit Observations of Near-Earth Asteroids, provides an end-to-end walkthrough of how to create a Solar System proposal, and the associated ETC workbook is described in detail in the Step-by-Step ETC Guide for NIRSpec IFU and Fixed Slit Observations of Near-Earth Asteroids.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Webcasts and presentation packets

Presentation chart packets from JWST workshops and Townhall events at AAS Division of Planetary Sciences meetings are linked below. They cover in considerable detail topics such as using the Astronomer's Proposal Tool (APT) and Exposure Time Calculator (ETC) for planning observations, tracking capabilities of the observatory, and processing data in the pipeline.

October 16-21, 2016: JWST at the 48th Annual Division for Planetary Sciences (Joint with EPSC) Meeting

February 7, 2017: Solar System Community Webinar: JWST Early Release Science Program

February 14, 2017: JWST Community Lecture Series - Observing Solar System Targets with JWST

November 13-15, 2017: Planning Solar System Observations with JWST - STScI venue

December 13-15, 2017: Planning Solar System Observations with JWST - ESTEC venue

February 13, 2018: Planning Solar System Observations with JWST in Cycle 1

October 21-26, 2018: JWST at the 50th Annual Division for Planetary Sciences Meeting

September 15-20, 2019: JWST at the 51st Annual Division for Planetary Sciences Meeting (Joint with EPSC)

List of articles

Expand all Expand all Collapse all Collapse all

Additional resources

- JWST Moving Target Visibility Tool Help
- NIRSpec IFU and Fixed Slit Observations of Near-Earth Asteroids

References

Magnum, J., ed. 2016, *PASP*, 128, 959
Special Issue: Innovative Solar System Science with the James Webb Space Telescope
PDF

Milam, S., et al. 2016, *PASP*, 128, 959
The James Webb Space Telescope's Plan for Operations and Instrument Capabilities for Observations in the Solar System
ADS arXiv

Norwood, J., et al. 2016, *PASP*, 128, 960
Solar System Observations with the James Webb Space Telescope
arXiv

JWST Observations in the Solar System flyer

Published	26 May 2017
Latest updates	• 16 Dec 2019 Combined with Moving Targets Useful References and Links. Added links to new flyers. • 08 Nov 2018 Added new links to new and updated 2-page flyer. • 06 Mar 2018 Added link to the Moving Target Visibility Tool (MTVT).

Moving Target Roadmap

A roadmap to guide users, step-by-step, through the process of creating moving target (Solar System) observations with JWST.

1. Familiarize yourself with policies related to moving targets.
   Moving Target Policies
   Moving Target Overheads

2. Familiarize yourself with apparent motion and pointing constraints for moving target observations with JWST.
   Moving Target Acquisition and Tracking
   Field of Regard Considerations for Moving Targets

3. Generate an ephemeris using the JPL/Horizons system to determine the best time to observe the target.
   JWST Moving Target Visibility Tool Help
   Moving Target Ephemerides

4. Determine the instrument and observing mode for your moving target observation.
   Moving Target Observing Strategies

5. Calculate the required exposure time and detector readout parameters using the Exposure Time Calculator (ETC).
   Moving Target ETC Instructions
   JWST ETC Target Acquisition

6. Fill out the Astronomers Proposal Tool (APT) for your observation.
   Moving Target APT Instructions
   Moving Target Observing Strategies

7. Familiarize yourself with the different options for creating a moving target in the APT.
   Solar System Targets
   Solar System Standard Targets
   Tutorial on Creating Solar System Targets in APT

8. Familiarize yourself with the procedure for creating a moving target observation in the APT and the optional special requirements used to constrain the observation's schedulability.
   Solar System Special Requirements
   Tutorial on Creating Solar System Observations in APT

9. If you specified dithers, visualize the dithers in APT.
   Tutorial on Visualizing Dithers of a Solar System Observation in APT

Go to the Getting Started Guide to complete the steps for proposal submission.

Published	01 May 2019
Latest updates	• 17 Dec 2019 Edited links and added an additional step.

Moving Target Proposal Planning

A list of articles about moving target proposal planning instructions.

Expand all Expand all Collapse all Collapse all

Proposal Planning

- Observing Procedures
- ETC Instructions

  APT Instructions
- Recommended Strategies
- Instrument Specific Considerations

Published	29 Nov 2019
Latest updates	

Moving Target Acquisition and Tracking

Procedures for acquisition of guide stars and tracking of moving targets with apparent rates of up to 30 mas/s (108 arcseconds/hour).

On this page

Main article: Fine Guidance Sensor (FGS)

JWST's scheduling will be event-driven (see JWST Observing Overheads and Time Accounting Overview). This requires flexibility in the selection of guide stars over the scheduling window because not all guide stars will be usable for the entire window due to the motion of the target.

Once an appropriate guide star is selected, guiding on the moving target is performed by treating the guide star as a moving target in the Fine Guidance Sensor (FGS) and keeping the moving target stationary in the frame of reference of the science instrument (NIRCam, NIRISS, NIRSpec, or MIRI). Targets moving up to 30 mas/s (108 arcseconds/hour), the maximum rate of Mars, can be tracked by JWST without streaking.

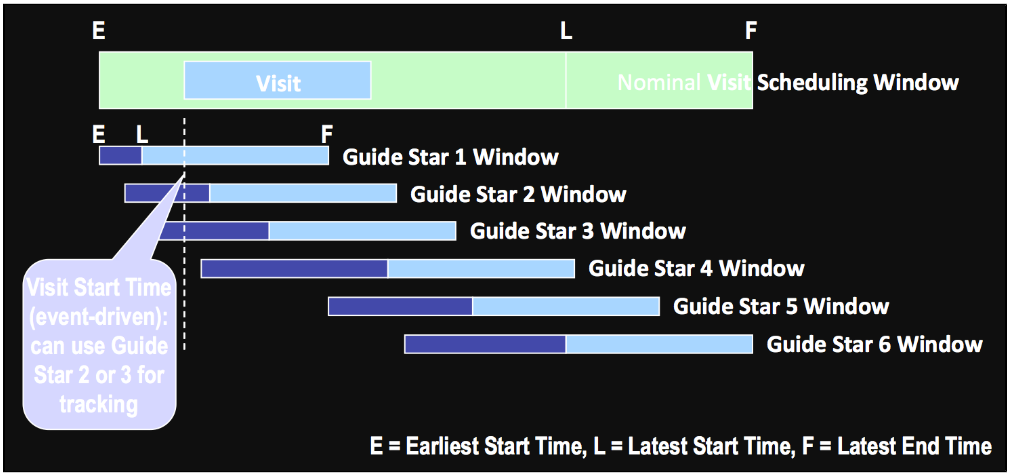
Guide stars for moving target observations

Main article: JWST Guide Stars

Due to the nature of JWST scheduling, a moving target will have multiple guide star candidates available for each window. At the time of the observation (the "Visit" in Figure 1), the first usable guide stars will be selected for tracking. The faintest guide stars that can be used for moving targets are ~1 mag brighter than those used for fixed targets. The smaller number of available guide stars will not prevent a moving target observation from executing. However, in rare circumstances involving observations with very tight constraints, suitable guide stars may not be available within the constraint windows, particularly for targets far from the galactic plane (high galactic latitudes). Loosening geometric or timing constraints will improve schedulability.

Long observations (>1 hour) can use multiple guide stars, but must be broken into multiple visits for each guide star. The visit splitting distance is 30" for moving targets, meaning that if a target moves more than 30" during an observation it will be split into additional visits with new guide star acquisitions. A new visit and separate guide stars, of course, will be required for any observations with a different instrument.

Figure 1. Example scheduling window for a moving target observation



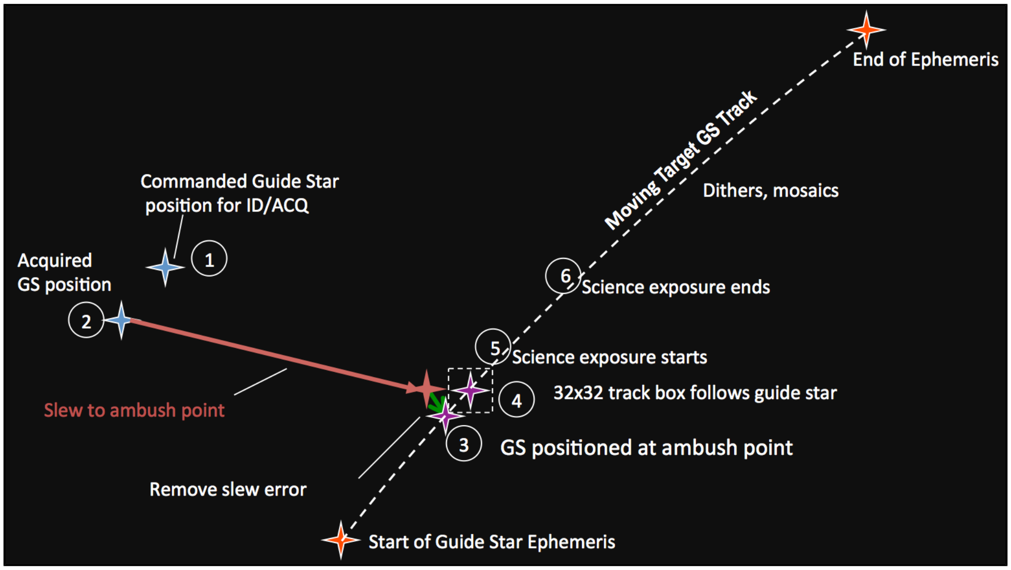
The scheduling window is assigned multiple sets of guide stars in order to maintain scheduling flexibility. The large green bar at the top represents the window for the observations to be made, with the distance between the latest start time and latest end time equal to the length of the visit. The position of the latest start time in a given guide star window is determined by the length of the visit and the duration of the guide star's availability. If the visit time is longer than the selected guide star's observability window, it may be split into multiple visits using multiple guide stars, and incur the necessary additional overheads.

Telescope pointing for moving targets

The start time of a moving target observation (and therefore the target position) is not known ahead of time due to the event-driven nature of JWST scheduling. To allow for this flexibility, and as described above, multiple guide star candidates are identified during the scheduling process on the ground such that one or more will be available regardless of when the observation actually begins.

Once a moving target observation reaches the front of the event-driven schedule queue, the onboard system identifies appropriate guide star(s) for that start time, and the observatory slews to place one of the guide stars in the Fine Guidance Sensor (FGS) field of view. The system then performs guide star identification, finds the position of the selected guide star in the FGS, computes the slew needed to put the science target at the appropriate location (ambush point) in the science instrument field of view, and then executes that slew. A small extra amount of time is included such that the slew to the science pointing is guaranteed to complete before the science target reaches the ambush point.

Figure 2. Schematic showing guide star acquisition in the Fine Guidance Sensor (FGS) for moving target observations



Steps 1 and 2 are the same as those for fixed targets. The slew after step 2 repositions the guide star in the FGS FOV such that the telescope points slightly ahead of the incoming science target, ready to intercept it when it enters the instrument's FOV. Tracking is then engaged when the science target moves to the correct position in the science instrument. Note that the FGS and associated software are tracking the guide star, not the science target itself. The 32 × 32 pixel guide box moves in the FGS field of view as the telescope tracks, such that the science target remains fixed in the reference frame of the science instrument for the entire observation.

Shadow observations

Observations of faint, extended sources, e.g., comets with faint comae, can benefit from "shadow observations." These are observations of the background field at a later time when the science target has moved out of the field; the shadow observation is then subtracted from the original science observation. The target must be completely out of the field when the shadow observation occurs. Additionally, even for a target moving at the maximum tracking rate, a non-zero time interval is required between the science and shadow observations for the target to move fully out of the field. The time between observations can be shorter for faster-moving targets; shorter times between observations are preferable and will prevent the background from changing significantly.

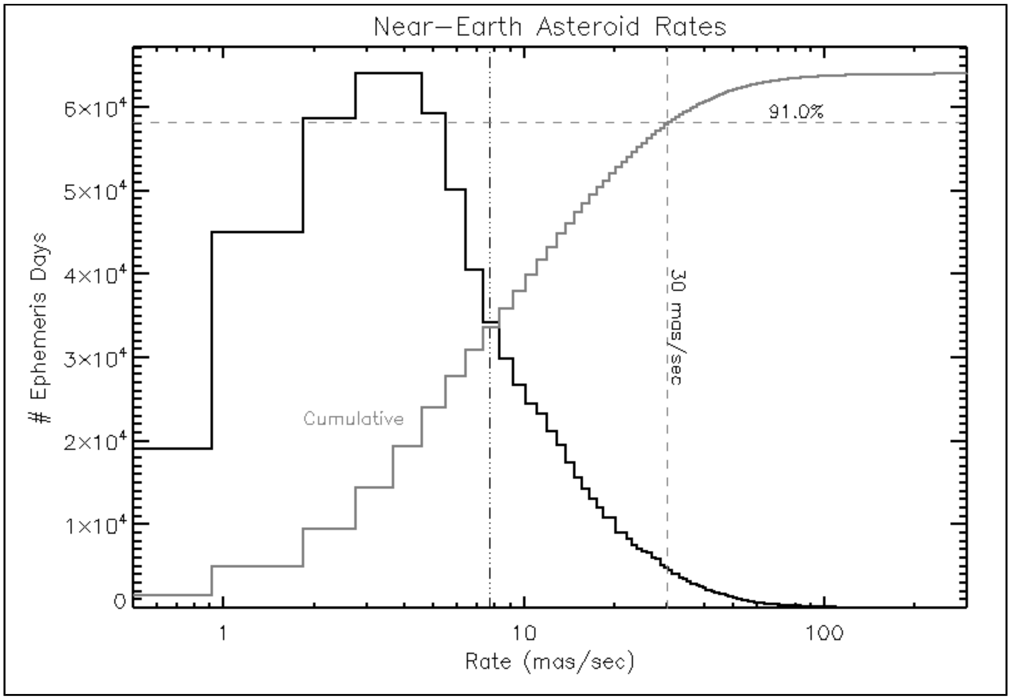
The shadow observation must be tracked in the exact same way as the science observation so that the star streaks are replicated and can be appropriately subtracted. This requires the science observation to occur *before* the shadow observation so that the exact track from the science observation can be used to plan the shadow observation; this ordering is due to the event-driven nature of JWST scheduling.

Shadow observations will not be implemented in APT for the Cycle 1 proposal period but are expected to be available in APT for the Cycle 2 proposal period. This means that shadow observations may possibly be supported for some approved Cycle 1 observations after acceptance and before placement on the long-range plan. So, if your observations require shadow observations, the procedure would be to duplicate the science observation and replace the science target with a generic target. A description of this observation should be given in the Technical Justification section of the Proposal Narrative.

Non-sidereal tracking

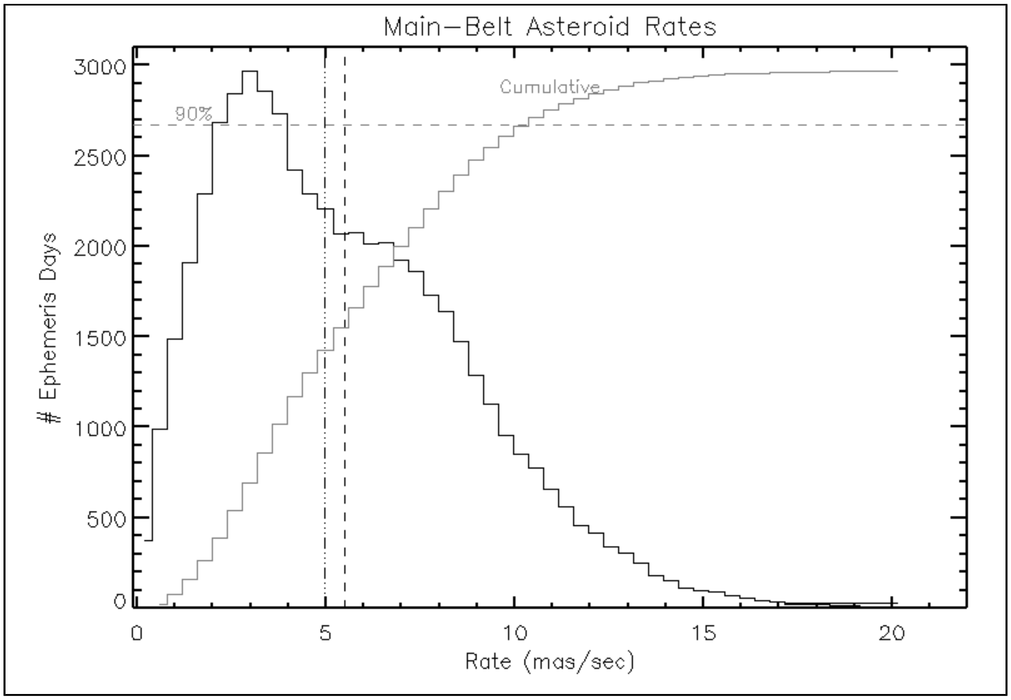
JWST will support tracking rates of up to 30 mas/s (108 arcseconds/hour), the maximum rate of Mars. Nearly any target, including comets and near-Earth asteroids (NEAs), in the field of regard can be tracked (see Figures 3–6). Models show JWST's pointing stability for moving targets (<10 mas over a 1,000 s period) is comparable to the pointing stability for fixed targets (Milam et al. 2016). This excellent tracking rate and pointing stability will effectively render moving targets into fixed targets on the detector frame during individual exposures and leave background sources (stars, galaxies, slower moving Solar System targets, etc.) streaked. Dithers and mosaics will be supported.

Figure 3. Near-Earth asteroid (NEA) rates



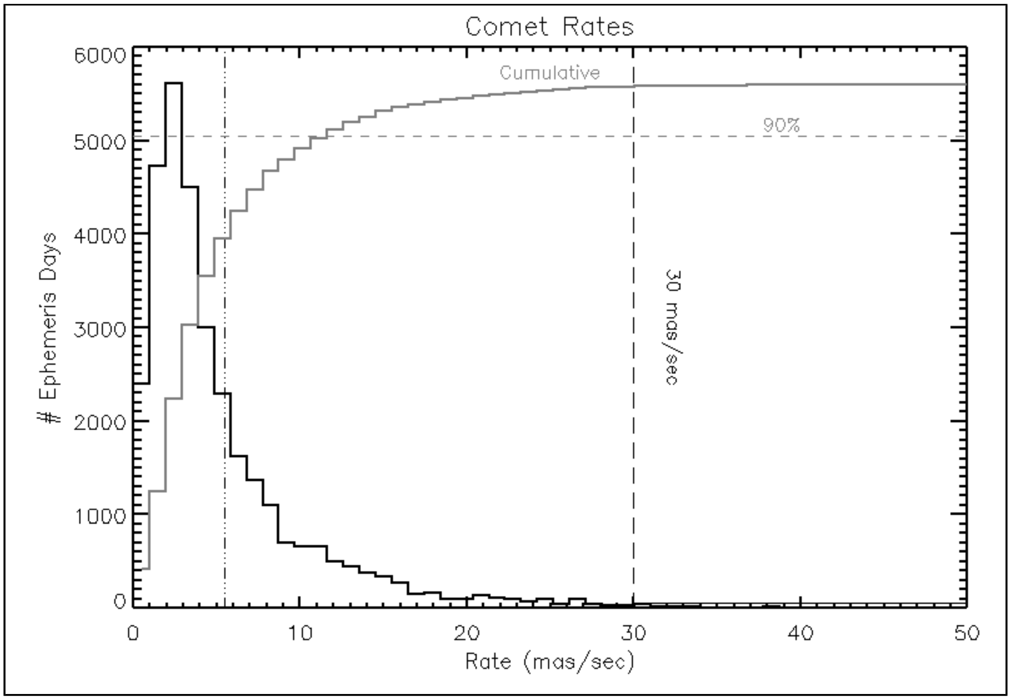
Apparent rates of 11,467 near-Earth asteroids (NEAs) observable in 2019. The dark curve is the histogram of the number of days that NEAs are observable within different rate bins (1 mas/s bin width), only considering dates when the objects are within JWST's field of regard (elongation angles between 85° and 135°). The gray curve is the cumulative histogram normalized to fit in the same plot area (the values on the y-axis do not apply to the gray curve). The vertical dot-dashed line is the average rate of the NEAs and the vertical dashed line marks the maximum 30 mas/s rate observable by JWST. On a date when a given NEA is within JWST's field of regard there is a 91% probability that it can be tracked by JWST. (Milam et al. 2016)

Figure 4. Main belt asteroid rates



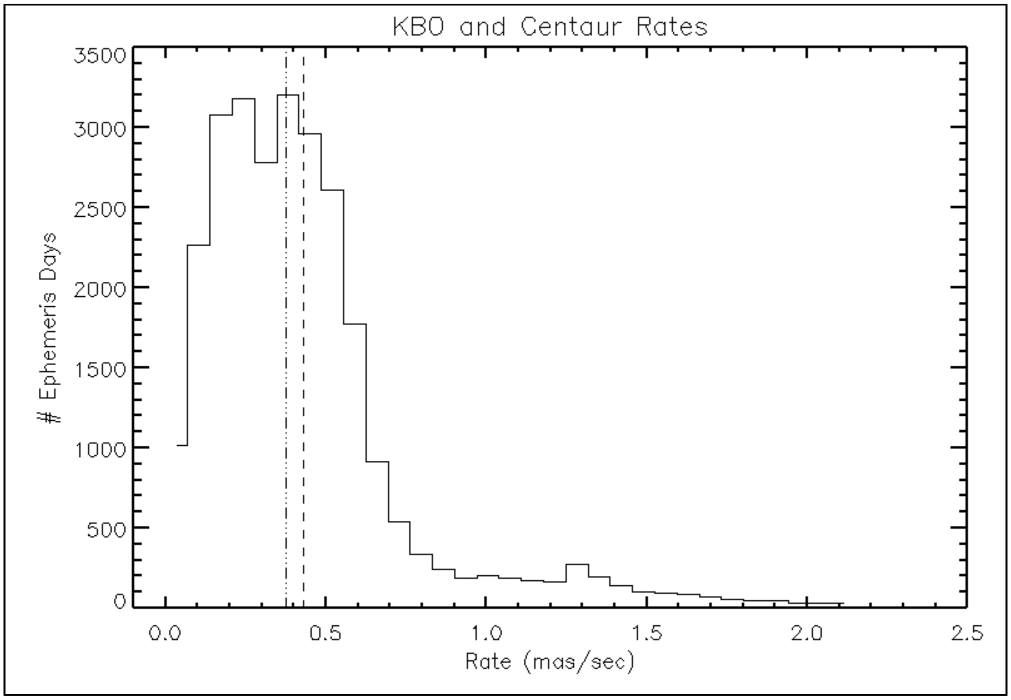
Apparent rates of 305 main belt asteroids (MBAs) observable from 2019 to 2020. The dark curve is the histogram of the number of days that MBAs are observable within different rate bins (1 mas/s bin width), only considering dates when the objects are within JWST's field of regard (elongation angles between 85° and 135°). The gray curve is the cumulative histogram normalized to fit in the same plot area (the values on the y-axis do not apply to the gray curve). The vertical dot-dashed and dashed lines are the average and median rates of the MBAs, respectively. All MBAs can be tracked by JWST on any given date that they are in the field of regard. (Milam et al. 2016)

Figure 5. Comet rates



Apparent rates of 170 comets observable from 2019 to 2020. The dark curve is the histogram of the number of days that comets are observable within different rate bins (1 mas/s bin width), only considering dates when the objects are within JWST's field of regard (elongation angles between 85° and 135°). The gray curve is the cumulative histogram normalized to fit in the same plot area (the values on the y-axis do not apply to the gray curve). The vertical dot-dashed line is the average rate of the comets and the vertical dashed line marks the maximum 30 mas/s rate observable by JWST. Only 1 comet cannot be tracked during the time period, and 6 are only trackable for a fraction of the time period. (Milam et al. 2016)

Figure 6. KBO and centaur rates



Apparent rates of 130 Kuiper Belt Objects (KBOs) and Centaurs observable from 2019 to 2020. The dark curve is the histogram of the number of days that the KBOs and Centaurs are observable within different rate bins (1 mas/second bin width), only considering dates when the objects are within JWST's field of regard (elongation angles between 85° and 135°). The vertical dot-dashed and dashed lines are the average and median rates of the KBOs and Centaurs, respectively. All KBOs and Centaurs can be tracked by JWST on any given date that they are in the field of regard. By extension, all of the giant planets, which have semi-major axes between the MBAs and KBOs, can be tracked by JWST on any date that they are in the observatory's field of regard.

References

Milam, S., et al. 2016, *PASP*, 128, 959
The James Webb Space Telescope's Plan for Operations and Instrument Capabilities for Observations in the Solar System
ADS arXiv

Published	11 Jul 2017
Latest updates	

	• 12 Dec 2019 Wording clarifications. • 27 Jun 2019 Fixed reference links in text.

Moving Target ETC Instructions

The ETC has not implemented any specific features for Solar System targets, but can be used to approximate reflected sunlight and thermal emission from them.

On this page

Main article: JWST Exposure Time Calculator Overview

The JWST ETC can be used to model the spectra of moving targets, but is limited to doing so for a single target brightness. For distant targets (those at least as far from the Sun as Jupiter) on nearly circular orbits, this isn't a major problem because their brightness is fairly constant during the period when the the target is within the JWST field of regard. For more nearby targets the brightness can change by much more than 50%, so observers must account for those variations manually when creating ETC sources and scenes to represent the target.

Reflected light can be approximated using the Phoenix stellar model G2V template spectrum, and thermal emission can be approximated using the blackbody template. The user must determine the correct normalizations to apply to those template spectra in order to accurately represent the emission from their target on a given date. Targets expected to have both reflected light and thermal emission components within the wavelength range of interest can be specified as two sources that coincide in the ETC scene.

Normalizing target spectra

The emission from a target has to be normalized in a way to represent the physics controlling the flux density of the spectrum as received at JWST. These factors include:

- Observing circumstances such as heliocentric and observatory-centric distances
- Phase angle
- Size and albedo
- Thermal properties

Observing circumstances can be retrieved from the JPL Horizons web service by entering the string "@jwst" in the observatory search field (see Moving Target Ephemerides).

> It is critical to include solar elongation constraints of 85°–135° when using Horizons to generate target ephemerides within the JWST field of regard.

Point and extended sources

For targets too small to be resolved by JWST, the spectrum can be modeled using the ETC point source target type.

Extended targets can also be specified in the ETC as elliptical shapes with brightness distributions that are flat, r^{-k} power law, Gaussian, or Sersic profiles (the latter is typically used for galaxies).

For observers interested in Jupiter, Saturn, Mars, and highly extended comets, capabilities of the ETC web interface limit the size of the scene to a few arcseconds across. This doesn't prevent estimates of SNR for a given observation, but does require observers to properly normalize the surface brightnesses of these sources. Additionally, see the Solar System Sample Workbook for a workaround for dealing with large, extended sources in the ETC.

User supplied spectra

Video Tutorial:

Uploading Spectra to the ETC

Main article: JWST ETC User Supplied Spectra

The ETC allows users to upload their own spectra for sources. ASCII and FITS format are supported, and the spectrum in either case consists of 2 vectors containing wavelength and flux density. Format and other requirements are described in the ETC documentation and help (see JWST ETC User Supplied Spectra).

Example workbooks

Main article: JWST ETC Using the Sample Workbooks

See JWST Moving Target Observations for instructions on how to access the Solar System Sample Workbook and the **Example Science Program Workbooks***. These workbooks focus on providing examples of how to construct an ETC scene useful for Solar System observers and give details on how to set up ETC calculations.

The ETC contains a Solar System Sample Workbook with 3 scenes:

1. An asteroid modeled as a point source using the superposition of a reflected light and thermal component.

2. A comet modeled as a point source nucleus and 2 extended sources representing the coma. Reflected light and thermal emission components are included for nucleus and coma.

3. A giant planet modeled as a smaller extended source with a total area of 1 square arcsecond. This demonstrates the workaround for determining the SNR for large, extended sources.

The moving target example science program, NIRSpec IFU and Fixed Slit Observations of Near-Earth Asteroids, provides an end-to-end walkthrough of how to create a moving target proposal. An example ETC workbook and example APT file are available for download so you can follow along with the associated pages.

Bold italics* style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Limitations

The ETC does not currently have:

- A method for using an albedo spectrum to modify the predicted reflected light spectrum

- More realistic models for thermal emission, such as the standard thermal model (STM) or near-Earth asteroid thermal model (NEATM)

- A way to compute a target spectrum based on basic inputs such as the size of and distance to the target, and an albedo

- A shortcut to use typical background values near the ecliptic plane. Instead, users must specify an RA and DEC corresponding to a position near the ecliptic plane.

Future improvements

Template spectra

- A template spectrum for the Sun, absolutely calibrated to represent flux density at 1 AU, and at a spectral resolution high enough to support modeling for the high resolution gratings of NIRSpec and for the MIRI MRS is under development.

- Template spectra for the giant planets (disk-integrated) are also under development.

- A community-based effort to create template spectra for a range of spectral classes and/or representative examples of asteroids and TNOs will be explored at various community forums.

One or more of these template spectra may be implemented instead as a library of spectra users can share external to the ETC and then upload, rather than residing within the ETC as true template spectra. As these materials are completed, observers can find additional information on this page, and should look for announcements on Solar System community forums such as the DPS and PEN newsletters.

References

JWST Exposure Time Calculator Tool

Pontoppidan, K. M., et al. 2016, *Proc. SPIE* 9910, Observatory Operations: Strategies, Processes, and Systems VI, 991016
Pandeia: a multi-mission exposure time calculator for JWST and WFIRST

Published	18 May 2017
Latest updates	• 16 Dec 2019 Made minor wording changes. Added video link. • 27 Jun 2019 Fixed incorrect links. • 12 Nov 2018 Updated for ETC 1.3, which includes an r^{-k} profile for comets.

Moving Target APT Instructions

Details of how the JWST Astronomer's Proposal Tool (APT) can be used by Solar System observers, with descriptions of current APT limitations and walkthrough examples for creating a proposal for various classes of Solar System targets.

On this page

Main article: JWST Astronomers Proposal Tool Overview

The JWST Astronomer's Proposal Tool (APT) is used for designing JWST proposals and contains special options for Solar System ("moving") target observations. Before using APT, you should estimate exposure times with the Exposure Time Calculator and take a quick look at your target's visibility using JPL Horizons and the Moving Target Visibility Tool (MTVT). The latter tools could cut down the time you spend testing the schedulability of observations in APT.

With these pre-steps complete, you will be ready to start designing your APT proposal. A typical workflow would be:

1. Define the target. You have tremendous flexibility to identify specific targets and pointing positions relative to targets using a system of target Levels. *Level 1* targets are Solar System bodies directly orbiting the Sun (planets, comets, and asteroids), while *Level 2* and *Level 3* targets are moons of, or positions on, or relative to, the specified Level 1 or Level 2 target. Moving targets are also divided in APT between *standard targets* and *minor bodies* (asteroids and comets). For standard targets, ephemerides can be computed using information directly accessible to and maintained by APT. For the minor bodies, you must supply orbital elements, either manually or by retrieving them from the JPL Horizons system using the built-in APT tool. See Tutorial on Creating Solar System Targets in APT.

2. Define the observations. For each observation, you must select a target, an instrument, and a science template. Note that *moving targets can be observed with any instrument and any observing template*,

although not all templates are optimal for Solar System observations; see Moving Target Observing Strategies. Also see Tutorial on Creating Solar System Observations in APT.

3. Define scheduling constraints on the observations. These include date, time, separation from another body, apparent rate of motion, rotational phase, phase angle, etc. See the Tutorial on Creating Solar System Observations in APT. A full list of generic and moving target-specific special requirements can be found in Special Requirements and Solar System Special Requirements, respectively.

4. Evaluate the schedulability of observations.

5. Submit your proposal.

You are advised to first read the JWST Astronomers Proposal Tool Overview article for a general understanding of APT.

On this page, we describe APT's current limitations for moving targets and walk through the creation of moving target proposals.

APT limitations for Solar System observations

APT is still under development and for moving targets some capabilities are not expected to be available until later cycles. The following list is not exhaustive. If you have questions please contact the help desk.

1. APT does not (and is not planned to) provide sensitivity information. You must use the JWST Exposure Time Calculator (ETC). See Moving Target ETC Instructions.

2. Currently, APT does not allow observation visualization against all-sky images/catalogs for moving targets. This includes visualization of the object ephemeris. You must use a fixed target as a proxy to examine dithers, coverage, and orientation. A workaround is described in Tutorial on Visualizing Dithers of a Solar System Observation in APT. Accurate orientations for the Aladin viewer can be determined using the Moving Target Visibility Tool (MTVT).

3. APT does not currently support shadow observations. See Moving Target Acquisition and Tracking for information on a workaround until this is implemented.

General APT information

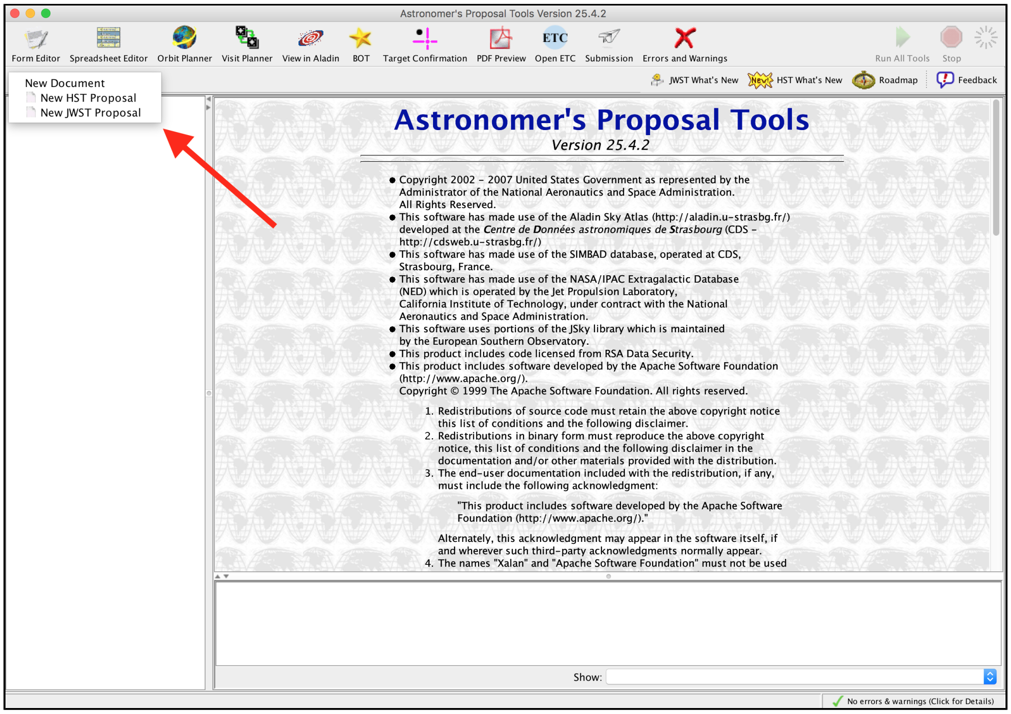
Download APT

The most recent release of APT is available at http://apt.stsci.edu.

Begin a JWST proposal

Click on the ***New Document*** button in the upper left. You will have the option of starting either a new HST or new JWST proposal.

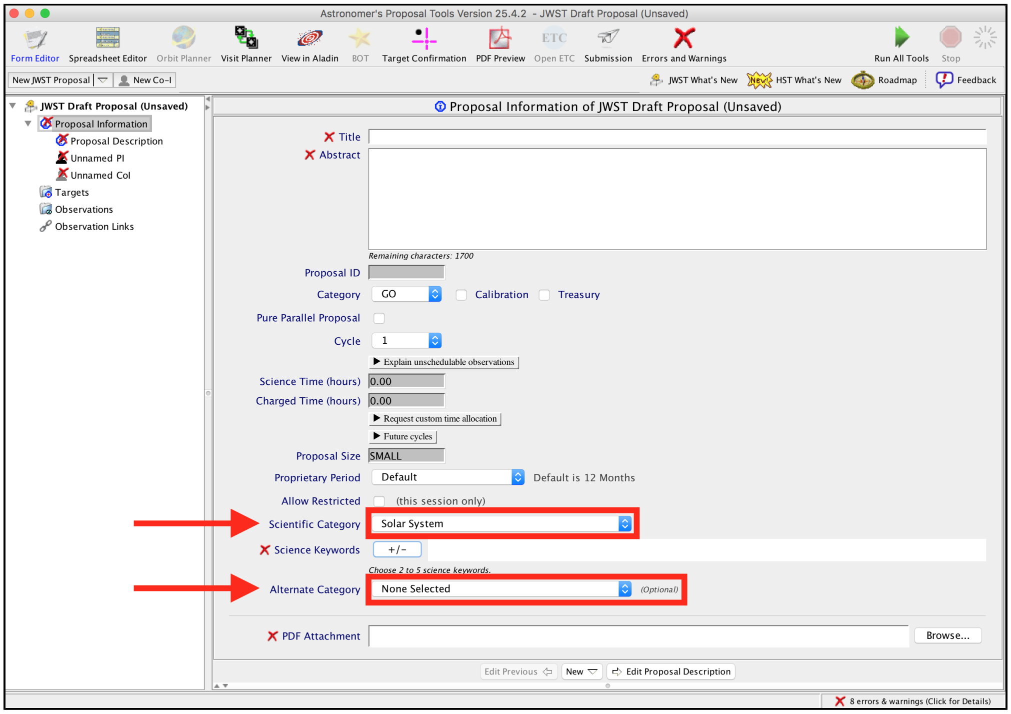
Figure 1. Starting a new JWST proposal



Edit proposal information

More extensive directions for filling out this form can be found at JWST Astronomers Proposal Tool Overview. Moving target observers should select ***Solar System*** as either the ***Scientific Category*** or ***Alternate Category***.

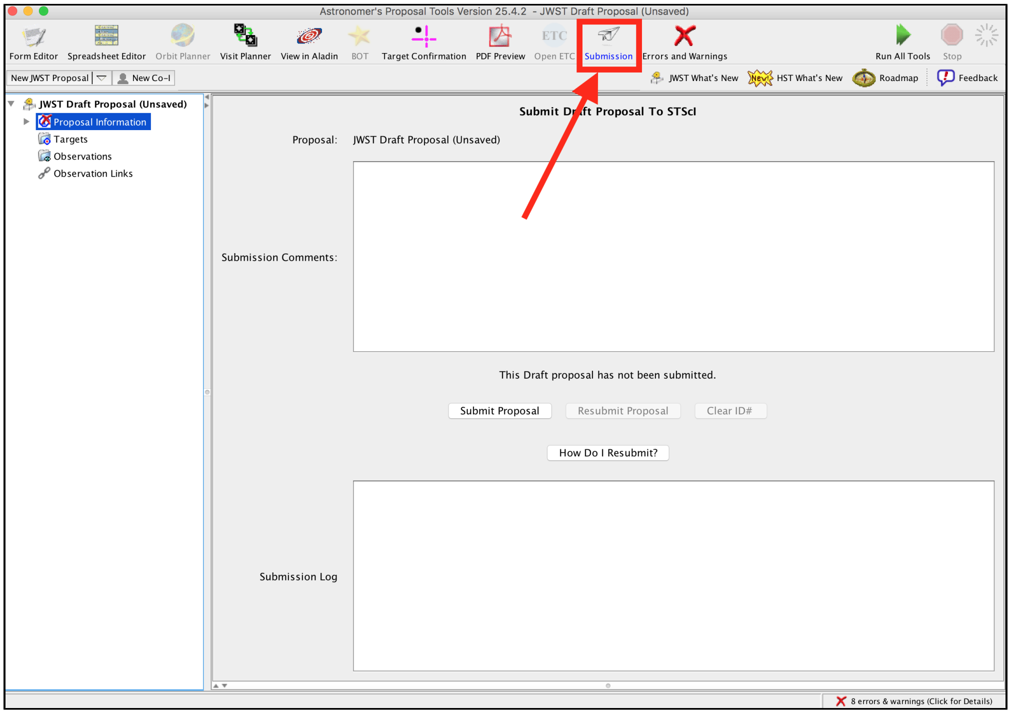
Figure 2. Proposal Information page



Submit proposal

When you are ready to submit, click the paper plane icon, and fill in the form. Proposals can be re-submitted as needed up to the deadline. Any outstanding errors or warnings must be explained to complete the submission process.

Figure 3. Submitting a proposal



Tutorials and tools

For additional information on APT, see JWST Astronomers Proposal Tool Overview. The following will only concern the unique case of specifying a moving target observation.

Create targets

Moving targets have unique parameters in APT. Some examples are illustrated in Tutorial on Creating Solar System Targets in APT.

You can also read in-depth about Solar System targets for APT and look at the list of Solar System standard targets.

Create observations and define scheduling constraints

See Tutorial on Creating Solar System Observations in APT.

You can read about moving target APT constraints in Solar System Special Requirements. To learn about the observation templates available for each instrument, see APT Observations.

Visualize dithers and mosaics using a fixed target as a proxy for your moving target

Currently APT does not have the capability to display a visualization of moving target dithers with the Aladin viewer. For a workaround, see Tutorial on Visualizing Dithers of a Solar System Observation in APT.

Target acquisition

Target acquisition (TA) is not required (or recommended) for standard targets or most numbered minor bodies for IFU observing modes (MIRI MRS, NIRSpec IFU) or the NIRSpec MSA "long slit" but may be necessary for other long slit observing modes (MIRI LRS, NIRSpec fixed slit). NIRSpec TA for moving targets will use the 1.6” aperture and the observer can then put the target in any fixed slit, IFU, or MSA “long slit.” See Moving Target Observing Strategies for more information and additional links.

More general information about APT target acquisition is in the article APT Target Acquisition.

Evaluate the schedulability of observations

APT has tools to visualize and check the schedulability of your observations (to visualize dithers, read the Tutorial on Visualizing Dithers of a Solar System Observation in APT). You can also check for duplications and estimate the total time needed to execute your proposal.

References

Download the Astronomer's Proposal Tool

Go to the online JWST Exposure Time Calculator

Published	26 May 2017
Latest updates	

	• 16 Dec 2019 Minor wording changes. • 12 Nov 2018 Removed warning about the long run time of the Visit Planner for nearby objects, as this is no longer applicable. • 06 Mar 2018 Added wording about the Moving Target Visibility Tool (MTVT).

Tutorial on Creating Solar System Targets in APT

Four examples of creating a Solar System target in the JWST Astronomer's Proposal Tool (APT).

On this page

Main article: JWST Astronomers Proposal Tool Overview

You should first read how the JWST Astronomers Proposal Tool (APT) defines Solar System targets. Here we walk through 4 examples for creating a new Solar System target in APT:

1. Defining a Level 1 "standard target" planet
2. Defining a non-"standard" Level 2 satellite
3. Defining a Level 3 feature
4. Defining a Level 1 minor body

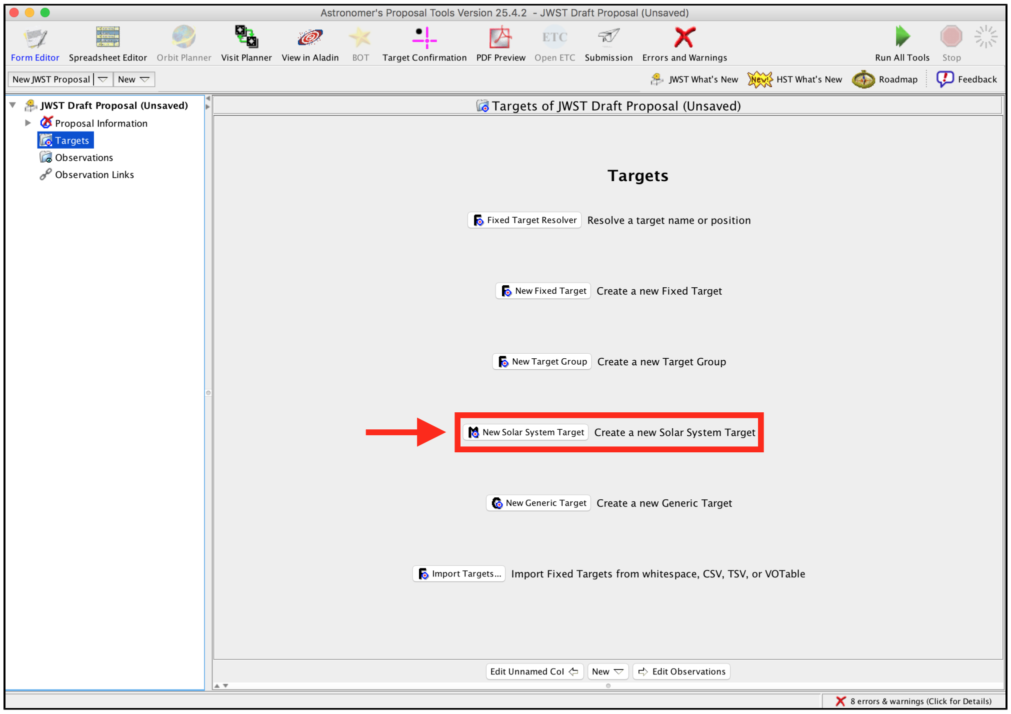
To learn how to download APT and start a JWST proposal, see Moving Target APT Instructions. After this tutorial you may want to read Tutorial on Creating Solar System Targets in APT and Tutorial on Visualizing Dithers of a Solar System Observation in APT.

The following examples are by no means exhaustive. If you have questions please contact the help desk.

Getting started creating a new Solar System target

To create new targets, select the **Targets** folder and click the ***New Solar System Target*** button.

Figure 1. APT Solar System targets page



A new **Solar System Targets** folder will be created with an empty sub-folder, **Unnamed Target**. To create additional targets, you can click the ***New Solar System Target*** button either at the **Targets** level or the **Solar System Targets** level.

To define your first target, select the **Unnamed Target** folder. Inside you will see that there are three "levels" to defining a Solar System target.

- ***Level 1 Type***: Observation will track the center of a planet, comet, asteroid, etc.
- ***Level 2 Type***: Observation will track a feature, satellite, ring, position angle, etc. of the Level 1 target.
- ***Level 3 Type***: Observation will track a feature, satellite, ring, position angle, etc. of the Level 2 target.

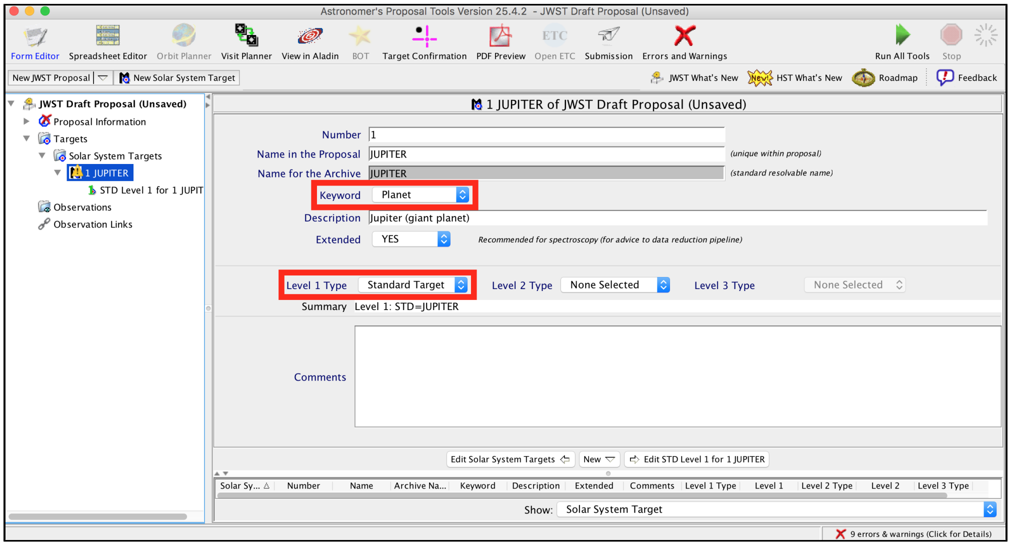
See also APT Targets for a more general discussion. The following examples illustrate a subset of the Solar System targets that may be defined.

Example 1: Defining a Level 1 Standard Target planet

The simplest target to define is a Level 1 ***Standard Target***.

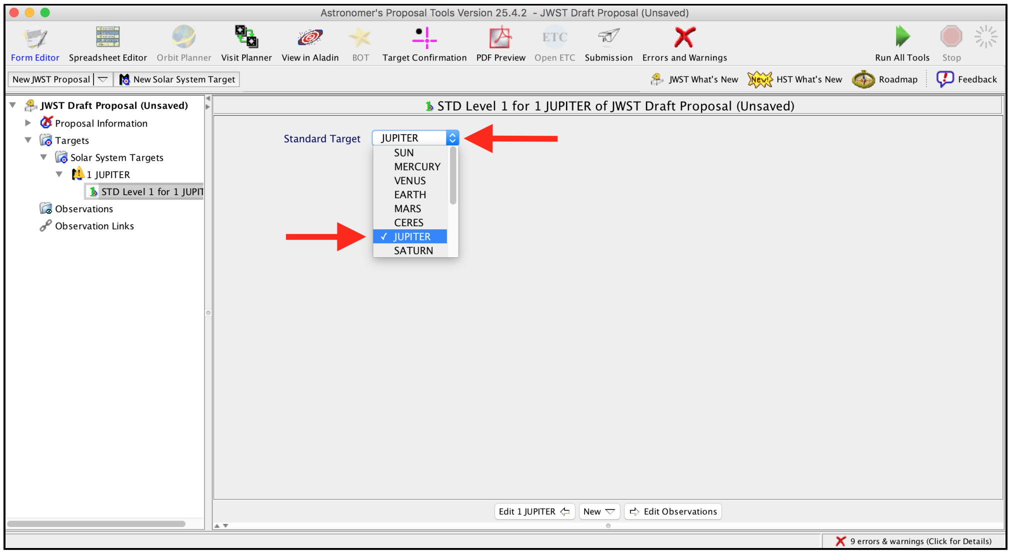
Type the name of your target in ***Name in the Proposal***, select ***Planet*** from the ***Keyword*** drop-down choices, and add a description. The keyword is for archiving purposes only. Note that if you choose ***Dwarf-Planet*** for ***Keyword*** but select Mars as the Level 1 target, the ***Keyword*** value remains unchanged, even though it is not an accurate description (making this mistake will not affect the evaluation of your proposal). Therefore, to properly define your target type, select a value among the three "level" parameters: for a simple observation of Jupiter, select ***Standard Target*** from the ***Level 1 Type*** drop-down choices.

Figure 2. Keywords and Level 1 targets



Next, you will be taken to the screen shown in Figure 3. Scroll through the ***Standard Target*** drop-down choices and select ***Jupiter***.

Figure 3. Choosing a standard target

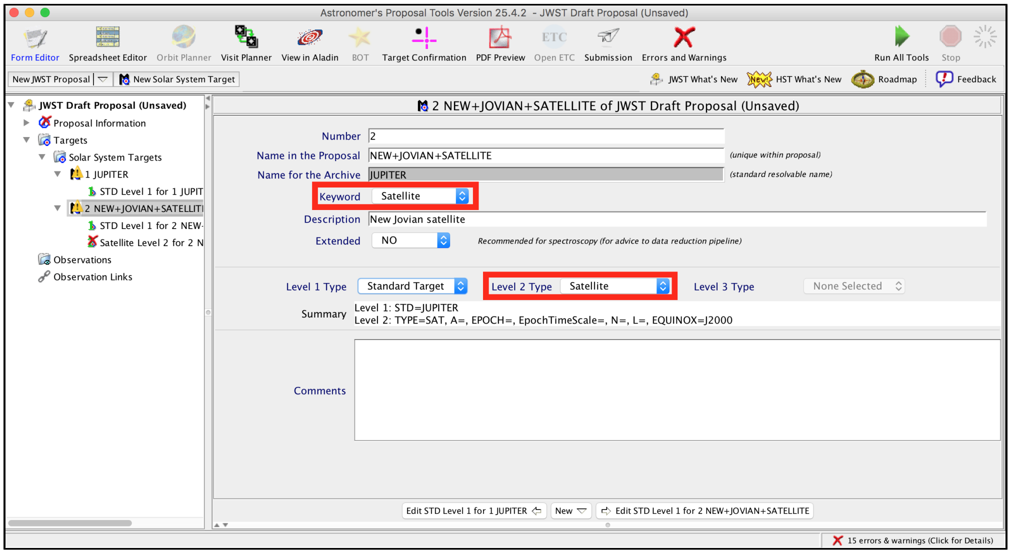


Example 2: Defining a non-"standard" Level 2 satellite

If you are observing a satellite that is not listed among the "standard targets," you can define it. This can work in any of the levels, but we will illustrate it at Level 2 by creating a new satellite for Jupiter.

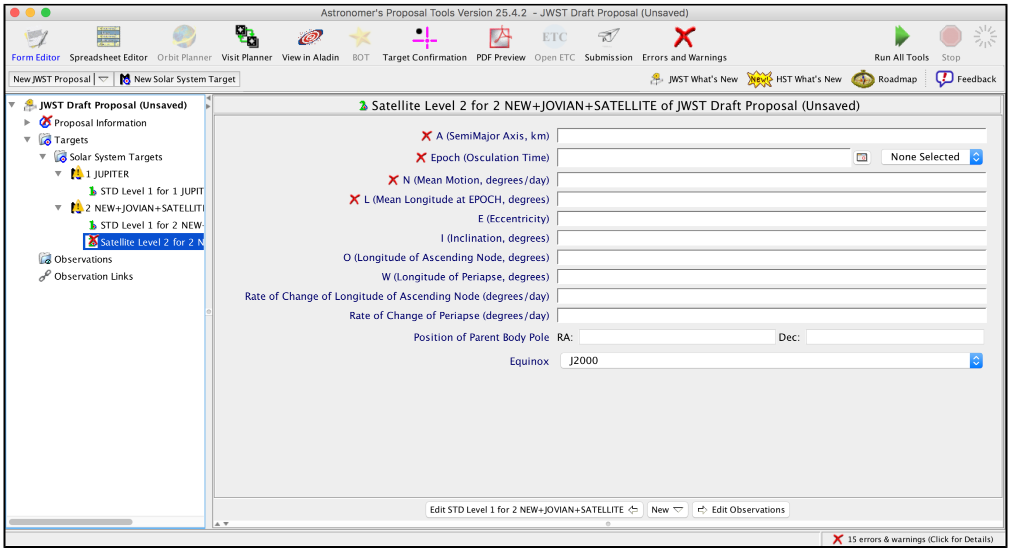
Create a new target sub-folder, select ***Satellite*** from the ***Keyword*** drop-down choices, and enter a name and description. As in the example above, select ***Jupiter*** as the Level 1 ***Standard Target***. Then in the Level 2 drop-down choices, select ***Satellite***.

Figure 4. Level 2 targets



You will be taken to the form shown in Figure 5 where you can enter the satellite's orbital parameters.

Figure 5. Defining a new Jovian satellite

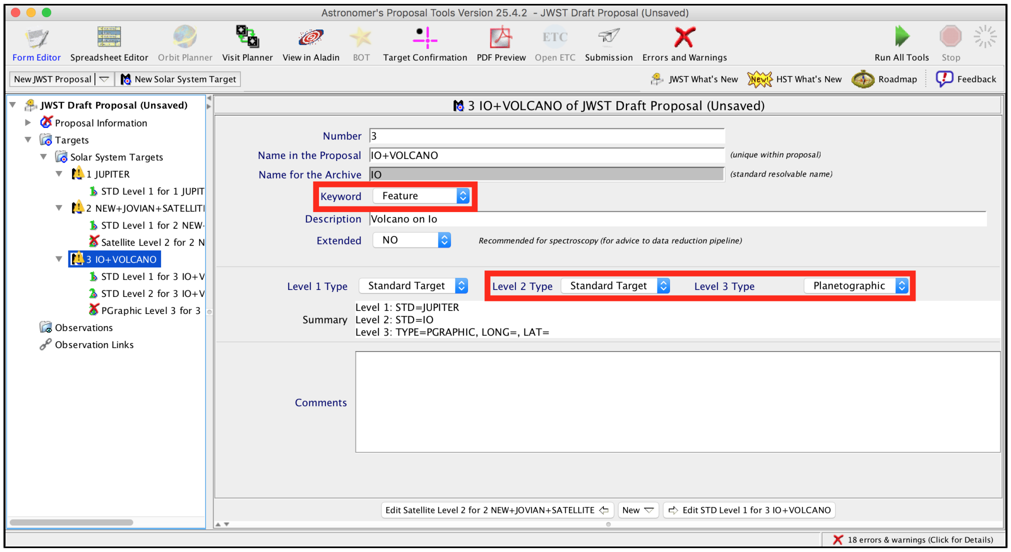


Example 3: Defining a Level 3 feature

At Level 3, you can define a feature to track on a Level 2 target. In this example, we will define the location of a volcano on the surface of the Jovian satellite Io.

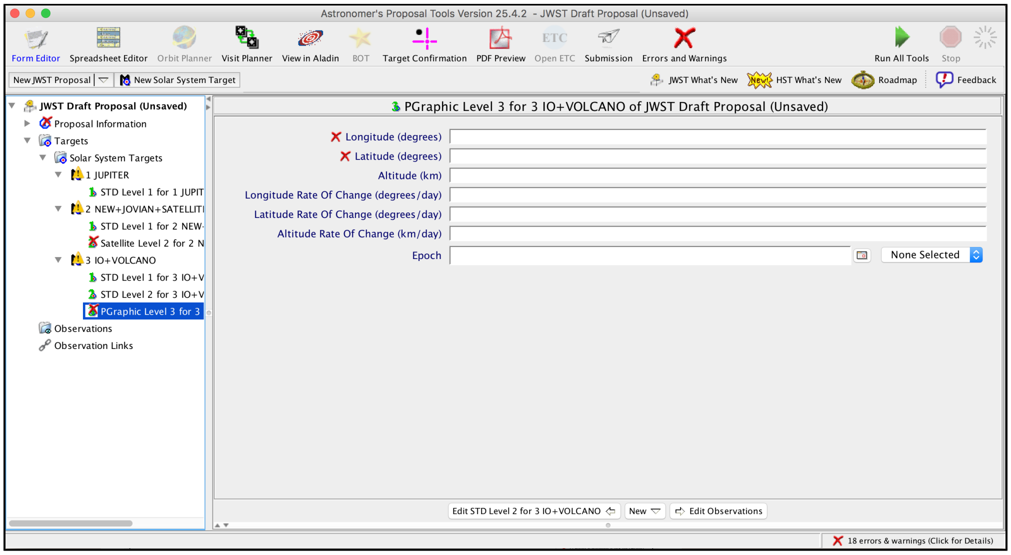
Select ***Feature*** from the ***Keyword*** drop-down choices, ***Jupiter*** as the Level 1 **Standard Target**, and ***Io*** as the Level 2 ***Standard Target***. Finally, select ***Planetographic*** from Level 3 to set the Level 3 target's coordinates to be in longitude and latitude relative to the Level 2 target. You can find the full list of coordinate frames in the article Solar System Targets Position Levels 2 and 3.

Figure 6. Level 3 features



You will be taken to the form shown in Figure 7, where you can define the volcano's longitude, latitude, etc.

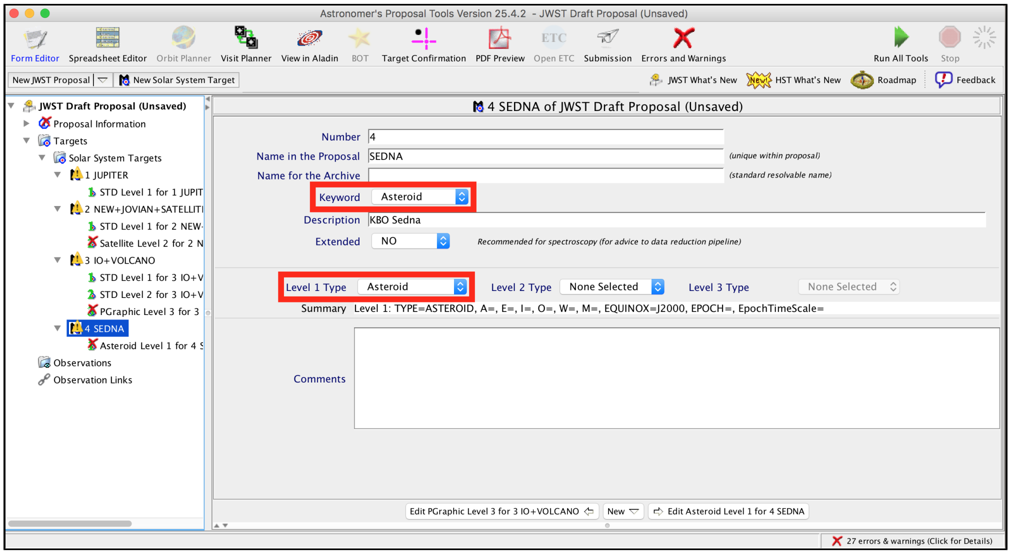
Figure 7. Defining a volcano on Io as a Level 3 feature



Example 4: Defining a Level 1 minor body

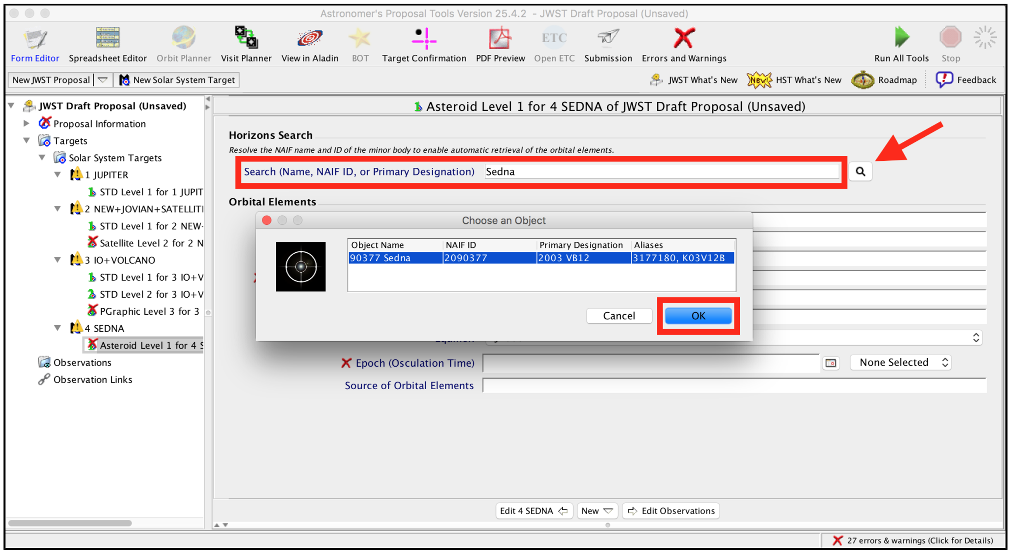
Most minor bodies such as asteroids, comets, and KBOs are not considered standard targets and must be selected from either the ***Comet*** or ***Asteroid*** categories, the latter including outer Solar System minor planets. For example, to define the trans-Neptunian object Sedna, select ***Asteroid*** from the Level 1 drop-down choices.

Figure 8. Defining a Level 1 asteroid



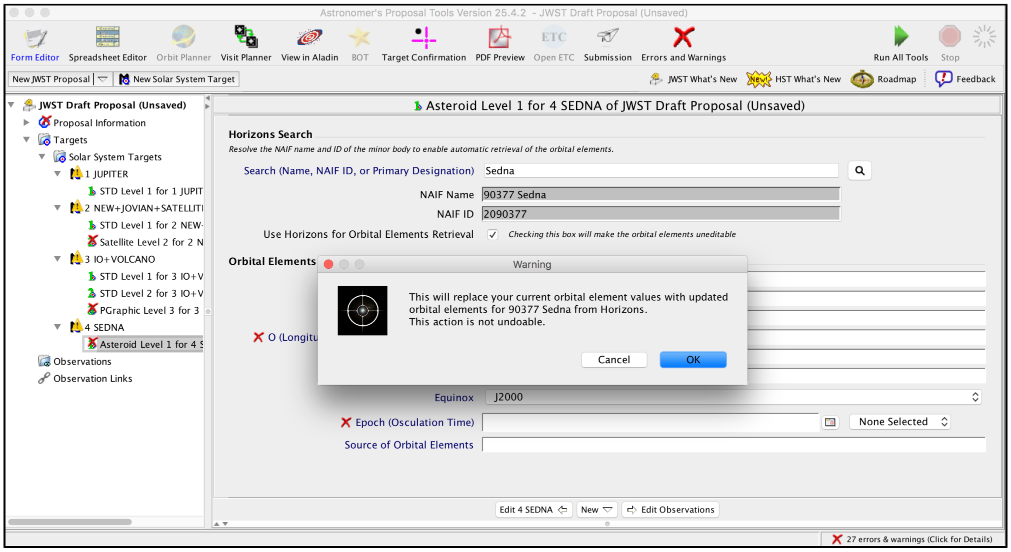
On the next form, shown in Figure 9, type "Sedna" into the ***Search*** box. Choose the object from the pop-up window and click ***OK***.

Figure 9. Using the JPL Horizons search tool



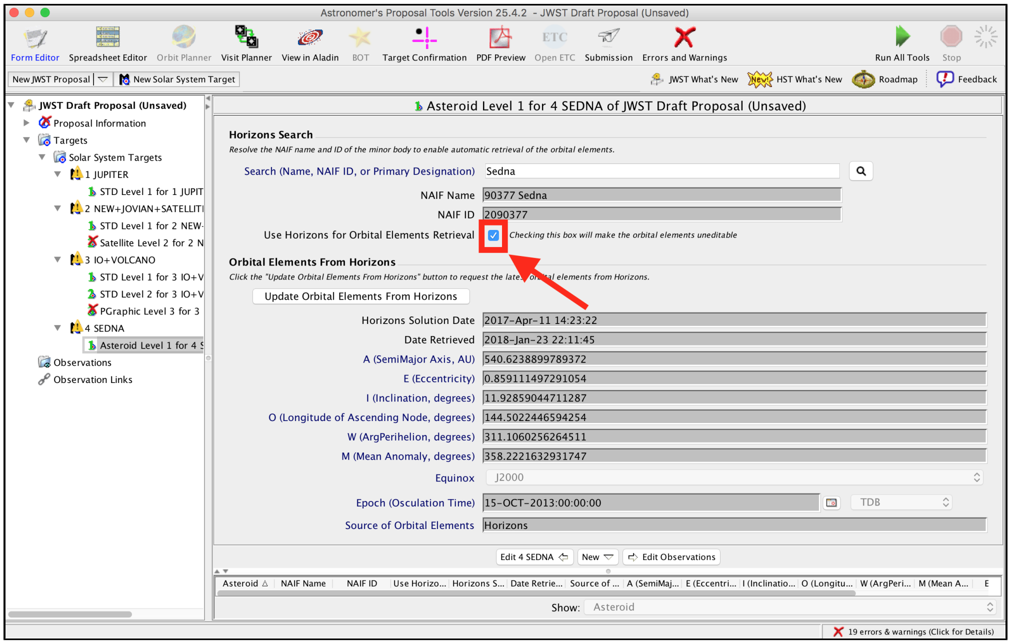
Next, APT will retrieve the object's orbital elements from JPL Horizons. If you had previously entered any elements into this form, they will be overwritten unless you click ***Cancel***.

Figure 10. Loading orbital elements



If you wish to edit the JPL Horizons elements (which is not recommended), uncheck the box indicated in Figure 11.

Figure 11. Updating orbital elements



References

Download the Astronomer's Proposal Tool

Published	26 May 2017
Latest updates	• 16 Dec 2019 Minor wording changes. • 27 Jun 2019 Fixed the link in the references section.

Tutorial on Creating Solar System Observations in APT

This page walks through how to create a Solar System observation in the JWST Astronomer's Proposal Tool (APT).

On this page

Main article: JWST Astronomers Proposal Tool Overview

In this article, we walk through an example for creating new Solar System observations in the JWST Astronomer's Proposal Tool (APT). This is a very basic example; the article Solar System Special Requirements describes in greater detail the options for constraining moving target observations.

To learn how to download APT and start a JWST proposal, see Moving Target APT Instructions. Before this tutorial you may want to read Tutorial on Creating Solar System Targets in APT, and after, Tutorial on Visualizing Dithers of a Solar System Observation in APT. If you have questions please contact the help desk.

Getting started creating a Solar System observation

You must first create targets before creating observations.

The workflow for creating an observation is:

- Pick a target
- Pick an instrument (MIRI, NIRCAM, NIRISS, NIRSpec)
- Pick a science template (Imaging, IFU Spectroscopy, etc.)

Moving targets can be observed with any instrument and any observing template.

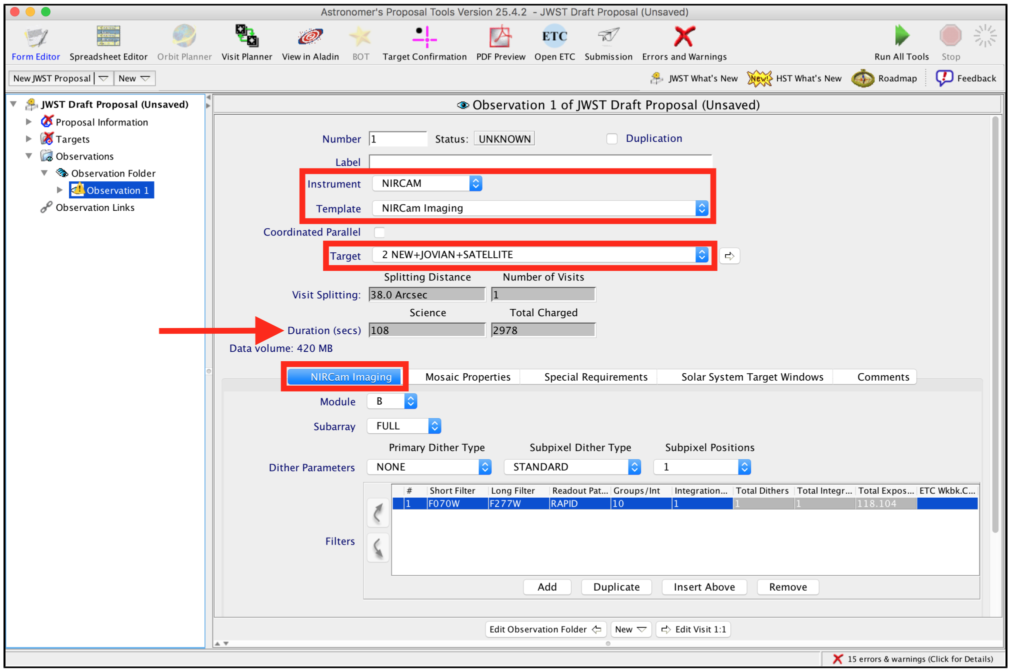
To create observations for your targets, click on the **Observations** folder and then on the ***New Observation Folder*** button. An empty **Observation Folder** will be created in the left sidebar, containing an empty **Observation 1**. Inside **Observation 1** is a blank form where you can select the target, instrument, template, etc.

The article APT Observations describes APT observations more generally and APT Observation Templates describes the available instrument templates. An example for setting up a NIRCam Imaging observation is provided below; other modes, of course, have their own unique parameters.

A NIRCam imaging example

To create a NIRCam imaging observation, select ***NIRCAM*** from the ***Instrument*** drop-down choices, ***NIRCam Imaging*** from the ***Template*** drop-down choices, and one of the previously defined targets from the ***Target*** drop-down choices. After you have selected the template, a new form will appear at the bottom, where you can define the template's parameters such as the subarray, dither pattern, and filters. Notice how the estimated time in the ***Duration*** box changes as you tweak the parameters.

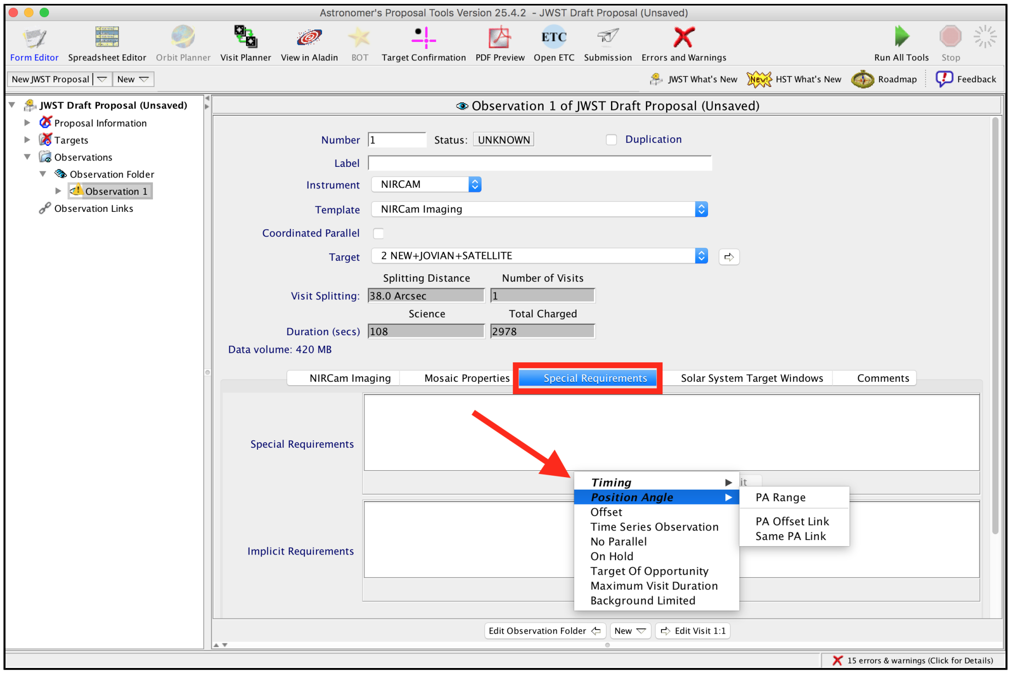
Figure 1. Selecting the observing template



In the other tabs on the template form you can, for example, modify observation constraints such as timing and position angle under **Special Requirements**. These can differ between observing templates; more general information can be found in APT Special Requirements.

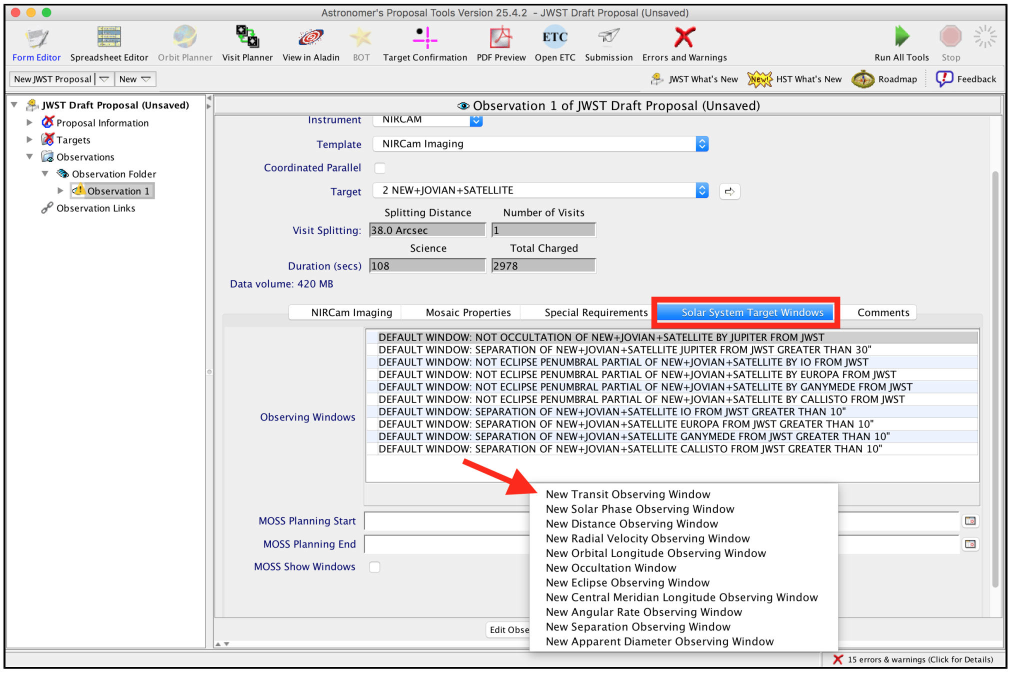
Keep in mind that defining constraints depends on the circumstances of your observation. Using either the **Special Requirements** (Figure 2) or **Solar System Target Window** (Figure 3) tabs can significantly restrict the scheduling period for the observation, and may incur a Direct Scheduling Overhead. Note that if you were to create a constraint requiring that the observation be made in a small window (to observe a particular longitude on an object, for example), your program will be charged an additional overhead. See Moving Target Overheads and Time Constrained Observations for additional information.

Figure 2. Special Requirements



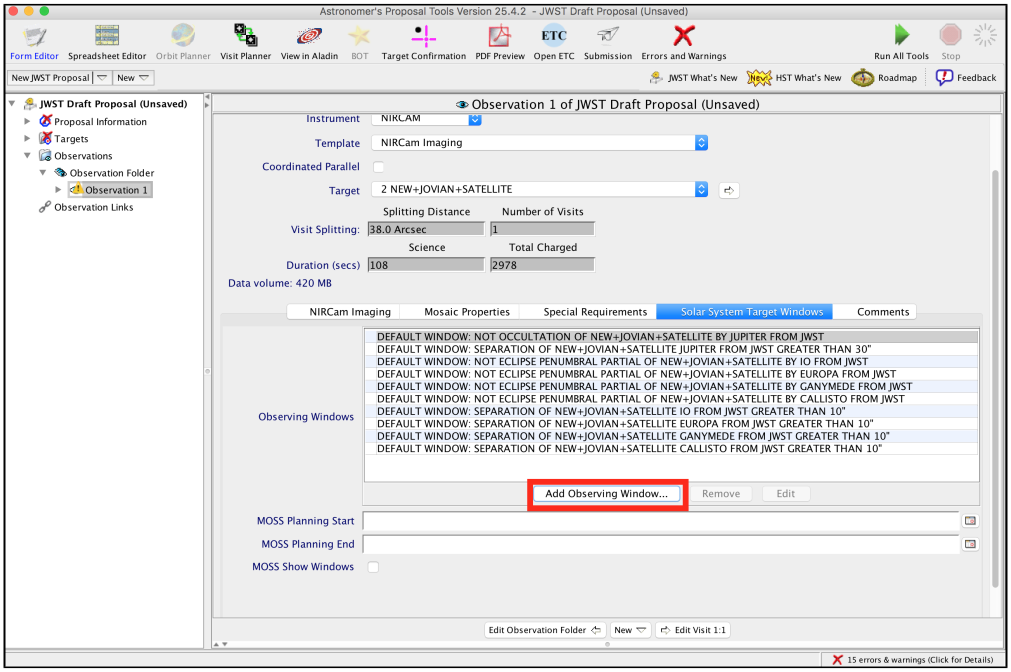
You can modify the observation windows under the **Solar System Target Windows** tab. As seen in Figure 3, observations of Jupiter, its pre-defined satellites, and user-defined satellites will, by default, have 4 entries in the **Solar System Target Windows** tab for each of the Galilean satellites. Times during which the Galilean satellites eclipse Jupiter or each other will be automatically removed from the observing window. Default Solar System target windows are available in this list.

Figure 3. Solar System Target Windows



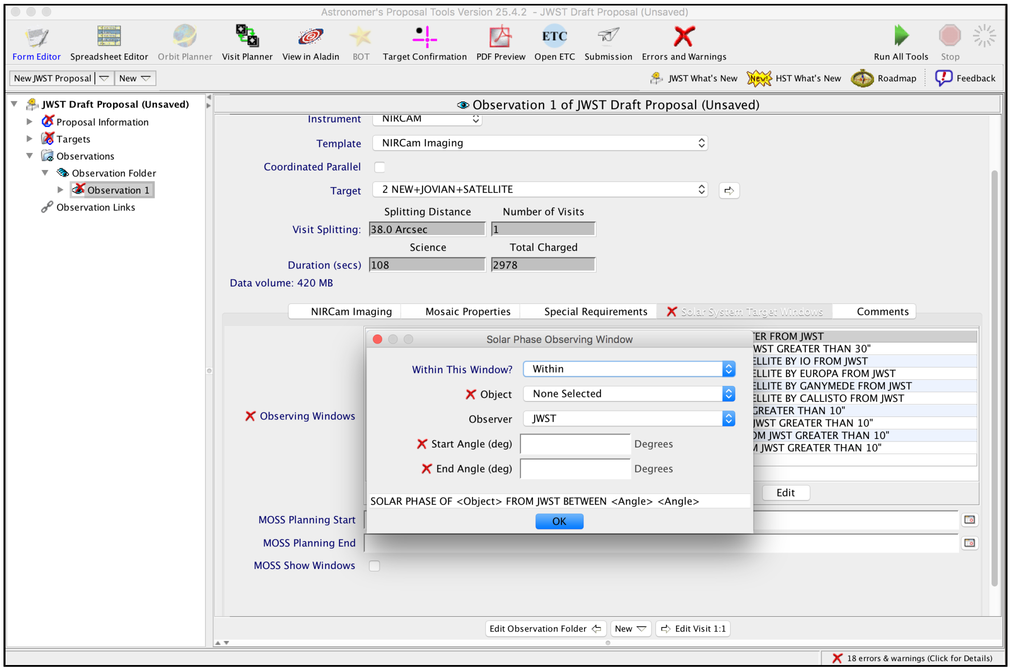
Let's add a solar phase constraint. In the **Solar System Target Windows** tab click on the ***Add Observing Window*** button and select ***New Solar Phase Observing Window*** from the drop-down choices.

Figure 4. Adding a Solar System Target Window



You will get a pop-up window as shown in Figure 5. For **Object**, select from a list of any of your defined targets or solar system standard target, and likewise from the **Observer** drop-down choices.

Figure 5. Adding a Solar Phase Observing Window



Solar System Target Windows

The Solar System Special Requirements article has a full list of available Solar System target windows, with descriptions. A few notes about specific ones are provided below.

- ***Separation of ...*** vs. ***Distance ...*** special requirements:
  The ***Separation of <object1> <object2> from <observer> <condition> <angle>*** observing window allows you to define the separation between 2 objects in angular units. The ***DISTANCE <object1> <object2> <condition> <distance>*** observing window allows you to specify that an observation should occur at a particular separation between 2 objects in distance units (AU). There are no specific target windows for defining a heliocentric or observer-centric distance; either can be specified using the ***Distance*** observing window and choosing the appropriate object (***SUN*** or ***JWST***) for ***<object 2>***.

- ***Central Meridian Longitude of ...*** special requirement:
  This observing window allows the user to specify a longitude on a rotating Solar System object. This is similar to the ***Phase*** constraint available under the **Special Requirements** tab, except that the ***Central Meridian Longitude*** observing window only applies to a handful of standard targets: ***Mars***, ***Jupiter***, ***Saturn***, ***Uranus***, ***Neptune***, ***Io***, ***Europa***, ***Ganymede***, ***Callisto***,

Mimas, ***Enceladus***, ***Tethys***, ***Dione***, ***Rhea***, ***Titan***, ***Iapetus***, ***Ariel***, ***Umbriel***, ***Titania***, ***Oberon***, ***Miranda***, ***Triton***, ***Pluto***, and ***Charon***. Specifying a ***Central Meridian Longitude*** constraint on an object not in this list will result in a warning when running the Visit Planner. Rotational constraints for other objects not in this list should be specified instead with the ***Phase*** constraint.

> ⚠ The ***Phase*** Special Requirement and ***Central Meridian Longitude*** Solar System Window can be used interchangeably for any targets with defined coordinate systems. However, keep in mind that the entire observation must occur within the window specified by a ***Central Meridian Longitude*** constraint, whereas the ***Phase*** constraint only specifies when the observation should begin. In other words, the schedulability window for the start time of an observation with a ***Central Meridian Longitude*** constraint will be reduced by the length of the observation; if the observation is longer than the specified window, it will not be schedulable. The ***Phase*** constraint thus increases schedulability, but there is a possibility that the observations will not actually occur between the desired rotational phases.

- ***Transit of ...*** vs. ***Occultation of ...*** special requirements:
  A transit begins when the entire disk of the transiting body is in front of the transited body and ends when the limb of the transiting body first crosses over the limb of the transited body. In other words, the transit duration covers only the time when the entire disk of the transiting body is on the disk of the transited body. An occultation begins when the limb of the transiting body first touches the limb of the transited body and ends when the two bodies are no longer in contact. The duration of an occultation is therefore always longer than the duration of a transit.

- ***Eclipse ...*** special requirement:
  An eclipse begins when the limb of the eclipsed sphere first touches the umbra or penumbra (depending on which is specified) and ends when the limb of the eclipsed sphere touches the umbra or penumbra for the last time. In other words, the eclipse duration covers the entire time that any part of the eclipsed sphere is in the shadow.

You should be aware that drop-down choices for choosing Solar System objects, available in a few of the **Solar System Target Windows**, will list targets you defined in the APT file first, followed by standard targets, satellites of standard targets, and JWST at the bottom. (There is a second instance of JWST between the standard targets and their satellites, and either can be used.)

References

Download the Astronomer's Proposal Tool

Published	26 May 2017
Latest updates	• 16 Dec 2019 Wording changes.

Tutorial on Visualizing Dithers of a Solar System Observation in APT

A tutorial on how to view dithers for a solar system observation in the JWST Astronomer's Proposal Tool (APT).

On this page

Main article: JWST Astronomers Proposal Tool Overview

Currently, APT does not have the capability to display an Aladin visualization of moving target dithers. Until such time that a fix is implemented, moving target observers can use a fixed target as a proxy to visualize their dithers. Accurate instrument field of view orientations can be determined using the Moving Target Visibility Tool (MTVT).

To learn how to download APT and start a JWST proposal, see the Moving Target APT Instructions. Before this tutorial, you may want to read Tutorial on Creating Solar System Targets in APT and Tutorial on Creating Solar System Observations in APT. If you have questions please contact the help desk.

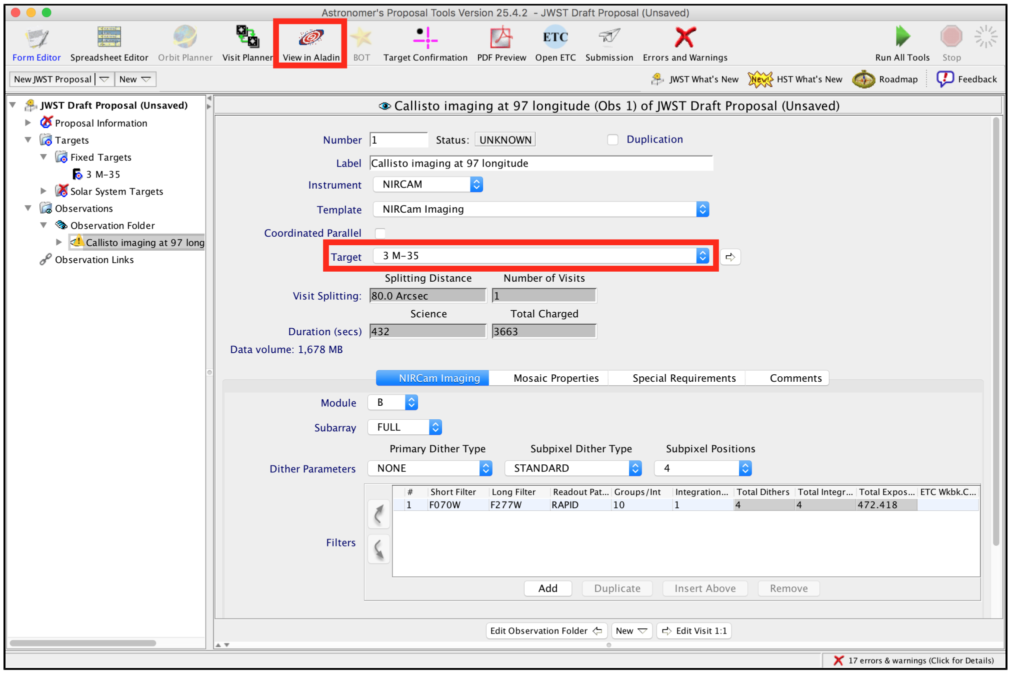
Viewing dithers with a proxy moving target

In the example below, we define a fixed target, M-35 (an open cluster in the ecliptic), as a proxy for Callisto. Visualization of the instrument FOV, placement of the FOV for various dither and mosaic-tile offsets, and depth of coverage is then possible by changing (temporarily) the target of the observation from Callisto to M-35.

⚠ Switching targets in APT, for example, M-35 back to Callisto, will cause the Default Solar System target windows to repopulate. If you previously deleted any of the editable default target windows, you will have to do so again.

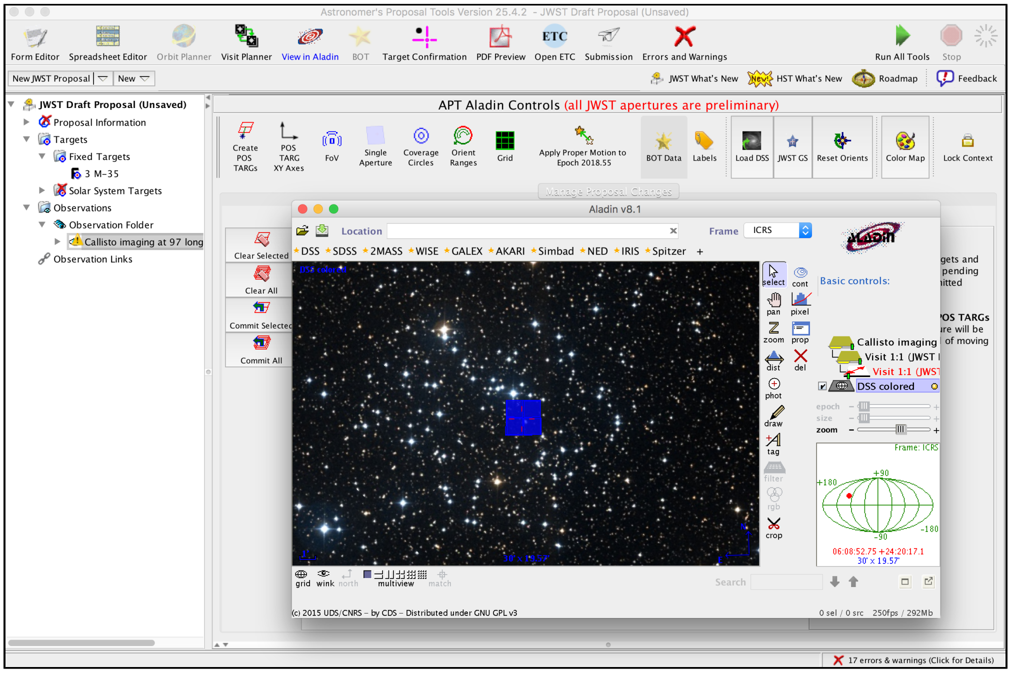
In order to visualize the dithers, click on the **View in Aladin** button at the top of the window. The Aladin viewer is discussed in the APT Aladin Viewer article.

Figure 1. Defining a fixed target proxy



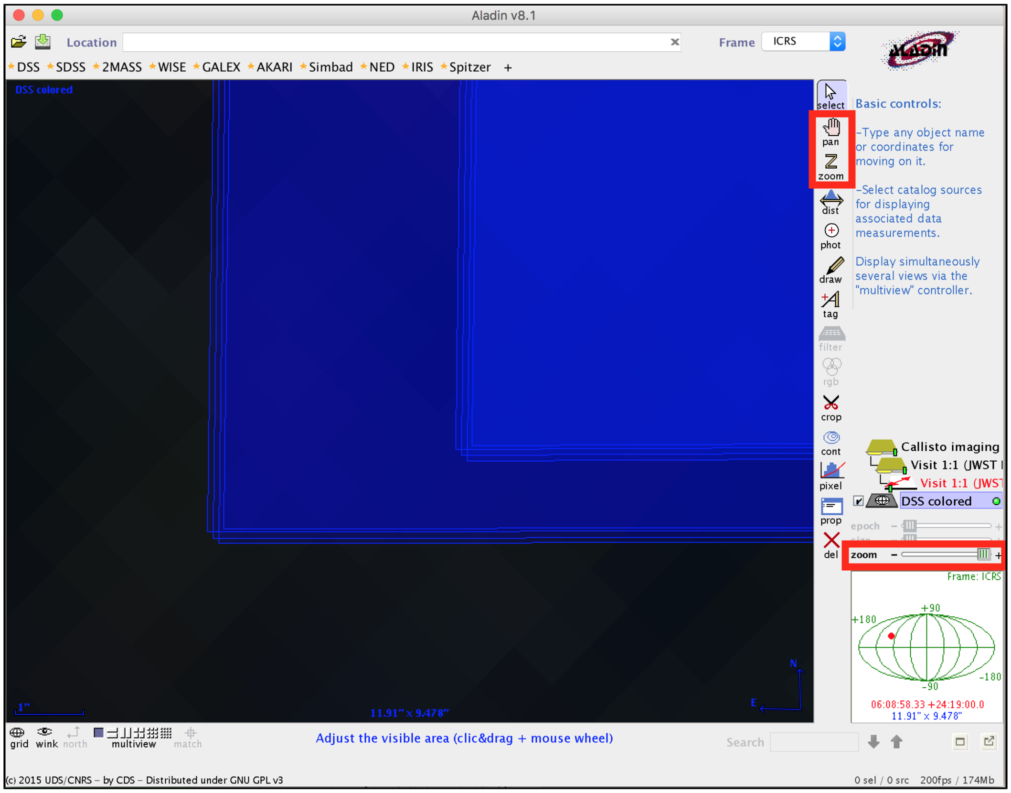
In the Aladin window, as shown in Figure 2, any observations you have highlighted in the left sidebar will be displayed over the sky catalog of your choice (DSS, 2MASS, Simbad, etc.).

Figure 2. Viewing the observation in Aladin



Pan and zoom to display at the level you want. Figure 3 shows a screenshot of a NIRCam subpixel dither.

Figure 3. Visualizing a sub-pixel dither



References

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Moving Target Observing Strategies

A summary of general and instrument-specific recommended strategies for creating moving target observing programs.

On this page

The diversity of JWST observing modes present many opportunities for new and innovative solar system science. Below are a list of recommendations for the JWST instruments and features that the proposer should keep in mind when developing observing programs. The recommendations are broken into general and instrument-specific categories. The general recommended strategies deal mostly with target definition, Solar System target windows, and the Visit Planner in APT. Instrument-specific recommended strategies cover the most commonly proposed instrument modes for solar system observations. This list is not exhaustive.

General recommended strategies for moving targets

Defining moving targets

The following minor bodies, in addition to the planets and their known satellites, are "standard targets" and should be selected from the standard target list: Ceres, Pluto (Charon, Styx, Nix, Kerberos, Hydra), Makemake, Haumea (Hi'iaka, Namaka), and Eris (Dysnomia).

Minor body ephemerides should be checked in JPL Horizons for positional uncertainties; in rare cases, even numbered objects can have uncertainties large enough to impact their observability. This is particularly true of observing modes that have small fields of view, which include NIRSpec IFU, NIRSpec WATA, NIRSpec fixed slits, MIRI MRS, MIRI LRS (slit), NIRCam ***SUB64P***[*] subarray, and NIRISS AMI.

Use the JPL Horizons search tool provided in APT when defining non-standard targets whenever possible. Avoid typing in the orbital elements by hand to minimize the chance of making an error.

Solar System Target Windows

A full list of **Solar System Target Windows** can be found in the Solar System Special Requirements article.

The Tutorial on Creating Solar System Observations in APT provides clarification on specific **Solar System Target Windows**, such as:

- the difference between ***Separation*** and ***Distance*** windows;
- the difference between ***Transit*** and ***Occultation*** windows;
- the different options for ***Eclipses***; and
- when ***Central Meridian Longitude*** constraints can be applied.

Unless absolutely necessary for your science goals, do not alter or delete the ***Default Windows*** that are automatically populated for observations of specific targets.

[*] ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

MIRI recommended strategies for moving targets

Main article: MIRI Observing Strategies

The Mid-Infrared Instrument (MIRI) can be operated in 4 different observing modes: (1) imaging, (2) low-resolution spectroscopy, (3) medium-resolution spectroscopy, and (4) coronagraphy.

Target acquisition

The primary MIRI modes for solar system observations are imaging, low resolution spectroscopy with the LRS, and medium resolution spectroscopy with the MRS. Both the LRS and MRS require targets with well-constrained orbital solutions for accurate placement in the science aperture. The LRS requires that the target be kept centered in the slit as accurately as possible because even small deviations will result in inaccurate wavelength solutions. Placing the source offset from the center of the slit could result in shifted wavelength solutions (Kendrew et al., 2015). Target acquisition (TA) is therefore recommended for placing point sources on the LRS slit. The LRS in slitless mode does not support dithering.

MRS observations

Avoid target acquisition (TA) for MRS observations, if possible. This will save time and should not be used for extended objects or objects with low-uncertainty orbits, such as standard targets (planets, dwarf planets, and their satellites) and most numbered minor bodies.

Choose a 4-point dither for MRS observations. A 2-point dither is acceptable but not ideal for artifact rejection, proper spectral sampling, and proper spatial sampling. Do not choose less than 2 dither positions, as this will almost certainly result in data quality issues.

Simultaneous imaging will incur some small overheads, but in general, it is a good idea to select this option in APT when observing with the MRS. Simultaneous observations with the MIRI imager in a field adjacent to your target could yield serendipitous detections of minor bodies, especially asteroids, which have peak thermal emissions at MIRI wavelengths. However, it is not recommended that simultaneous imaging be selected when observing near giant planets, as this will likely saturate the detector.

Dedicated background observations are highly recommended when observing giant planets (or other extended objects, like comets) that fill the smallest MRS field of view (3.3" × 3.7"). These background observations should be placed a few arcminutes from the science target using the ***Level 2 Type*** APT parameter's ***Position Angle*** setting, in the **Solar System Targets** form. For these dedicated background observations, no TA should be specified and dithering is not necessary. Simultaneous imaging may be selected.

The FWHM of the MRSPSF roughly corresponds to the slice width, which varies with wavelength. The PSF FWHM is ~0.176" at the shortest wavelengths and expands to ~0.645" at the longest wavelengths (Wells et al., 2015). Pluto and Charon (maximum angular separation of ~0.8"), for instance, will be easily separable at the shorter wavelengths, but will possibly be blended at the longer wavelengths. As another example, spatial resolution on Titan will significantly degrade with increasing wavelength.

LRS observations

Proposers should always specify a TA for LRS observations. Even objects with lower uncertainty orbits may not be properly placed on the LRS slit (0.51" thickness) with the blind pointing accuracy of JWST.

Coronagraphic imaging

Three of the MIRI coronagraph apertures are 4-quadrant phase masks (4QPMs), meaning they do not have Lyot stops and can provide much smaller inner working angles (IWAs) (Boccaletti et al., 2015). A possible application of this mode is thedetection ofsatellites around minor bodies in the solar system (primarily asteroids and KBOs). A drawback is the need to place the target exactly on the center of the phase mask, and keep it there for the duration of the observations, which may be more difficult for moving targets. Additionally, it is unlikely that observations of extended objects with the 4PQMs will yield useful results.

NIRSpec recommended strategies for moving targets

Main article: NIRSpec Observing Strategies

The Near Infrared Spectrograph (NIRSpec) can be operated in 4 different observing modes: (1) multi-object spectroscopy (MOS), (2) integral field unit (IFU) spectroscopy, (3) fixed slits spectroscopy, and (4) bright object time-series (BOTS) spectroscopy.

Target acquisition

The primary NIRSpec modes for solar system observations are IFU and fixed slits (FS) spectroscopy. The fixed slits have no covers and are always open; the ***ALLSLITS*** subarray can be used to simultaneously record spectra through all the slits, if desired. Both the IFU and FS modes require targets with well-constrained orbital solutions for accurate placement in the science aperture. Any observations with the 0.2" fixed slit, and likely the 0.4" fixed slit, will require target acquisition (TA). Wide aperture target acquisition (***WATA***) for moving targets will use the S1600A1 fixed slit, so the uncertainties on the ephemeris must be small enough to first place the object in a 1.6" × 1.6" box.

Fixed slit observations

NIRSpec fixed slit observations will require a TA with the S1600A slit (1.6” × 1.6” FOV), referred to as wide aperture target acquisition (***WATA***), and will add 8–15 minutes of overhead to each visit. If your science goals can be accomplished with the IFU and can tolerate the uncorrected initial pointing errors, it may be possible to avoid this overhead by skipping the ***WATA*** acquisition. Since the IFU is the largest spectroscopic aperture on NIRSpec (3” × 3” FOV), it can be advantageous to select this mode when pointing uncertainties are a concern.

IFU observations

If you are worried about a target falling in the IFU (3” × 3” FOV) with blind pointing, then it will likely not fall within the ***WATA*** FOV (1.6” × 1.6”) either. The best advice is to get more astrometric measurements of your target prior to the cycle you are proposing for.

Regarding TA with NIRSpec, the MSATA option is not available for moving targets. Observers can choose between performing a ***WATA*** acquisition in the 1.6" × 1.6" aperture followed by a slew to place the target in the IFU, or they can rely on the initial JWST blind pointing accuracy and skip the target acquisition. In the latter case, the user can choose whether or not to obtain a verification image through the IFU aperture prior to the spectroscopic observations (***TA Method*** = ***VERIFY_ONLY*** or ***TA Method*** = ***NONE***). For moving targets, it will usually make sense to take any verification image with the MSA (***PV MSA Configuration***) set to ***ALLCLOSED*** to reduce light leakage.

The choice of dithers is inherently tied to the accuracy of the target acquisition, as is quantified in the NIRSpec Target Acquisition Recommended Strategies article. When in doubt, choose a ***CYCLING*** dither type with ***SMALL*** size for NIRSpec IFU observations. This is especially important for extended objects, since the ***2-POINT NOD*** and ***4-POINT NOD*** have large throw distances. Observations of minor bodies with higher uncertainty orbits should use the ***SMALL*** size dithers as well to ensure they stay in the FOV between dithers.

Observations of targets in the NIRSpec IFU are subject to stray light from both failed open shutters and light leakage through the MSA. The latter can cause a significant increase in the background, due to the "pile up" of dispersed background (similar to slitless spectroscopy modes). In general, leakage calibration exposures ("leak cals"), which can measure and subtract this signal, are not recommended for moving targets, since the leaking astronomical background will have moved between the science and leak cal exposure.

For observations of giant planet satellites, it would be best to avoid placing the planet in the MSA FOV. The Moving Target Visibility Tool can be used to evaluate the allowable position angles of the NIRSpec FOV over particular dates, in order determine the appropriate ***Position Angle*** special requirement in the APT. Finally, we note that, for light leaking through open shutters, the contaminated spaxels can be removed with dithering; in this case, 4 dithers are preferable to 2.

Multi-object spectroscopy (MOS)

Multi-object spectroscopy (MOS) with the micro-shutter assembly (MSA) is available for moving target observations with a "pseudo long slit." These custom long slits are available in quadrant 4 (Q4) of the MSA and may be ideal for observations of comets, Mars, and the giant planets. Scanning of the entire disks of Mars and giant planets can be made by allowing the object to rotate and leaving the long slit fixed in the MSA. Scanning across the disk of Mars and the giant planets in a shorter period of time, or scanning across a comet, can be specified in the NIRSpec MOS template starting in APT 28.0. It should be noted that the proposed investigation in Norwood et al. (2016) to observe the Uranian satellites with the MSA is not feasible at this time.

NIRCam recommended strategies for moving targets

Main article: NIRCam Observing Strategies

The Near Infrared Camera (NIRCam) can be operated in 5 different observing modes: (1) imaging, (2) coronagraphic imaging, (3) wide field slitless spectroscopy, (4) time-series imaging, and (5) grism time series.

Imaging

For most targets, observations using ***Module B*** only (as opposed to ***Module*** = ***ALL***) will provide sufficient field of view (approximately 2.2 × 2.2 arcmin), and will give you more flexibility for choosing exposure parameters.

Choosing a ***Subarray*** other than ***FULL*** will restrict the field of view further, but allow for more ***Groups*** in each integration ramp for bright sources. Generally, the SNR is better using more ***Groups*** for a given integration time.

For the planets and their major satellites, use of subarrays is frequently required in order to avoid saturation.

Choose at least 2 dither positions to allow for bad pixel replacement. For sharper images, particularly at wavelengths below 2 µm in the short wavelength channel, and 4 µm in the long wavelength channel, use at least 4 dither positions.

The primary NIRCam mode for solar system observations is imaging with one module (Module B).The same field of view can be observed through 2 different channels simultaneously (short wavelength: 0.6–2.3 µm; long wavelength: 2.4–5.0 µm). NIRCam has 2 modules providing 2 separate fields of view; however, for many observations (i.e., a single target) only a single module is necessary. The ***RAPID*** readout mode will not result in data volume issues when using only one module. Surveys would benefit from use of both modules combined with NIRISS imaging in parallel. Brightness limits can be found in the NIRCam imaging article.

Time-series imaging

NIRCam time-series imaging provides a maximum frame rate of ~20 Hz in conjunction with the smallest subarray (64 × 64 pixels, or 2.0″ × 2.0″). A possible application is for observing stellar occultations and mutual events. Brightness limits for this mode can be found in the NIRCam imaging article. The NIRCam coronagraphs (using traditional Lyot stops) provide IWAs of 0.4″, 0.63″, and 0.81″ (in radius) at wavelengths of 2.1, 3.35, and 4.1 µm, respectively. Possible application of the coronagraphs to solar system science are the study of Centaurs and distant comet comae, observations of the satellites and rings of Uranus and Neptune, and the discovery of faint, widely separated satellites of the largest Kuiper Belt objects.

NIRISS recommended strategies for moving targets

Main article: NIRISS Observing Strategies

The Near Infrared Imager and Slitless Spectrograph (NIRISS) can be operated in 4 different observing modes: (1) imaging, (2) single object slitless spectroscopy (SOSS), (3) wide field slitless spectroscopy (WFSS), and (4) aperture masking interferometry (AMI).

Aperture Masking Interferometry (AMI)

Of NIRISS's modes, AMI may present the most unique opportunities for solar system observers. AMI uses a 7-hole aperture mask with 21 unique baselines to provide high spatial resolution imaging of up to 75″, with a contrast sensitivity of ~10 mag at 4.6 µm. Keep in mind that the 7 holes in the aperture mask correspond to 7 mirror segments; this means that light from 11 mirror segments is blocked, resulting in throughput of only ~15%.

Faint objects, such as KBO binaries, are therefore not ideal AMI targets. However, AMI's performance observing Io's volcanoes and binary asteroids has been extensively investigated. When observable by JWST, Io's diameter will, on average, cover 16 pixels on NIRISS, with a plate scale of ~65 mas/pixel. Simulations of AMI images of active Io eruptions show it is possible to measure emission from individual events and to resolve bright events separated by only 88 mas; see Thatte et al. (2015) and Keszthelyi et al. (2016). The accepted Solar System ERS proposal (program 1373) makes use of the AMI mode for observations of volcanos on Io, and its APT file is available to download in APT. To do so in APT, select **File→Retrieve from STScI→Retrieve using proposal ID**, then type ***1373*** in the pop-up window. Binary asteroids with separations under 75 mas and contrasts less than 10 mag, such as Ida/Dactyl (70 mas and 6.7 mag, respectively), will be resolvable using AMI (Rivkin et al., 2016).

Imaging

Compared to NIRCam, NIRISS has a smaller pixel scale and higher sensitivity to extended emission <2.5 µm (Norwood et al., 2016). The pixel scales of the 2 instruments are comparable at wavelengths >2.5 µm. The imaging mode contains similar filters (0.9–5 µm) to NIRCam two channel imaging, and in effect NIRISS imaging becomes a "third channel" when operated in parallel. Note that it is not possible to select NIRISS imaging as a primary mode; this is to encourage proposers to take advantage of NIRCam's ability to image simultaneously through two filters.

SOSS and WFSS

The single object (SOSS) and wide field (WFSS) slitless spectroscopy modes, provided by grisms ***GR150C***,***GR150R***, and***GR700XD***, may not be the most optimal modes for solar system observers; however, such programs are not without precedence. For instance, the G141 grism on Hubble's WFC3 has been used to observe the Pluto system (HST program 13667, PI M. Buie).

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Published	10 Feb 2018
Latest updates	• 12 Dec 2019 Wording clarifications. Removed the Visit Planner recommendation because it is no longer valid. Combined with Instrument Specific Considerations page. Renamed. • 27 Jun 2019 Fixed formatting issues

	• 21 Feb 2019 Changes made to NIRSpec section • 08 Nov 2018 Changed the title of the article. Updated some bullet points based on recent APT work. • 06 Mar 2018 Added wording about the Moving Target Visibility Tool (MTVT) to the NIRSpec section.

Moving Target Instrument Specific Considerations

The different JWST instruments and modes have specific capabilities, constraints, and drawbacks for observing moving targets.

On this page

The diversity of JWST observing modes present many opportunities for new and innovative solar system science. However, there are also special considerations and drawbacks to particular modes. Below are a list of the JWST instruments and features that the proposer should keep in mind when developing observing programs. This list is not exhaustive.

MIRI

Main articles: MIRI Imaging, MIRI Low Resolution Spectroscopy, MIRI Medium Resolution Spectroscopy

- The Mid-Infrared Instrument (MIRI) can be operated in 4 different observing modes: (1) imaging, (2) low-resolution spectroscopy, (3) medium-resolution spectroscopy, and (4) coronagraphy.

- The primary MIRI modes for solar system observations are imaging, low resolution spectroscopy with the LRS, and medium resolution spectroscopy with the MRS. Both the LRS and MRS require targets with well-constrained orbital solutions for accurate placement in the science aperture. The LRS requires that the target be kept centered in the slit as accurately as possible because even small deviations will result in inaccurate wavelength solutions. Placing the source offset from the center of the slit could result in shifted wavelength solutions (Kendrew et al., 2015). Target acquisition (TA) is therefore recommended for placing point sources on the LRS slit. The LRS in slitless mode does not support dithering.

- The FWHM of the MRS PSF roughly corresponds to the slice width, which varies with wavelength. The PSF FWHM is ~0.176" at the shortest wavelengths and expands to ~0.645" at the longest wavelengths (Wells et al., 2015). Pluto and Charon (maximum angular separation of ~0.8"), for instance, will be easily separable at the shorter wavelengths, but will possibly be blended at the longer wavelengths. As another example, spatial resolution on Titan will significantly degrade with increasing wavelength.

- The MIRI coronagraphs are 4-quadrant phase masks (4QPMs), meaning they do not have Lyot stops and can provide much smaller inner working angles (IWAs) (Boccaletti et al., 2015). A possible application of this mode is the detection of satellites around minor bodies in the solar system (primarily asteroids and KBOs). A drawback is the need to place the target exactly on the center of the phase mask, which may be more difficult for moving targets. Additionally, it is unlikely that observations of extended objects with the 4PQMs will yield useful results.

NIRCam

Main articles: NIRCam Imaging, NIRCam Coronagraphic Imaging

- The Near Infrared Camera (NIRCam) can be operated in 5 different observing modes: (1) imaging, (2) coronagraphic imaging, (3) wide field slitless spectroscopy, (4) time-series imaging, and (5) grism time series.

- The primary NIRCam mode for solar system observations is imaging with one module. The same field of view can be observed through 2 different channels (short wavelength: 0.6–2.3 μm; long wavelength: 2.4–5.0 μm) simultaneously. NIRCam has 2 modules providing 2 separate fields of view, but it is suggested that only one module could be used if observing one specific target because almost all targets, including comets, can be observed using one module. The ***RAPID****** readout mode will not result in data volume issues when using only one module. Surveys would benefit from use of both modules combined with NIRISS imaging in parallel. Brightness limits can be found in the NIRCam imaging article.

- NIRCam time-series imaging provides a maximum frame rate of ~20 Hz in conjunction with the smallest subarray (64 × 64 pixels, or 2.0″ × 2.0″). A possible application is for observing stellar occultations and mutual events. Brightness limits for this mode can be found in the NIRCam imaging article. The NIRCam coronagraphs (using traditional Lyot stops) provide IWAs of 0.4″, 0.63″, and 0.81″ (in radius) at wavelengths of 2.1, 3.35, and 4.1 μm, respectively. Possible application of the coronagraphs to Solar System science are the study of Centaurs and distant comet comae, observations of the satellites and rings of Uranus and Neptune, and the discovery of faint, widely separated satellites of the largest Kuiper Belt objects.

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NIRISS

Main article: NIRISS Aperture Masking Interferometry

- The Near Infrared Imager and Slitless Spectrograph (NIRISS) can be operated in 4 different observing modes: (1) imaging, (2) single object slitless spectroscopy (SOSS), (3) wide field slitless spectroscopy (WFSS), and (4) aperture masking interferometry (AMI).

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NIRSpec

Main articles: NIRSpec IFU Spectroscopy, NIRSpec Fixed Slits Spectroscopy

- The Near Infrared Spectrograph (NIRSpec) can be operated in 4 different observing modes: (1) multi-object spectroscopy (MOS), (2) integral field unit (IFU) spectroscopy, (3) fixed slits spectroscopy, and (4) bright object time-series (BOTS) spectroscopy.

- The primary NIRSpec modes for Solar System observations are IFU, fixed slits spectroscopy, and MOS configured into a long slit. The fixed slits have no covers and are always open; the ***ALLSLITS*** subarray can be used to simultaneously record spectra through all the slits, if desired. Both modes require targets with well-constrained orbital solutions for accurate placement in the science aperture. Any observations with the 0.2" fixed slit, and likely the 0.4" fixed slit, will require target acquisition (TA). Wide aperture target acquisition (***WATA***) for moving targets will use the S1600A1 fixed slit, so the uncertainties on the ephemeris must be small enough to first place the object in a 1.6" × 1.6" box.

- Multi-object spectroscopy (MOS) with the micro-shutter assembly (MSA) is available for moving target observations with a "pseudo long slit." These custom long slits are available in quadrant 4 (Q4) of the MSA and may be ideal for observations of comets, Mars, and the giant planets. Scanning of the entire disks of Mars and giant planets can be made by allowing the object to rotate and leaving the long slit fixed in the MSA. Scanning across the disk of Mars and the giant planets in a shorter period of time, or scanning across a comet, can be specified in the NIRSpec MOS template starting in APT 28.0. It should be noted that the proposed investigation in Norwood et al. (2016) to observe the Uranian satellites with the MSA is not feasible at this time.

References

Boccaletti, A., et al. 2015, *PASP*, 127, 633
The Mid-Infrared Instrument for the James Webb Space Telescope, V: Predicted Performance of the MIRI Coronagraphs
PDF, Univ. of Arizona

Buie, M. et al. HST program 13667
Observations of the Pluto System During the New Horizons Encounter Epoch

Kendrew, S., et al. 2015, *PASP,* 127, 623
The Mid-Infrared Instrument for the James Webb Space Telescope, IV: The Low-Resolution Spectrometer
PDF, Univ. of Arizona

Keszthelyi, L., et al. 2016, *PASP*, 128, 959
Observing Outer Planet Satellites (Except Titan) with the James Webb Space Telescope: Science Justification and Observational Requirements
arXiv

Norwood, J., et al. 2016, *PASP* 128, 960
Solar System Observations with the James Webb Space Telescope
arXiv

Rivkin, A. S., et al. 2016, *PASP*, 128, 959
Asteroids and the James Webb Space Telescope

Thatte, D., Sivaramakrishnan, A., Stansberry, J. 2015, *STScI Newsletter*, Volume 32, issue 02 (PDF)
Vulcanism on Io with Aperture Masking Interferometry on Webb's NIRISS

Wells, M., et al. 2015, *PASP,* 127, 646
The Mid-Infrared Instrument for the James Webb Space Telescope, VI: The Medium Resolution Spectrometer
PDF, Univ. of Arizona

Published	31 Jul 2017
Latest updates	• 21 Feb 2019 Changes made to NIRSpec section • 08 Nov 2018 Fixed nomenclature issue in NIRCam section. Fixed units in NIRISS section. • 27 Jun 2019 Fixed incorrect link.

Moving Target Supporting Technical Information

A list of articles providing additional details on moving targets.

Expand all Expand all Collapse all Collapse all

Published	29 Nov 2019
Latest updates	

Moving Target Overheads

Except for an additional overhead for guide star acquisition and tracking set-up, there are no other overheads exclusive to moving targets. Examples of general overheads for specific moving target observations are provided.

On this page

Guide star acquisition and tracking

Main article: JWST Guide Stars, Moving Target Acquisition and Tracking

Guide star acquisition and initiation of tracking for moving targets will incur a 90 s overhead. An additional 30 s will be applied for each dither. These overheads are unavoidable for all moving target observations.

Time critical observations

Any observations specified to occur within a short window is considered time critical and will incur an additional overhead. Please see Time Constrained Observations for more details. Examples for solar system targets include, but are not limited to, observing:

- an object at a specific date and time,
- an object at a specific rotational phase,
- an object at a particular phase angle,
- a satellite at a particular elongation or position angle, and
- a satellite during a transit or when in shadow.

See Solar System Special Requirements and Timing Special Requirements for complete lists of constraints available for moving target observations in APT.

It is recommended that efforts be taken to avoid making your observations time critical, but in some cases, the scientific program may require it. Careful consideration of science requirements can avoid this overhead.

If complete longitudinal coverage is desired for a quickly rotating body, remaining on the object during an entire rotational period is recommended. For example, full rotational coverage of Jupiter can be obtained in ~10 consecutive hours of observations and avoids the overhead because specific phases are not required.

Observations of faster moving objects (asteroids, NEAs, nearby comets, etc.) at specific phase angles are more likely to incur the overhead than observations of slower moving objects (Centaurs, KBOs, the giant planets, etc.).

⚠ The ***Phase*** special requirement and ***Central Meridian Longitude*** Solar System window can be used interchangeably for any targets with defined coordinate systems. However, keep in mind that the entire observation must occur within the window specified by a ***Central Meridian Longitude*** constraint, whereas the ***Phase*** constraint only specifies when the observation should begin. In other words, the schedulability window for the start time of an observation with a ***Central Meridian Longitude*** constraint will be reduced by the length of the observation; if the observation is longer than the specified window, it will not be schedulable. The ***Phase*** constraint thus increases schedulability, but there is a possibility that the observations will not actually occur between the desired rotational phases.

Target of opportunity (ToO) observations

Main articles: JWST Target of Opportunity Observations, JWST Target of Opportunity Program Activation

There are 2 different categories for ToO observations: disruptive and non-disruptive. These are discussed in more detail on the Target of Opportunity Observations page.

Making use of smart accounting

Main article: APT Smart Accounting

Smart Accounting is available for planning moving target observations. The **Smart Accounting**[*] tool looks at the full set of proposed observations in a proposal and decides which sub-groupings can logically be scheduled together to reduce the total amount of charged time for slewing; however, this does not guarantee that the observations will actually be scheduled together during execution. Without smart accounting, the slew time for each visit is set at 30 minutes (1800 s) by default. In reality, consecutive visits to the same target do not require 30 minutes of time to slew to the target because the observatory is already pointed at the target. Using Smart Accounting, the slew time overhead charged to the program can be significantly reduced. For example, an observation of Titan with the NIRSpec IFU followed right afterwards by an observation of Titan with the MIRI MRS would be charged 30 minutes for the initial slew to Titan for the NIRSpec observations and a significantly shorter time (<5 minutes) for switching instruments to MIRI, target acquisition, and re-acquiring a guide star.

To run smart accounting in APT, follow the instructions on the APT Smart Accounting page.

[*] ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Published	11 Jul 2017
Latest updates	• 16 Dec 2019 Linked to CfP pages and removed specifics for overheads. • 08 Nov 2018 Updated wording in the Smart Accounting section.

Moving Target Field of Regard

The JWST field of regard will constrain the time of year a target can be observed. Because Solar System targets and the observatory are moving with respect to each other, the duration of the visibility windows could differ significantly from the standard durations.

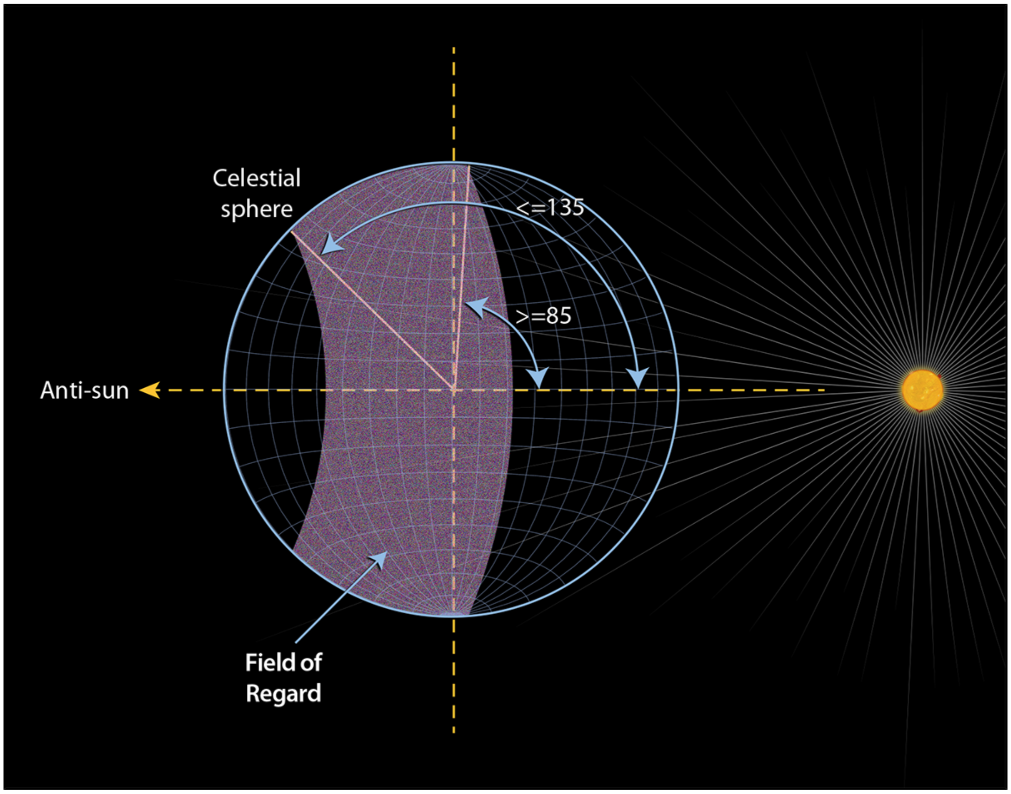
On this page

Field of regard

Main article: JWST Observatory Coordinate System and Field of Regard

The JWST field of regard (FOR) is the region of the sky where scientific observations can be conducted safely at a given time. The FOR is defined by the allowed range of boresight pointing angles for the observatory relative to the sun line, which must remain in the range 85° to 135° at all times to keep the telescope behind the sun shield. Thus, the FOR is a large torus on the sky that moves roughly 1° per day in ecliptic longitude, following the telescope in its path around the sun. Over time, this annulus sweeps over the entire celestial sphere. As a result of the FOR, JWST can observe about 39% of the full sky on any given day and can access 100% of the sky over 6 months. Figure 1 shows a schematic of the FOR.

Figure 1. The JWST field of regard



The JWST field of regard extends from a solar elongation of 85° to 135° and changes over time as the observatory orbits the sun. (Adapted from: JWST Mission Operations Concept Document, Figure 4.10.)

See JWST Observatory Coordinate System and Field of Regard for a more detailed look at the field of regard (FOR) and observatory pointing constraints.

Constraints on moving targets

The constraints on elongation angle define the time of year a target can be observed. The JWST field of regard can be thought of as a hemisphere with a hole in it. The hole is due to the need to avoid observing at or near the anti-solar point. This shape results in 2 observing windows each year for objects along the ecliptic, each ~50 days long. Again, due to the shape of the field of regard, the time between the end of the first window and the beginning of the second is ~90 days. The end of the second window is followed by ~170 days until the first window opens again.

These numbers are rough estimates for fixed targets and slow-moving objects near the ecliptic; actual window lengths and spacings depend on the distance from the ecliptic and the magnitude of the apparent motion. Generally, objects further from the ecliptic will have larger observing windows, and the slower the apparent motion of an object, the larger its observing window. We recommend that proposers determine the observing windows for their objects using JPL Horizons (option 23, Sun-Observer-Target ELONG angle, in the Table Settings page can be used to specify a range of solar elongation angles).

The following Solar System bodies can never be observed by JWST: the Sun, Mercury, Venus, Earth, and the Moon. These constraints also mean that Mars is observable only every other year.

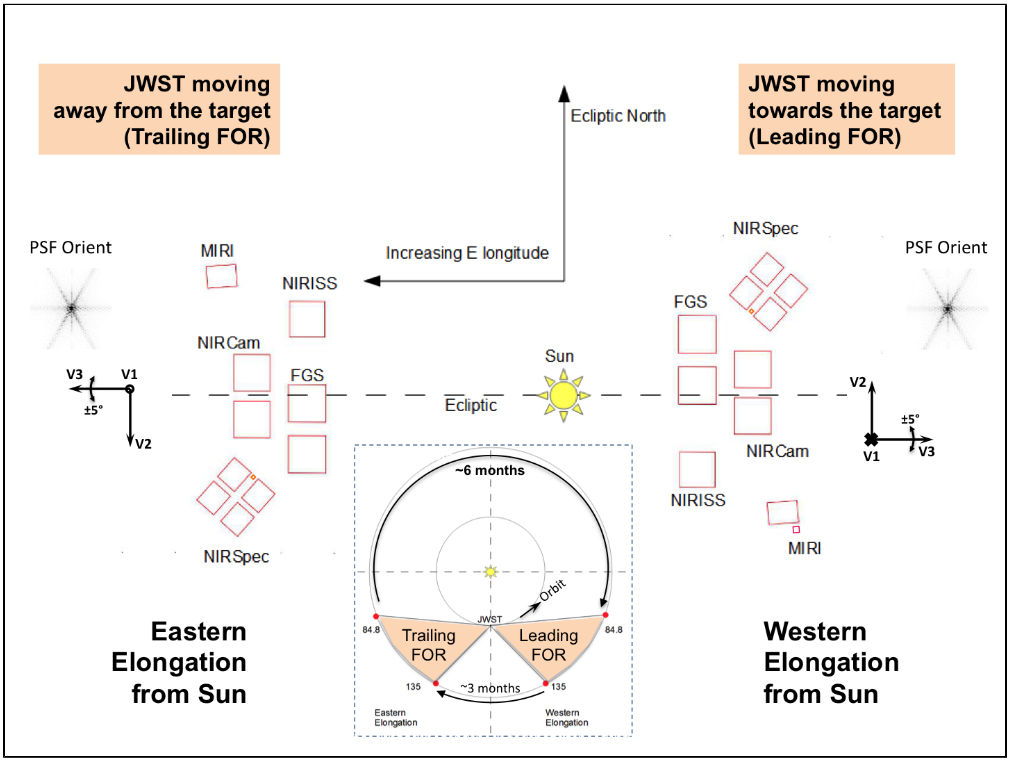
Instrument FOV orientations

Main article: JWST Field of View
See also: JWST Instrument Ideal Coordinate Systems; JWST Position Angles, Ranges, and Offsets

To evaluate the allowable position angles for the science instruments when observing moving targets, use the Moving Target Visibility Tool (MTVT).

The Aladin feature in APT does not present accurate orientations for the instrument FOVs; this is the case for observations of both fixed and moving targets. The default orientation in Aladin has the V3 direction parallel to equatorial north, which is never valid for observations of targets near the ecliptic. See Tutorial on Visualizing Dithers of a Solar System Observation in APT for a workaround.

Figure 1. JWST focal plane



Orientation of the JWST focal plane and instrument FOVs for observations in each section of the field of regard. The orientations shown above are the only 2 options for observations of objects along the ecliptic.

Published	11 Jul 2017
Latest updates	• 16 Dec 2019 Wording changes. • 08 Nov 2018 Added information on elongation angle option in JPL Horizons. Moved warning above figure. • Updated 06 Mar 2018 Added a sentence and link for the Moving Target Visibility Tool (MTVT).

Moving Target Ephemerides

Details of how JWST and APT obtain and use moving target ephemerides, how a proposer can obtain ephemerides using JPL Horizons, and how JWST's orbit affects ephemeris accuracy.

On this page

Using the orbital elements specified in APT and the relative positions of the guide star and the moving target, a 5th-order polynomial is constructed that describes the path of the *guide star* across the field of view of the Fine Guidance Sensor (FGS). The FGS then tracks the guide star along this path; this keeps the moving target fixed in the science instrument reference frame (see the Moving Target Acquisition and Tracking article for more details). Ephemeris data will not be included in the FITS headers, but pointing information obtained every 64 ms will be included, enabling a reconstruction of the target's motion across the sky (in RA/Dec coordinates). The heliocentric and observer distances will also be included in the FITS headers.

JWST in JPL Horizons

The observatory orbit will be updated after launch to reflect the actual launch date and the L2 halo orbit that is chosen. The halo orbit can differ substantially depending on launch date and course corrections, so ephemeris predictions even for main belt asteroids can be highly uncertain (up to 20') until the final JWST orbit has been determined. For trans-Neptunian objects, the initial ephemeris uncertainty will be around 1", but will become much smaller once the orbit of JWST is known.

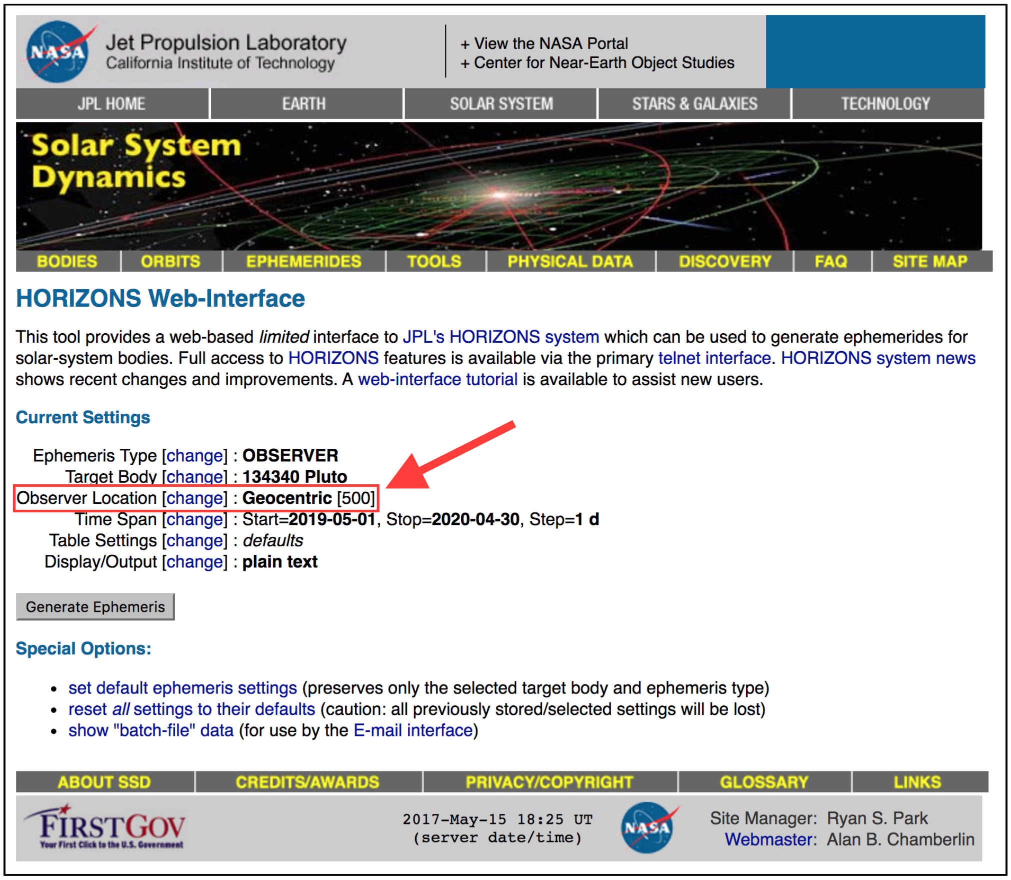
Station-keeping to maintain the observatory's orbit about the L2 point will be performed every 21 days. Therefore, it is expected that the updated JWST orbit from each station-keeping procedure will be sent to JPL and incorporated in Horizons roughly every 21 days. A description of the orbit and the station-keeping procedures can be found on the JWST Orbit page.

A nominal JWST orbit is available in the JPL Horizons ephemeris generation system. There are 2 ways to specify JWST as the ***Observer Location***[*] in Horizons: ***@jwst***, or the observatory code, ***500@-170***. Figures 1–3 provide a quick walkthrough for specifying the ***Observer Location*** in Horizons.

Step 1. JPL Horizons home page

On the main page of the JPL Horizons web interface, locate the ***Observer Location*** row, as highlighted in Figure 1. Click on ***change***.

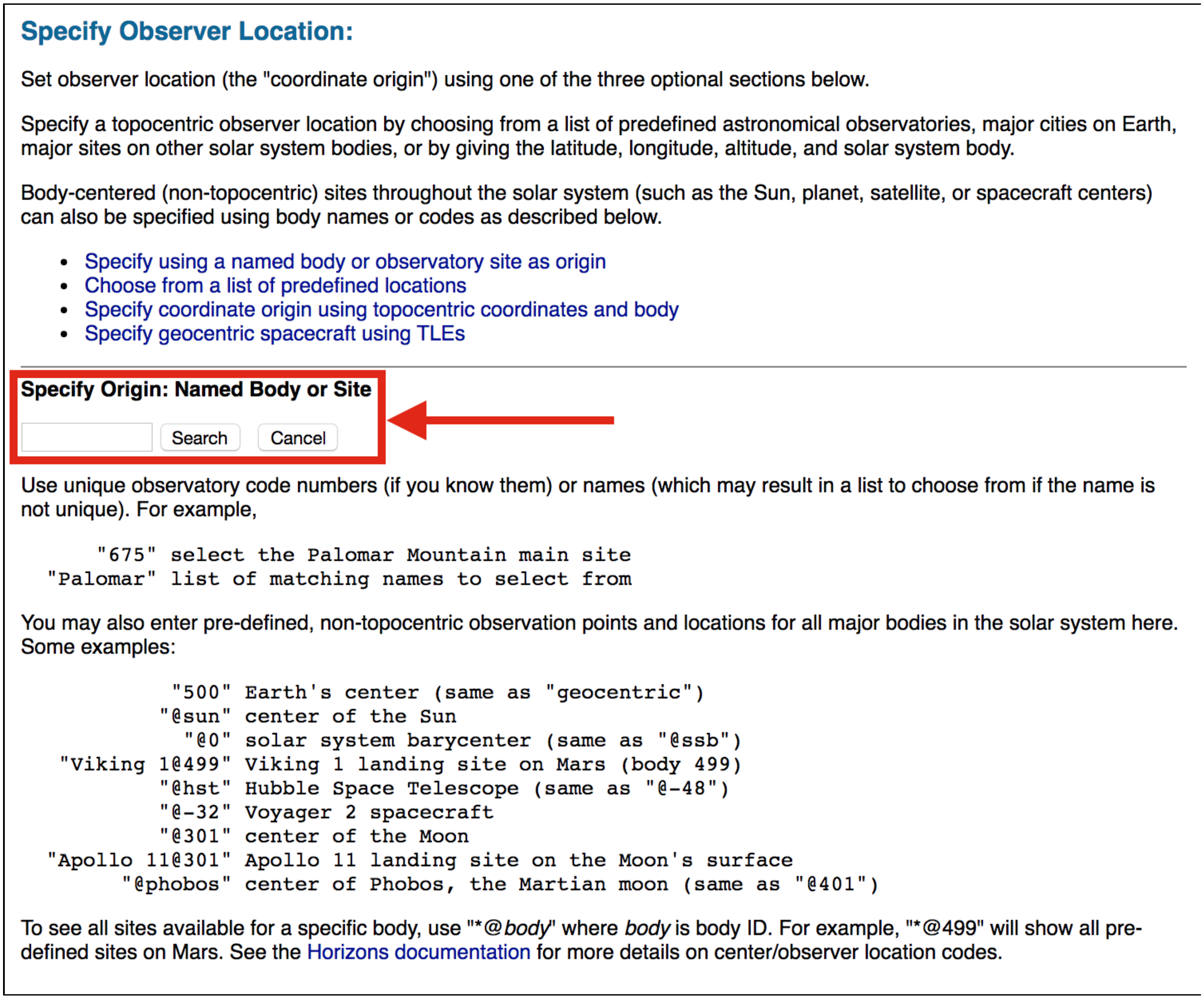
Figure 1. JPL Horizons home page



Step 2. *Observer Location* page

After clicking on ***change***, you will be redirected to the **Specify Observer Location** page. Locate the ***Specify Origin: Named Body or Site*** section and the search box. Input either ***@jwst*** or ***500@-170***, and click the ***Search*** button. Then, you will be redirected back to the main page.

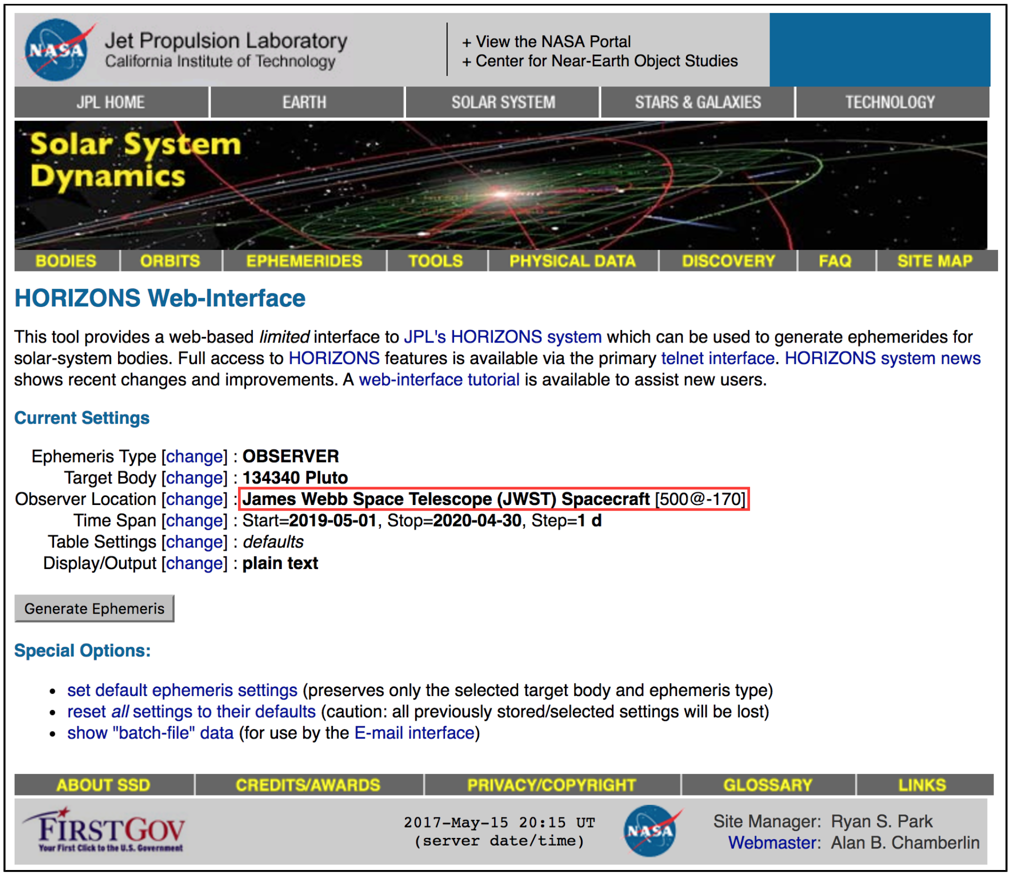
Figure 2. Specifying the observer location



Step 3. Check that *Observer Location* was updated

After being redirected to the main page, the ***Observer Location*** should have updated to read "***James Webb Space Telescope (JWST) Spacecraft [500@-170]***, as highlighted in Figure 3.

Figure 3. Observer location set to JWST.



* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Ephemerides and the APT Visit Planner

Video Tutorial:

APT Visit Planner

Main article: APT Visit Planner

The Visit Planner in the Astronomer's Proposal Tool (APT) uses orbital elements directly from JPL Horizons to construct ephemerides and determine observing windows. See the Tutorial on Creating Solar System Targets in APT for step-by-step instructions on obtaining orbital parameters for any moving target.

References

JPL Horizons web interface

Published	11 Jul 2017
Latest updates	• 16 Dec 2019 Added video link, made minor wording and formatting changes.

Moving Target Calibration and Processing

The JWST calibration pipeline has the ability to co-add moving target exposures. Many steps in the pipeline are identical for moving and fixed targets; steps specific to moving targets are outlined on this page.

On this page

Main article: JWST Data Reduction Pipeline

JWST's science instrument calibration pipeline will support co-addition of moving target exposures. The calibration pipeline outputs products at 3 levels, with the unique steps for moving targets outlined below for each level.

Calibration pipeline level 1

Level 1 processing includes data formatting, science frame re-orientation, and calculation of WCS keyword values. For moving targets, the WCS is expanded to include 4 moving target keywords per integration and 2 additional keywords per observation. The first unique moving target keyword is created by triggering the moving target flag in APT: `MTWCS` (moving target world coordinate system).

The right ascension and declination values of the reference pixel at the mid-time of the *observation* are recorded with the following keywords:

- `RA_REF0`
- `DEC_REF0`

The right ascension and declination values of the reference pixel at the mid-time of *each integration* are recorded with the following keywords:

- `RA_REF`
- `DEC_REF`

Then the following keywords are calculated using the standard WCS keywords `CRVAL1` and `CRVAL2`:

- `CRVALMT1 = CRVAL1 + (RA_REF0 - RA_REF)`
- `CRVALMT2 = CRVAL2 + (DEC_REF0 - DEC_REF)`

Dither and mosaic offsets are preserved.

Calibration pipeline level 2

Level 2 processing, or single exposure calibration processing, outputs calibrated single exposure count rate images. These steps are very similar to those for fixed targets, since the moving target is essentially "fixed" to the detector frame through telescope tracking. One unique consideration for moving targets is that the stars trail through the scene. The trails can cause transient increases in detected signal in the pixels they cross. In Cycle 1, these transient signals will be treated as cosmic rays in the ramps-to-slopes.

Calibration pipeline level 3

Level 3 processing combines the Level 2 products through co-adding exposures and mosaicking. For moving targets, co-addition of exposures occurs in the target's co-moving frame. The pipeline will accomplish this by implementing existing fixed target algorithms, and instead of the normal WCS, using the unique moving target's WCS data. *Hershel* and *Spitzer* applied this approach and proved it workable; however, it was never implemented for the HST pipeline. Both imaging and spectroscopy will be supported.

Published	11 Jul 2017
Latest updates	• 16 Dec 2019 Minor wording and formatting changes.

Moving Target Policies

Science requirements for moving targets, as well as brief descriptions and links to appropriate pages about policies that affect moving target observing programs.

On this page

Science requirements for moving targets

JWST must be able to observe solar system targets when they move relative to the guide star at rates up to 0.030"/s (30 mas/s or 108"/hour). This will provide access to Mars and all of the more distant planets and their moons, asteroids, KBOs, and most comets over some part of their orbit (typically when a comet is more than 2 or 3 AU from the Sun; see Kelley et al. 2016). Precise trajectories are needed at the angular resolution of the observatory to avoid loss of angular resolution and to enable placing the moving targets on specific NIRSpec slits or the MIRI spectrometer field of view. It is recognized that the image quality requirements will have to be relaxed slightly while tracking moving objects, and that exposure times (or the track paths) will be limited by the path of the guide star. There are no requirements to track accelerating objects (curved trajectories), to track objects continuously as the guide stars cross sensor chip boundaries, to have special guide star availability, or to observe in any special orientations (Science Requirements Document, pg. 7-8).

"When commanded, the Observatory shall compensate for the apparent motion of a moving target which exhibits an angular velocity between 0 and 30 mas/s with respect to a guide star that remains within a single Fine Guidance Sensor field of view." (SR-31, Science Requirements Document, pg. 8-7)

Target of opportunity (ToO) policy

Main article: JWST Target of Opportunity Observations

The proposer should be aware that only a small number of disruptive target of opportunity activations will be allowed during any particular cycle due to their effect on the schedule. See Target of Opportunity Observations for a more thorough description of the ToO policy for JWST.

Duplication policy

Main article: JWST Duplicate Observations Policy
See also: JWST Duplication Checking

Observations of the same target with the same instrument and mode are considered duplicate observations. Duplicating an observation is typically discouraged unless the target shows intrinsic variability or a large-time baseline is needed to achieve the science goals.

Example of an *encouraged* duplication: Annual NIRSpec IFU observations of Jupiter's Great Red Spot.

Example of a *discouraged* duplication: Duplicate observations of a small asteroid with the NIRSpec IFU to increase the signal-to-noise ratio of a spectrum obtained with JWST in a previous cycle.

See JWST Duplication Checking for how to check for duplicate observations. Keep in mind that target/mode combinations in Guaranteed Time Observation (GTO) and Early Release Science (ERS) programs are subject to these policies in Cycle 1.

Moving target-specific overheads

Main article: JWST Observing Overheads Summary

See the Moving Target Overheads article for a description of general overheads that apply to moving target observations.

References

Kelley, M.S.P., et al. 2016, *PASP*, 128, 018009 (arXiv)
Cometary science with the James Webb Space Telescope

James Webb Space Telescope Project, Science Requirements Document (July 10, 2012)

Published	11 Jul 2017
Latest updates	• 16 Dec 2019 Updated links.

	• 27 Jun 2019 Fixed in-text links. • 08 Nov 2018 Added wording about GTO and ERS to duplication policies section

Moving Target Useful References and Links

A collection of links to moving target-specific APT files, ETC workbooks, peer-reviewed publications, and webcasts

On this page

Example APT files

GTO & ERS

APT files from the Guaranteed Time Observations (GTO) programs are currently available at the Guaranteed Time Observations webpage.

APT files from the Early Release Science (ERS) programs are currently available at the Early Release Science webpage.

APT files can also be downloaded from APT using the tool's main menu: *File* → *Retrieve from STScI* → *Retrieve using Proposal ID*, then enter the proposal ID in the pop-up box, and click *OK*. Proposal IDs for the solar system GTO and ERS programs can be found at the links above and on the GTO & ERS 2-page flyer.

JWST Demonstration proposals

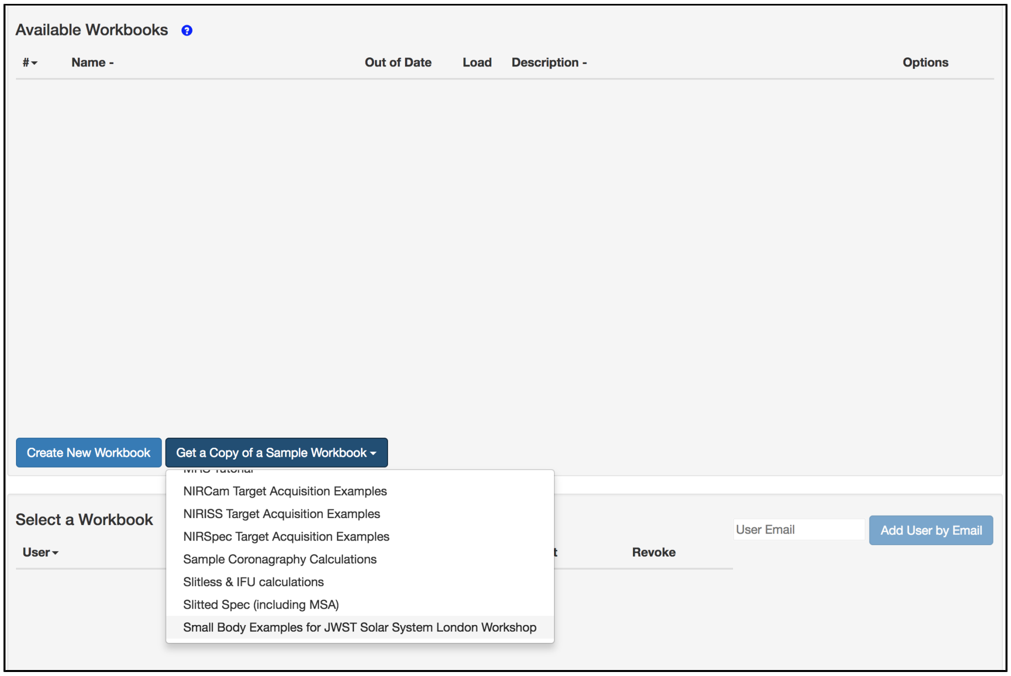
An example APT file for observations of Solar System objects can be found in the APT tool (starting in APT 25.4.1), from the main menu under *File* → *JWST Demonstration Proposals* → *Solar System Example*. This example file includes observations of minor bodies, comets, satellites, and giant planets using the instruments and modes most suitable for Solar System programs.

Example ETC workbook

Main article: JWST ETC Using the Sample Workbooks

There is currently one example workbook for solar system observations available in the JWST ETC. See the figure and caption below for instructions on how to access this workbook.

Figure 1. Using sample workbooks



Sample workbooks can be accessed on the Available Workbooks[*] page immediately after logging into the ETC (or choosing to work anonymously), as shown above. Simply click on the Get a Copy of a Sample Workbook drop down menu and select "Small Body Examples for JWST Solar System London Workshop" for a solar system example workbook. Then click the Load button after it is added to your available workbooks.

[*] ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Published reports

Magnum, J., ed. 2016, *PASP*, 128, 959
Special Issue: Innovative Solar System Science with the James Webb Space Telescope
PDF

Norwood, J., et al. 2016, *PASP*, 128, 960
Solar System Observations with the James Webb Space Telescope
arXiv

Webcasts and presentation packets

October 16-21, 2016: JWST at the 48th Annual Division for Planetary Sciences (Joint with EPSC) Meeting

February 7, 2017: Solar System Community Webinar: JWST Early Release Science Program

February 14, 2017: JWST Community Lecture Series - Observing Solar System Targets with JWST

November 13-15, 2017: Planning Solar System Observations with JWST - STScI venue

December 13-15, 2017: Planning Solar System Observations with JWST - ESTEC venue

February 13, 2018: Planning Solar System Observations with JWST in Cycle 1

October 21-26, 2018: JWST at the 50th Annual Division for Planetary Sciences Meeting

Published	11 Jul 2017
Latest updates	• 08 Nov 2018 Updated the figure for ETC v1.3. Added links to GTO & ERS APT files and presentations that occurred since the last update of the article.

JWST Parallel Observations

Some capabilities to use more than one science instrument simultaneously (in parallel) will be available for JWST Cycle 1. Additional instrument combinations may be offered in future cycles.

On this page

Parallel observing refers to simultaneously operating more than a single science instrument, each viewing a different area of the JWST focal plane. For JWST, there will be 2 basic modes of parallel operations: *coordinated parallels* and *pure parallels*.

Coordinated parallel observations are planned as part of a primary program, and are intended to amplify or supplement the primary science proposed in a given proposal. That is, the primary and parallel observations are planned together in a single program to accomplish the science goals, and hence are under the purview of a given proposal PI and science team.

Pure parallel observations are from programs that make use of parallel observing slots derived from other accepted proposals. Hence, pure parallel programs are separate proposals, have separate PIs, and are selected independently from any primary programs they may be attached to. It is expected that many calibration observations will be obtained using pure parallel opportunities, but there will be openings for pure parallel science observations as well.

There are a number of subtleties related to each of these modes of operation. For example, pure parallel observations are not permitted to impact or change the primary observations to which they are attached (with one exception described below), whereas coordinated parallel observations can be tailored to accommodate both the primary and parallel datasets since they are specified within a given proposal. (For example, dither patterns that work well with both instruments can be selected.) These subtleties are described below.

The goal of enabling parallel observing is to enhance the efficiency and science return of the JWST mission. However, users need to be aware that there are tradeoffs that need to be balanced. Not every potential parallel observing opportunity can be used for science. One example is the limited data downlink capability available to the observatory. For example, running NIRCam by itself in certain readout modes for several hours can use the entire data volume downlink capacity for a single contact period, leaving no room for storing parallel data taken during that period. Another consideration (for pure parallels) is that many calibration activities need to use pure parallel observing slots, and parallel calibration activities may take precedence over pure parallel science.

Only certain modes and combinations of instruments will be allowed for cycle 1 proposals (see below). Additional combinations may be made available in future observing cycles.

Principles in the use of parallel observing with JWST

Main article: JWST Science Parallel Observation Policies and Guidelines

A detailed description of the policies related to JWST parallel observing is available. In summary, there are 3 principles that govern the policies for proposing and planning parallel observations:

1. For coordinated parallels, the science goals of the parallel observations must be tightly linked to the science goals of the overall program. In other words, accomplishing the main goals of the proposal requires parallel observations. Coordinated parallels whose goal is to address ancillary topics will generally not be approved.

2. Pure parallel observations may not impact the primary observations they are attached to[†]. This means pure parallel exposures must fit under the resource footprint (exposure plus overheads) of the primary exposure to which they are attached.

3. The needs of the JWST calibration program, a large fraction of which takes place in parallel mode, take precedence over pure parallel science programs.

[†] As a practical matter, adding pure parallels will add a small additional overhead for setting up the instruments. This will be handled by the scheduling system and will not be assessed post-facto as an overhead on the primary observations. Further discussion of policies can be found in the Call for Proposals.

Coordinated parallels

Main article: APT Coordinated Parallel Observations
See also: JWST Position Angles, Ranges, and Offsets, JWST Background Model, JWST Data Rate and Data Volume Limits, JWST General Target Visibility Tool Help

Coordinated parallel observations are crafted within the APT template used for the primary instrument mode. Five template combinations were supported at the time of ERS proposing, but 3 additional modes have beed added for Cycle 1, as shown in Table 1.

Table 1. Template combinations supported for ERS (1-5) and cycle 1 observations

Ref. no.	First (Primary) template	Second (Parallel) template	Comments

1	NIRCam imaging [1]	MIRI imaging[1]	Either template can be selected as primary, with the other as parallel.
2	NIRCam imaging [1]	NIRISS WFSS	Either template can be selected as primary, with the other as parallel.
3	MIRI imaging	NIRISS WFSS	Either template can be selected as primary, with the other as parallel.
4	NIRCam imaging [1]	NIRISS imaging	NIRCam must be primary. Use to increase areal coverage, but note NIRISS differences in pixel size and available filters.
5	NIRSpec MOS	NIRCam imaging	NIRSpec MOS must be primary.
	(Modes added January 2020)		
6	NIRCam WFSS	MIRI Imaging	NIRCam WFSS must be primary.
7	NIRCam WFSS	NIRISS Imaging	NIRCam WFSS must be primary.
8	NIRSpec MOS	MIRI Imaging	NIRSpec MOS must be primary.

[1] Only direct imaging with standard narrow-, medium-, or broadband filters is allowed for NIRCam and MIRI observations in these coordinated parallel modes.

Instrument teams have worked with developers to provide several ways of scheduling joint observations in parallel, for instance, to designate one instrument as the primary, as shown in options 1–3 in Table 1.

One anticipated use case is to use both instruments at one epoch to observe adjacent areas of the sky, and to return at a second epoch when the instrument fields of view have rotated 180° on the sky. Users should obviously investigate the availability of the relevant position angles using the JWST target visibility tools since not all positions on the sky have the needed flexibility in available position angles to accommodate this strategy. Users should also be aware that background levels due to zodiacal emission and thermal emission from the telescope will change between two observations at different position angles. However, other science cases may not require such a "180° strategy" and can simply obtain observations (e.g., with NIRISS WFSS) of a nearby areal region to accompany NIRCam or MIRI primary imaging observations.

All dither patterns available for a given instrument template will also be available when it is selected as the primary instrument in coordinated parallel mode. However, you also have the option to select from sets of customized dither patterns that have been specifically designed to produce good results for both instruments simultaneously. The number and type(s) of customized dither patterns that are available depend on the specific prime+parallel instrument mode combination. When a parallel instrument is selected, these additional dither patterns will become available in the dither pull-down menu in the relevant APT template.

Issues regarding data volume per downlink period should also be considered, especially for options involving NIRCam. Since NIRCam observations involve up to 10 detectors (8 short wavelength and 2 long wavelength), proposers of coordinated parallel programs may need to consider selecting readout patterns that are less data intensive than they might otherwise choose. (Some of the most data intensive readout patterns for NIRCam are disallowed by APT in parallel mode.) Alternatively, depending on the science use case, a user may decide that areal coverage is less important than the parallel coverage and may opt to use only one of the two NIRCam modules. APT will compute and display the data volume for each exposure, and you can adjust the detector readout pattern and/or the number of modules being read out as needed to stay within the allowed limits.

A number of additional coordinated parallel options are being considered for future cycles, including the possibility of using up to 3 instruments simultaneously.

Pure parallels

Main article: APT Pure Parallel Observations

Unlike coordinated parallels, pure parallel observations are proposed as entirely separate programs of investigation. Pure parallels use parallel observing "slots" created by exposures from other accepted programs that do not already have parallel observations specified. Pure parallel observations will not be allowed to influence the dither patterns or other aspects of the observing strategy of the primary observations to which they are attached, since the primary observations will belong to different science proposals. There are 4 observing modes supported for pure parallel observations in Cycle 1:

MIRI imaging, NIRCam imaging, NIRISS imaging, and NIRISS WFSS.

Not all observing templates will be allowed to host pure parallel observations, for various technical reasons or concerns about how a pure parallel observation could potentially impact the data quality of the primary.

Templates that *are allowed* to have pure parallels attached are the following:
NIRCam imaging, NIRCam WFSS, MIRI imaging, NIRSpec MOS, NIRSpec IFU, NIRSpec fixed slits, NIRISS WFSS, MIRI MRS, and MIRI LRS (the latter only if Subarray = FULL).

Templates that *are not allowed* to have pure parallels attached are the following:
NIRCam time series, NIRCam grism time series, NIRCam coronagraphy, NIRSpec bright object time series, NIRISS AMI, NIRISS SOSS, MIRI coronagraphy, and MIRI LRS (if Subarray = SLITLESSPRISM).

The NIRISS WFSS mode requires direct imaging exposures before and/or after the dispersed grism spectral exposure to obtain images of the undispersed field. Hence, to obtain such a *set* of exposures in a pure parallel mode, appropriate *double or triple* slots will need to be identified to attach these observations.

Published	30 Mar 2017
Latest updates	• 02 Jan 2020 Final updates for 2020 cycle 1. • 14 Nov 2019 Added new coordinated parallel modes for Cycle 1. • 11 Oct 2019 Added allowed pure parallel modes for Cycle 1; other minor edits. • 08 Feb 2018 Made changes for consistency with current parallel capabilities being offered in Cycle 1. Removed Table 2 and streamlined listing in the text.

Coordinated Parallels Roadmap

A step-by-step guide through the process of adding coordinated parallel observations to an observing program for JWST.

> ⚠ Coordinated parallel observations must be scientifically justified. See the NASA policy for coordinated parallels.
>
> Not all instrument pairings are allowed, and in some cases, the primary and parallel instruments are not interchangeable. See the allowed pairings.

Coordinated parallel observations involve adding a second instrument in parallel with existing primary observations as part of the same proposal. Since the observations occur simultaneously, the two instruments will be pointing at different offset positions on the sky, depending on the instruments and modes selected (see JWST Field of View).

In this roadmap, you will be guided through the process of adding a coordinated parallel observation to a primary observation in APT. This roadmap prompts you with questions or directs you to make choices and provides links to relevant JDox articles. By policy, coordinated parallel observations must be scientifically justified; see NASA policy for coordinated parallels for more information.

Since coordinated parallel observing uses multiple instrument modes simultaneously, consider using the the "quick look" JWST Interactive Sensitivity Tool (JIST) to obtain a sense of the signal-to-noise and exposure time parameter space you may obtain with the same exposure time in both instrument modes you select.

> ⓘ Using the NIRISS WFSS (slitless grism) mode in parallel**:** specifying this mode in parallel is complicated by the need to take additional direct images before and/or after the parallel grism exposures. This requires the addition of short "primary" exposures to handle the needed extra parallel exposure slots. If using one of these modes, see the worked example of handling this situation.

Specifying coordinated parallel observations

Here are questions and decision points to help you plan JWST coordinated parallel observations:

- What instrument pairing is needed for your science, and which instrument will be specified as “primary” or “parallel”? Even if both instruments are equally important, one must be specified as the primary in the Astronomers Proposal Tool (APT).
  Not all instrument pairings are allowed, and in some cases, the primary and parallel instruments are not interchangeable.
  Check the allowed pairings.

- Work with the Exposure Time Calculator (ETC) to understand the relative exposure times needed for both instrument configurations you want to use. Select the instrument requiring longer exposures to be your primary instrument since your parallel instrument exposures need to fit within the primary exposure times.

- Understand what you plan to do with dithering. Most imaging parallel modes have dither patterns that will work for both instruments. These are selectable within the APT observing templates once your primary and secondary instruments are specified.
  Parallel observations taken with NIRSpec MOS primary observations must adopt the MOS dither or nod pattern. See the APT coordinated parallel article where this is discussed.

- Enter the information for the primary instrument exposure specifications into the appropriate APT observing template. If this is an imaging mosaic, you may want to verify mosaic details by using the Aladin visualization tool.
  Verify the schedulability of your primary observation with the APT Visit Planner and address any scheduling issues prior to adding your desired coordinated parallel specifications.

- Find and select the ***Coordinated Parallel***[*] checkbox in the APT observation template of your primary observation. Then select the desired parallel instrument and mode from the pull-down choices.

- Open the parallel instrument's tab in the observing template and fill out the exposure specifications for your parallel instrument. There needs to be a one-to-one match between primary and parallel exposures. Hint: hover the cursor over any red X's in APT for help in resolving any errors reported.

- Once errors are resolved, run the Visit planner again to verify schedulability of the combined observations.

Go to the Getting Started Guide to complete the steps for proposal submission.

[*] ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

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Latest updates	

Coordinated Parallels Custom Dithers

For coordinated parallels, additional customized dither patterns are available to mitigate bad pixels and support good subpixel dithering for both instruments. The selection options appear in the dither selection of the primary instrument.

On this page

Main articles: JWST Dithering Overview, APT Coordinated Parallel Observations

When you specify coordinated parallel observations, additional dither pattern selections appear in the Astronomer's Proposal Tool (APT) dither list for the instrument designated as the primary. These custom dither patterns have been designed to work well for both the primary and the selected parallel instrument mode. There are specific dither pattern choices for different combinations of prime and parallel instruments.

Custom dither patterns improve the effective spatial resolution of the final combined (drizzled) images for both the prime and the parallel instruments by providing mitigation of bad pixels and flat field uncertainties, while also providing subpixel sampling.

For all coordinated prime+parallel mode combinations, the custom dither patterns involve non-zero steps along both detector axes (x and y) such that none of the dithers fall on the same detector row or column. Each dither constitutes an integer plus a fractional pixel (subpixel) step. The integer pixel component of the dither step mitigates bad pixels and flat field uncertainties, while the fractional pixel component improves PSF sampling and achievable spatial resolution in the combined image.

The sections below describe the general philosophy behind these dither patterns, followed by the specifics for the different instrument combinations.

General determination of customized dither pattern steps

Subpixel sampling of the customized dither patterns

The fractional pixel components of the dither patterns are chosen to sample the 2-D pixel phase in a nearly optimal way, with better subpixel sampling for patterns with more steps. Custom patterns have been designed with 2, 3, 4, and 9 steps. The desired subpixel shifts are listed in Table 1.

Table 1. Fractional pixel component of customized dither patterns

Number of dithers	Pixel phases (x, y)			
2	(0.00, 0.00)	(0.50, 0.50)		
3	(0.00, 0.00)	(0.33, 0.33)	(0.67, 0.67)	
4	(0.00, 0.00)	(0.00, 0.50)	(0.50, 0.00)	(0.50, 0.50)
9	(0.00, 0.00)	(0.33, 0.00)	(0.67, 0.00)	
	(0.00, 0.33)	(0.33, 0.33)	(0.67, 0.33)	
	(0.00, 0.67)	(0.33, 0.67)	(0.67, 0.67)	

Determination of dither step sizes

Dither step sizes take into account the detector properties of the prime and parallel instruments:

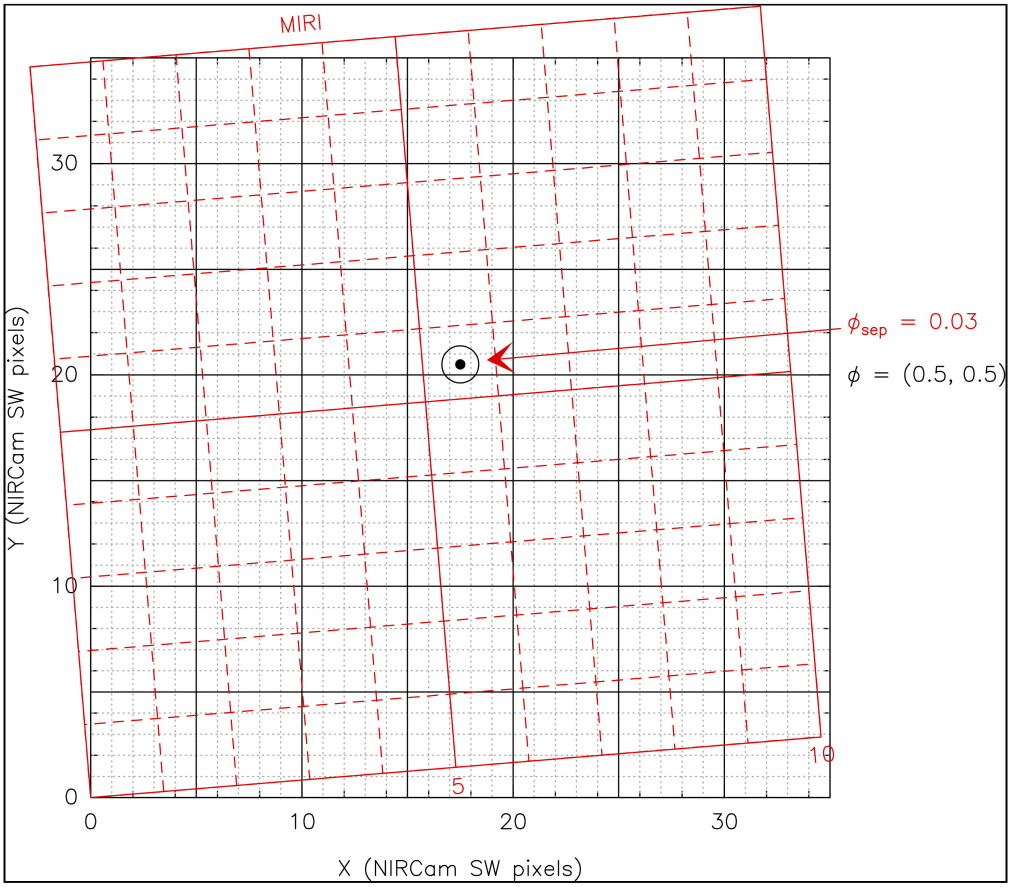
1. their relative orientation in the JWST focal plane (as measured during the 3rd cryovacuum test performed at GSFC during the summer of 2016), and
2. their (mean) pixel sizes in units of "/pixel.

For the prime instrument, the customized dither patterns nominally place the target on the exact pixel phases listed in Table 1. For the parallel instrument, target placement is generally precise to within a radius of 0.05 pixels. This radius is similar to the nominal pointing uncertainty of small angle maneuvers with JWST, which is 5 mas. Exceptions to this general rule are noted in the following sections.

The customized dither patterns provide several choices for the overall size of the pattern. The largest sizes will be best for mitigating flat-fielding uncertainties, especially for extended objects. However, due to the geometric distortions of the images, the subpixel phases will vary more across the detector for the larger patterns. Also, there is less detector overlap after image combination for the larger patterns. Therefore, the choice of pattern is a compromise that will depend on the specific goals of the observations.

Figure 1 illustrates a 2-step dither pattern that works well for NIRCam imaging + MIRI imaging. The MIRI detector pixel array has an orientation on the sky that's offset by ~4.76° counter-clockwise with respect to that of the (average[1]) NIRCam detector. It is shown in red on top of the black NIRCam shortwave (SW) detector pixel array. The encircled black point shows a dither of size (17.50, 20.50) in NIRCam SW pixels, which yields an offset of (5.516, 5.469) in MIRI pixels. The latter is within a radius of 0.034 pixels, of the goal of (0.50, 0.50) in fractional pixels.

Figure 1. Illustration of the determination of step sizes of custom dither patterns



The MIRI detector pixel array (with 0.11" pixels) is shown in red on top of the NIRCam shortwave detector array (with 0.031" pixels, shown in black). The encircled black dot represents a dither step that yields a pixel phase () of (0.5, 0.5) for both instruments (exactly for NIRCam and to within 0.03 pixels for MIRI).

[1] The "average" refers to the average orientation on the sky of the 10 NIRCam detectors.

Instrument-specific requirements for customized dithers

The requirements outlined below specify the factors that were used in designing the customized parallel dithers for each instrument.

NIRCam requirements

Main article: NIRCam Overview

The PSF undersampling is most severe in the short wavelength (SW) channel of NIRCam: up to a factor ~3 with the F070W filter (versus up to a factor ~1.5 for the F277W filter in the long wavelength (LW) channel). As such, the custom dither patterns for all combinations involving NIRCam were designed to provide optimal benefits for the 0.031" pixels in the SW channel of NIRCam.

For combinations in which NIRCam is the parallel instrument, the requirement that a given pixel phase is reached to within 0.05 pixels for the parallel instrument is softened to 0.11 pixel. Since the pixel size of the NIRCam SW detectors is so small, the resulting misplacement is still smaller than the nominal pointing uncertainty of small angle maneuvers with JWST.

An additional requirement from NIRCam is that dithers cannot be placed within 2 pixels in X and Y of any other point in the same dither pattern.

MIRI requirements

> *Main article: Mid Infrared Instrument*

Dithering for MIRI imaging requires that the distance between all steps in a dither pattern is at least 3 times the FWHM of the PSF (mainly to avoid overlap with latent images from preceding exposures). Since the size of the MIRI PSF changes significantly among the various MIRI filters, all custom dither patterns involving MIRI have been established specific to the selected MIRI filter.

For combinations in which MIRI is the parallel instrument, the requirement that a given pixel phase is reached to within 0.05 pixel for the parallel instrument is only enforced for MIRI filters with central wavelengths <10 μm (i. e., for MIRI filters F560W and F770W). This is because the MIRI PSF is well sampled at longer wavelengths.

An additional requirement for MIRI is that dithers cannot be placed within 2 pixels in X and Y of any other point in the same dither pattern.

NIRISS requirements

> *Main article: Near Infrared Imager and Slitless Spectrograph*

The only specific requirement for NIRISS is that dithers cannot be placed within 2 pixels in X and Y of any other point in the same dither pattern.

NIRSpec requirements

> *Main articles: Near Infrared Spectrograph, NIRSpec Multi-Object Spectroscopy*

Customized dither patterns are offered for the NIRSpec MOS + NIRCam imaging combination. For this case, the main restriction on dither size is to keep the NIRSpec science targets positioned near the nominal center of the NIRSpec MSA shutters to minimize additional aperture throughput losses. As such, the requirement that a given pixel phase is reached to within 0.05 pixels for the parallel instrument is *not* enforced for this combination.

Instead, 3 subpixel dither step sizes are offered for the user to choose from. The relative pixel phases reached by the dither patterns for this combination are illustrated in the article on Coordinated Parallel Dither Tables.

ASCII tables of customized dither patterns

Users may want to study the characteristics of the dither patterns customized for coordinated parallels in detail prior to selecting the most appropriate pattern for their needs. The patterns are available as ASCII tables at this page: Coordinated Parallel Dither Tables. All pointing offsets are relative to the reference position of the selected prime instrument's aperture ideal coordinate frame.

Published	30 Mar 2017
Latest updates	• 05 Dec 2019 Minor update to the NIRSpec Requirements section. • 08 Feb 2018 Minor updates and text clarifications. • 22 Nov 2017 Minor updates and link changes for Nov. 30, 2017 release.

Coordinated Parallel Dither Tables

Custom dither tables for JWST coordinated parallel observations are available to help users select appropriate dithers for their observations.

Main article: JWST Dithering Overview, APT Coordinated Parallel Observations
See also: JWST Instrument Ideal Coordinate System

ASCII files containing spatial offsets for dither patterns for coordinated parallel observations are available to users who want to study the characteristics of dither patterns in more detail, prior to selecting the appropriate pattern for their needs.

Spatial offsets are given in units of arcsec, as well as in pixels of the prime and parallel instruments (see file headers). All offsets are relative to the reference position of the selected aperture of the prime instrument, in that aperture's ideal coordinate system.

Tables are provided in two formats, as described below. In both cases, abbreviations for the instruments are as follows: MIR = MIRI, NIS = NIRISS, NRC = NIRCam, and NRS = NIRSpec.

File names have the following format:

1. *APT_<Prime Instrument>_<Parallel Instrument>.txt* tables list all dither patterns for the prime-parallel instrument combinations in the file name. The spatial offsets for each dither pattern are preceded by a line stating the name of the dither pattern in question.

2. <Prime Instrument>_<Parallel Instrument>_dithers.zip are zip files containing tables for all individual dither patterns in ASCII format for those prime-parallel instrument combinations.

For prime-parallel combinations involving NIRCam and NIRISS (or vice versa), the names of dither patterns for *small*, *medium*, and *large* spatial offsets are preceded by a character line ending in *S*, *M,* and *L*, respectively. The small dither offsets are typically <0.4", the medium ones are ~0.6", and the large ones are ~1.0". Note: dithers with small offsets are not available for all custom patterns.

For prime-parallel combinations involving MIRI, names of dither patterns are listed at the MIRI filter level, with syntax *MIR* followed by the filter's central wavelength in tenths of microns. Only *wide* MIRI filters are considered in this context. Example: dither patterns calculated for MIRI's F1280W filter have names with the characters *MIR128*. Note: not all custom dither patterns are available for all MIRI filters. If the pattern you are interested in is not available for a given MIRI filter, using the pattern for a filter at the next longer central wavelength is recommended (e.g., use F770W instead of F560W, F1280W instead of F1130W, etc.).

For the prime-parallel combination NIRSpec MOS + NIRCam Imaging, the dither patterns come in 3 offset sizes (size1, size2, and size3). These constitute "secondary" dither patterns which are executed at each NIRSpec MOS "nod" (the latter are moves from one shutter in the Multi-Shutter Array to an adjacent one "above" or "below" it). The zip file "NRS_NRC_dithers.zip" contains tables that list the resulting dither offsets for the cases of 2 and 3 NIRSpec "nods". The names of the latter tables are "<dither pattern name>.2nods.txt" and "<dither pattern

name>.3nods.txt" for 2 and 3 NIRSpec nods, respectively. The relative NIRCam pixel phases populated by these dither patterns are illustrated in Figure 1 below.

Tables with all dither patterns for a given prime/parallel instrument combination:

APT_MIR_NIS.txt

APT_MIR_NRC.txt

APT_NIS_MIR.txt

APT_NIS_NRC.txt

APT_NRC_MIR.txt

APT_NRC_NIS.txt

APT_NRS_NRC.txt

Zip files containing tables of all individual dither patterns for a given prime/parallel instrument combination:

MIR_NIS_dithers.zip

MIR_NRC_dithers.zip

NIS_MIR_dithers.zip

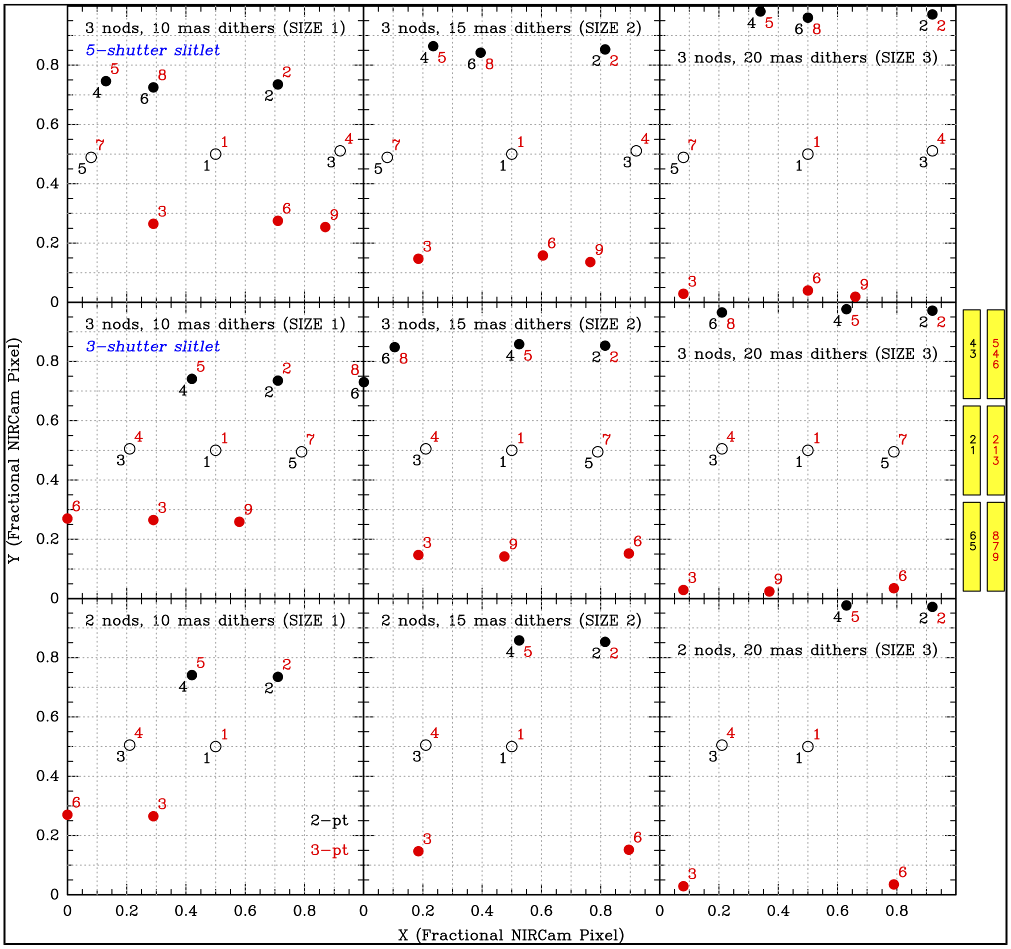
NIS_NRC_dithers.zip

NRC_MIR_dithers.zip

NRC_NIS_dithers.zip

NRS_NRC_dithers.zip

Figure 1. NIRCam/SW pixel phases covered by custom dither patterns for NIRSpec MOS + NIRCam Imaging coordinated parallels



Each panel shows the relative NIRCam SW pixel phases (i.e., fractional pixels in 2 dimensions) populated by the dither pattern in question. For reference, dither #1 is always plotted at pixel phase (0.5, 0.5). Black circles indicate positions for the 2-pt dither patterns (which have 4 dithers total for 2 NIRSpec MOS nods and 6 dithers total for 3 NIRSpec MOS nods), while the red circles indicate the "extra" positions populated by the third dither point (for each NIRSpec MOS nod) of the 3-pt dither patterns. The dither labels indicate the order in which the dithers are executed (in black for the 2-pt patterns and in red for the 3-pt patterns). The open circles represent the positions of the nominal NIRSpec nods (i.e., the ones that end up exactly in the center of the NIRSpec MOS shutters). Note: the middle row of panels shows the dithers for the case of 3 nods and 3-shutter NIRSpec MOS slitlets, while the top row of panels shows the dithers for the case of 3 nods and 5-shutter NIRSpec MOS slitlets. Observations that use 5 nods and 5-shutter MOS slitlets will sample the NIRCam SW pixel phases shown in the middle and top rows. The yellow rectangles on the right-hand side of the middle row of panels represent 3-shutter slitlets. The numbers in the shutters indicate the dither locations for the case of 3 nods (not to scale - just for illustrative purposes).

Finally, we remind the reader that these dither patterns are implemented in the APT templates for each prime instrument in the combination. Details are shown in the article APT Coordinated Parallel Observations.

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JWST Target of Opportunity Observations

A target of opportunity (ToO), for JWST observations, refers to requested observations that are linked to an event, such as supernovae, that may occur at an unknown time.

On this page

Main article: JWST Target of Opportunity Program Activitation
See also: Target of Opportunity Observations in the Call for Proposals material.

A target for JWST observation is called a *target of opportunity* (ToO) if the observations are linked to an event that may occur at an unknown time. ToO targets include objects that can be identified in advance but which undergo unpredictable changes (e.g., specific dwarf novae), as well as objects that can only be identified in advance as a class (e.g., novae, supernovae, gamma ray bursts, tidal disruption flares, newly discovered comets, etc.). ToO proposals must present a detailed plan for the observations to be performed if the triggering event occurs.

To check on the observability of a ToO for JWST, consider using one of the JWST Target Visibility Tools. When a given ToO triggers, the proposer should quickly assess whether the target is visible and available for immediate observation by JWST and for how long the visibility window remains open if monitoring is required. Also, the JWST Interactive Sensitivity Tool can be used to obtain a quick assessment of the S/N that can be achieved in a given exposure time.

What distinguishes ToOs from "time constrained" (or "time critical") observations, or potential director's discretionary time observations?

ToOs are generally not intended to be observations of periodic phenomena such as eclipsing binary stars, transiting planets, or Solar System objects. Observations of these types of objects are typically time constrained, and may be time critical if the observations must be done in a specified 24 hour window. For instance, if the objective is to observe a specified phase in the periodicity, lasting less than a day, then the observation is time critical. These types of observations are specified as regular fixed targets but with appropriate special requirements used to specify the timing requirements.

At the other extreme are unexpected phenomena, for which no plausible proposal could have been submitted in the previous proposal cycle. These types of observations are typically more appropriate for director's discretionary time. However, there are other criteria, including the likely impact of scientific results, that must be considered with proposals for director's discretionary time.

Observing constraints for ToOs

The minimum turnaround time for non-disruptive ToO activation, without significant impact to the schedule, is 14 days. Disruptive ToOs can be triggered with turnaround times of less than 14 days, provided all of the proposal details (except possibly the precise target position) are available in advance. However, because of the significant effect disruptive ToO observations potentially can have on the JWST schedule, there will be a limited number of disruptive activations allowed in each cycle. Moreover, due to their scheduling impact, disruptive ToOs that require triggering within 3 days will incur an additional overhead 0.5 hours (30 minutes) per activation. Linked subsequent observations do not necessarily incur additional overheads, unless they are specified as time critical visits.

Each cycle will have a limited number of disruptive ToO activations to allocate, based on an expectation of how many interruptions the scheduling can absorb. The number of allocations will be provided in the Call for Proposals.

Activating an approved target of opportunity program

Requesting Activation

The Principal Investigator (PI) or designated alternate initiates activation of a Target of Opportunity (ToO) proposal by submitting an activation request, which are submitted by navigating to the JWST Program Information webpage, searching for the appropriate program, and selecting the Activate a Target of Opportunity link in the Request section of the program page. In the request the PI identifies which visit (or visits) to activate and supplies all the information needed to implement and schedule the observation. This information should include target position, instrument filter/grating combinations, exposure times, and any scheduling requirements not already included proposal.

Because there may be critical implementation questions, you must let STScI know where you can be reached 24 hours a day.

After submitting the request, the PI (or alternate) must contact their Program Coordinator (PC) and verify that the activation request has been received by the Institute. The PC verifies receipt of the activation request and discusses with the PI any remaining questions on observation and scheduling requirements.

Evaluation and Implementation

STScI evaluates the effect of the ToO's interruption on the JWST schedule and how well the observations of this event meet the approved science goals. The STScI Director then makes the final decision whether to activate a ToO. The CS, the PC and Short Term Planning conduct a review of the proposal to assure the safety of the observations, to verify that the program complies with the observing time allocation and to identify execution opportunities.

Published	28 Mar 2017
Latest updates	• 11 Dec 2019 updated for 2020 Cycle 1.

Target of Opportunity Roadmap

A step-by-step guide through the process of designing a target of opportunity program with JWST.

On this page

Preliminary Considerations

A target of opportunity program is a special case because the details of targets and/or observations cannot be specified explicitly at the time of the initial proposal. The target could be a known target that may have an outburst at an unknown time or be a class of target (a supernova or a GRB) whose position and other information is not known until the triggering event occurs. The descriptive PDF file you attach to the proposal for submission is very important for ToO programs and needs to provide the details. This description should also clearly describe what the trigger mechanism will be for activating the ToO program.

1. Review the policies and properties of JWST ToO programs and their activation.
   Target of Opportunity Observations in the Call for Proposals material.
   JWST Target of Opportunity Observations
   JWST Target of Opportunity Program Activation

2. Understand the range of expected target fluxes or magnitudes for your potential targets in the wavelength range of interest.

Proposing for ToOs

1. Choose the instrument(s) suitable for your science. Understand what filters or gratings are needed and any other instrumental set-up information.

2. Use the ETC to determine the exposure parameters necessary to observe your target(s) when the ToO activates, and for any follow-up observations. For objects with an expected range of potential flux levels, you may want to evaluate both a best case and worst case to understand the range of potential resources needed.
   JWST Exposure Time Calculator Overview

3. Enter your target(s) into APT. Known targets that might go into outburst at an unknown time can be entered as regular fixed targets. Unknown targets (say a supernova brighter than some magnitude or a GRB) should be entered as generic targets.
   APT Targets

4. Fill out representative observing templates for each instrument and mode that you are proposing to use. For help, select the appropriate template from this listing:
   APT Observation Templates

   4a. In addition to entering your observation specifications, on each listed observation, you should open the Special Requirements tab and select “Target of Opportunity.” APT will pop-up a box for you to enter the requested turnaround time. Note: turnaround times <14 days are potentially disruptive to scheduling and are a limited resource of the observatory.
   JWST Target of Opportunity Program Activation

   4b. An “On Hold” special requirement will be generated automatically as well, and you will need to enter a comment.

5. Estimate the total resources your proposal will require if accepted and activated. APT will report numbers based on whatever you enter into templates, but it cannot take into account aspects that may only be described in your PDF.
   For example, perhaps you entered a single NIRSpec fixed slit observation into APT, but expect to execute it four times at some interval after the trigger, to watch the source fade. You could take the resource estimate APT makes for the single observation and estimate the total resource needed, assuming longer exposure times as the ToO fades.

6. The Proposal Information page in APT contains a box labeled “Request custom time allocation” which should be selected, and appropriate comments entered in the resulting pop-up window. Your assumptions should be described in detail in your Description of Observations section of your PDF attachment.

7. Finalize and attach your science PDF proposal, including science justification, description of observations, the triggering information, and the speed with which the trigger needs to be reacted to.

8. The Proposal Information page in APT contains a box labeled “Request custom time allocation” which should be selected, and appropriate comments entered in the resulting pop-up window. Your assumptions should be described in detail in your Description of Observations section of your PDF attachment.

9. When completed, use the submission tool in APT to submit your program. If any errors or warnings remain, explain them in the pop-up box provided at the time of submission.
   APT Submitting Your JWST Proposal

Activating ToOs

1. When a potential trigger for a given ToO target occurs, use the General Target Visibility Tool to assess its visibility for JWST observations.
   JWST General Target Visibility Tool Help

   Note: if your science involves a sequence of observations following the initial trigger and observation, verify not only that the target is observable, but that it will remain visible for the desired period of the follow-up observations.

2. Once you are convinced you are ready to trigger the ToO, contact the Program Coordinator who was assigned to your program at the time of acceptance. Refer to your acceptance letter.

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JWST Example Science Programs

Example science programs, available to prospective JWST proposers, provide a walk-through of all the elements in creating a JWST observing program, from posing a question, to identifying instrument-specific modes optimized for science goals, to using proposal preparation tools needed to create a valid proposal.

On this page

The example science programs listed in Table 1 are actual worked proposal examples for a number of JWST instruments, modes, and combinations of instruments. They are written as step-by-step guides to follow along, and will serve as a useful reference when crafting your own proposals.

These examples each include a description of the program, along with step-by-step guides to using Exposure Time Calculator (ETC) workbooks and Astronomers Proposal Tool (APT) files. Descriptions provide background on the science goals of each program and also walk through some of the technical decision-making steps in crafting realistic programs. ETC workbooks and filled-out APT files for the examples are available within each of those tools from a pull-down menu (see below).

Note the program reference numbers in the first column; they provides a numerical ID that ties together the description, ETC, and APT components of an example, as well as other relevant JDox articles.

If you have suggestions for additional examples that would be helpful in the future, please send your ideas via a JWST Help Desk ticket.

Example science programs by instrument

Table 1. Example science programs

Program reference #	Prime instrument (s) and template(s)	Parallel instrument and template (if any)	Example science program title (links go to the relevant articles)

MIRI			
28	MIRI MRS	---	MIRI MRS Spectroscopy of a Late M Star
(See other MIRI examples in the Multi-instrument section.)			
NIRCam			
22	NIRCam Imaging	MIRI Imaging	NIRCam Deep Field Imaging with MIRI Imaging Parallels
29	NIRCam TIme-Series	---	NIRCam Time-Series Imaging of HAT-P-18 b
30	NIRCam Grism Time-Series	---	NIRCam Grism Time-Series Observations of GJ 436b
37	NIRCam WFSS	---	NIRCam WFSS Deep Galaxy Observations
NIRISS			
23	NIRISS AMI	---	NIRISS AMI Observations of Extrasolar Planets Around a Host Star
31	NIRISS SOSS	---	NIRISS SOSS Time-Series Observations of HAT-P-1
33	NIRISS WFSS	NIRCam Imaging	NIRISS WFSS with NIRCam Parallel Imaging of Galaxies in Lensing Clusters
NIRSpec			
25	NIRSpec MOS	---	NIRSpec MOS Deep Extragalactic Survey
32	NIRSpec BOTS	---	NIRSpec BOTS Observations of WASP-79b
34	NIRSpec IFU+FS	---	NIRSpec IFU and Fixed Slit Observations of Near Earth Asteroids -- Moving Target Example
Multi-Instrument			
26	MIRI MRS, NIRSpec IFU	---	MIRI MRS and NIRSpec IFU Observations of Cassiopeia A

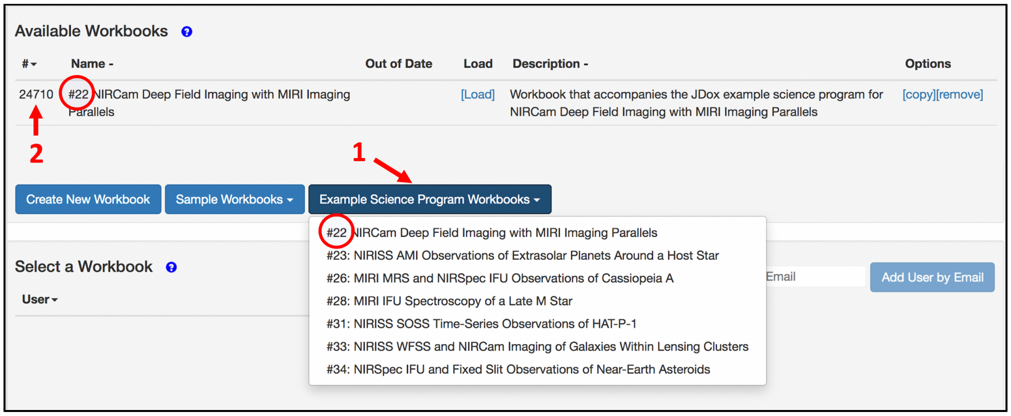
27	MIRI MRS, NIRSpec IFU	---	MIRI MRS and NIRSpec IFU Observations of SN1987A
35	MIRI Coronagraphy, NIRCam Coronagraphy	---	MIRI and NIRCam Coronagraphy of the Beta Pictoris Debris Disk
36	MIRI Coronagraphy, NIRCam Coronagraphy	---	NIRCam and MIRI Coronagraphy of HR 8799 b

Each of the example science programs linked above also links to two Step-by-step guide articles, one for creating the ETC information and the other for creating a valid APT file. The actual example ETC workbooks and APT files for each program are available from within each tool, as described below.

Accessing ETC workbooks and APT files for the example science programs

Each example science program has an attendant ETC workbook and APT file that can be used for reference as you work through each example. The relevant ETC workbooks are available within the ETC itself. A tab in the ETC GUI allows access to a drop-down menu that shows the example science program workbooks with the same titles and reference numbers shown in Table 1. Select the example workbook of interest and add it to your personal list of ETC workbooks to access the contents as shown in Figure 1.

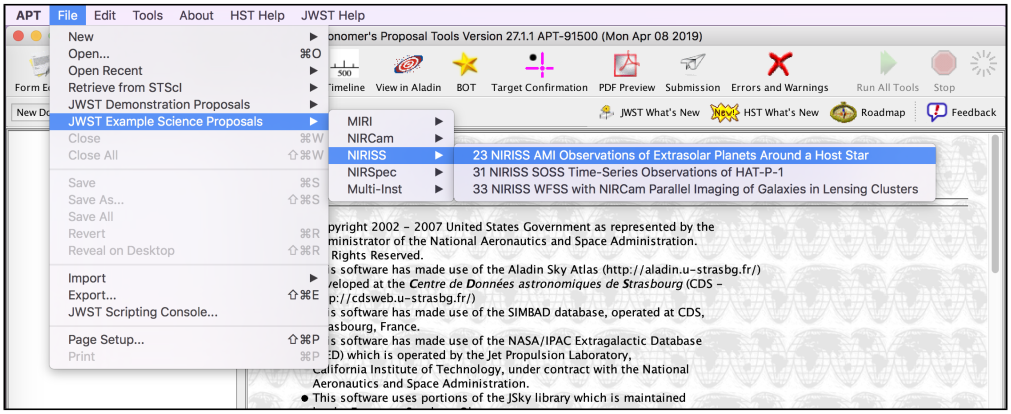
Figure 1. Accessing ETC workbooks for example science programs



In the ETC GUI, select the Example Science Program Workbooks tab (arrow 1) and then select an example workbook of interest (in this example, #22). That workbook then becomes available for your use, but is assigned a unique new ID number (arrow 2). Once you load this notebook, you can read it to follow along with the example program description, or edit it further as you like.

Likewise, the filled-out APT files for each example science program are available to users within APT and can be loaded as follows: from the top **File** menu, select the tab for **JWST Example Science Programs** and choose the APT file with the same title and reference number as the program you are interested in. (See Figure 2.)

Figure 2. Accessing APT example science program files in APT



From APT, you can retrieve the APT files for any example science program by accessing the top File pull-down menu and selecting JWST Example Science Programs. Then, slide right to select a category and a particular program of interest. Note that, unlike the ETC case, APT treats these example programs as if they are previously accepted programs. While you can edit them to experiment, you should use the Copy and Paste functions in the Edit menu to transfer any work you want to keep to a new proposal file.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Published	04 Jan 2018
Latest updates	• 09 Jan 2020 Final updated links to programs for 2020 Cycle 1. • 30 Sep 2019 Updated with placeholders for additional example programs for cycle 1. • 26 Apr 2019 Page completed revamped and updated to support the revised Example Science Program strategy and support methodology. This includes having the ETC workbooks and APT files for each program available directly from pull-down menus within the ETC and APT.

JWST Recommended Observing Strategies

Articles, based on the best pre-launch information, are available to help JWST observers make informed choices in selecting JWST instruments and modes.

JWST offers a broad array of instrument observing modes covering the wavelength range of 0.6–28.5 µm. Even though proposers use pre-defined observation templates to define their requested observations, there are still a variety of options that a proposer must consider. Specific aspects, such as target acquisition, detector readout patterns, dithering, and planning for proper background corrections (if necessary) need to be considered for obtaining good quality data.

This page provides links to instrument-specific articles that offer advice to proposers for selecting the proper instruments and observing parameters to support their science cases.

MIRI Observing Strategies
NIRCam Observing Strategies
NIRISS Observing Strategies
NIRSpec Observing Strategies

JWST Duplication Checking

Users are responsible for checking their proposed observations for potential duplications against accepted or previously executed observations, and either removing the duplication or explaining any such potential duplications in their science proposals.

On this page

> *See also: Identifying Potential Duplicate Observations and JWST Duplication policy*
> *Relevant Links outside of JDox: MAST Data Discovery Portal and JWST Program ID Look-up GUI*

As part of maximizing the science return of JWST, unnecessary duplication of observations needs to be avoided. Proposed observations that duplicate or potentially duplicate existing or planned observations must be scientifically justified by the proposer. The JWST Duplication Policy defines what constitutes a duplication.

Duplication checking prior to submission is the proposer's responsibility. Any duplications or potential duplications (for programs where the details are not known up front) must be discussed and/or justified in the text of the proposal. Failure to do so may result in the rejection of the proposed observation even after proposal acceptance. For accepted proposals, STScI will perform a detailed duplication check to catch and remove any duplications within the current pool of accepted proposals.

Pre-submission checking

> *See also: Identifying Potential Duplicate Observations, and JWST Duplication Policy*
> *Relevant Links outside of JDox: Summary listings of accepted GTO Program Information and ERS Program Information including links to the public APT files.*

To avoid unintentional duplications, proposers will be required to check their proposed observations against those already approved (both in the queue and previously observed). For cycle 1 general observers, guaranteed time observer (GTO) proposals and early release science (ERS) proposals must not be duplicated without a sound scientific justification. Hence, the information in these programs forms the basis of potential duplications for cycle 1. (As JWST observations are obtained and archived, all observations will go into the Mikulski Archive for Space Telescopes (MAST) and will also be available for duplication checking in future cycles.)

Note: You may want to perform this duplication checking step *prior to* going through the effort of entering and validating your own APT proposal, to avoid the potential of finding out after the fact that your observations had already been proposed. If there is a scientific justification for a duplication, such as a time-variable source or need for higher signal to noise than in the previously approved JWST observations, you can still request it but you should provide a justification for it in your science proposal text.

Target duplication checks

The MAST Data Discovery Portal will assist you in making checks for potential duplications, allowing you to quickly see whether your proposed targets appear in any previously approved JWST observations. Details are provided in the article Identifying Potential Duplicate Observations. *If no previously planned JWST observations are indicated by your check in MAST, no further checking is required.* This MAST target check may also identify data from HST and other missions that you may find useful.

Observation duplication checks

Targets are not protected, but rather *observations of targets with a particular instrument, instrument mode, and requested S/N* are protected against unjustified duplications. However, the MAST Portal does not provide all the information needed for duplication checking. Hence, you will need to inspect the APT files from any accepted JWST programs indicated in MAST to assess the details on the instrument configuration(s) and exposure times being requested to determine if a duplication exists.

There are several ways to view the details in accepted JWST programs:

1. Peruse the lists of program IDs and titles for ERS and GTO programs. Clicking on a program ID will take you to a program information page with links to a "public PDF" file and the program's APT file.

2. Alternatively, enter an accepted program ID number in the JWST Program Information tool to get the program information.

3. The APT files for accepted programs can be loaded directly into an APT session. In APT, go to the top **File** pull-down menu, select **Retrieve from STScI → Retrieve using Proposal ID,** and enter the program ID in the box.

To assess if your proposed observation is a likely duplication, open the APT file and check the instrument mode, filters/gratings, dithers, and total exposure time, as well as any other details relevant to the mode you are proposing. If desired, display relevant observations in Aladin to see the full dither pattern or mosaic being proposed.

If any duplications with your planned observations are identified, either justify the need for new data or adjust your proposed observing plan to avoid the duplication.

Some cases will be complicated enough that you can only discuss that a *potential* duplication exists. A prime example is NIRSpec MSA observations, where the specific objects for observation are not selected until a final MSA configuration is determined for the accepted program. Therefore, specific duplications may be unknowable at proposal time. See the JWST Duplication Policy for details.

Post-acceptance checking

Once a proposal is accepted, one of the first steps in proposal processing is a duplication check performed by STScI staff. Their software not only checks for duplications against previous and planned observations, but also checks the pool of accepted programs in a given cycle to catch potential duplications. STScI will contact affected PIs to resolve any such duplications if they occur.

Published	13 Sep 2017
Latest updates	• 02 Dec 2019 Removed duplications with JWST Duplication Policy article. • 17 Sep 2019 Article streamlined by removing redundancy and duplicate linking.

Identifying Potential Duplicate Observations

Investigators preparing JWST proposals can use the MAST Data Discovery Portal to identify potential duplications between targets they wish to observe and previously approved JWST observations.

On this page

Main article: JWST Duplication Checking
See also: JWST Duplicate Observations Policy
relevant links outside of JDox: MAST Data Discovery Portal and JWST Program Information Look-up

When preparing a JWST observing proposal, investigators are obliged to check their targets against existing or planned JWST observations for potential duplications. You may use the MAST Data Discovery Portal to discover planned (and eventually archived) JWST observations of most targets, and to visualize the approximate footprints of such observations on the sky. The portal will simultaneously provide important, but incomplete, ancillary information for the matched observations, such as the instrument(s) and some information about the observing configuration(s). If potential duplications are identified, you will need to inspect the public APT file of the accepted programs to get detailed exposure information to judge whether a duplication is real. The portal can also display the footprints of archived data from other hosted missions, such as HST images, which may be useful to plan your observations in detail.

Portal target search

The check for potential duplicate observations begins with searching the MAST Data Discovery Portal for your targets, with a radius that is appropriate for the instrument configuration you intend to use (see Table 1).

Table 1. Areal Observations—default duplication search radii

Observing Mode	Δr (arcsec)	Observing Mode	Δr (arcsec)
NIRSpec MOS	180	NIRSpec IFU	4
MIRI Imaging	120	MIRI MRS	4
NIRISS WFSS	140		
NIRCam Imaging	280		

General search procedures for observations of astronomical targets are described in Data Exploration with the MAST Portal. Exposures that overlap the selected target (or coordinates) within the search radius will be listed in a table, and the approximate footprints of those exposures will appear against a background image of the sky at the target location.

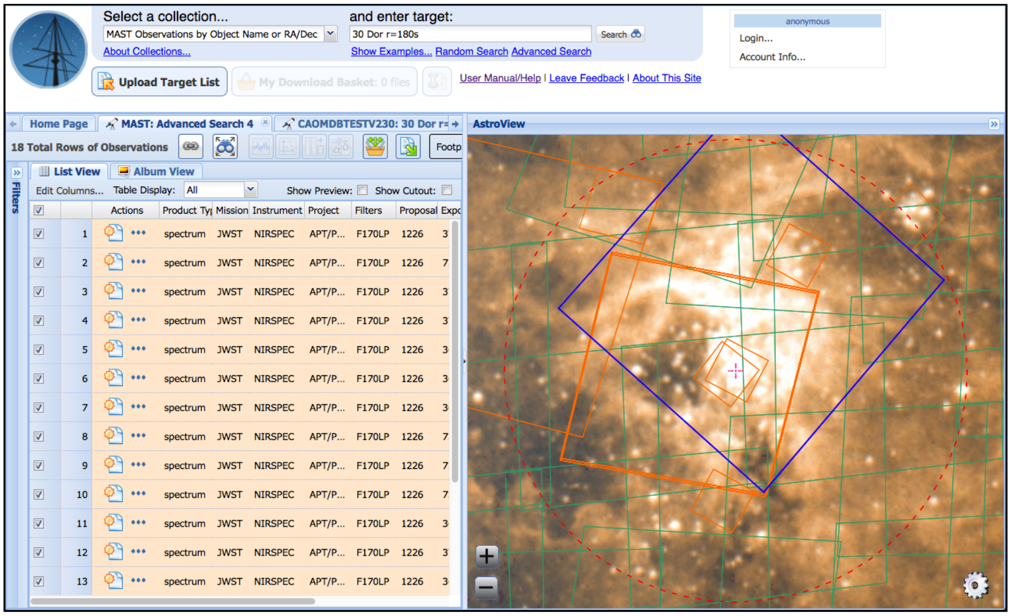
Potential vs. Actual Duplications

The MAST Portal capabilities described here will help you identify *potential* duplications between your intended observations and those that are planned or that have already executed. Note, however, that the complete footprint of dithered or mosaicked observations is not accurately represented (see Evaluating Potential Duplications below). You must evaluate the details of the planned observations by using the accepted program's APT file (and/or the Aladin display in APT, as appropriate) to determine if the potential duplications are genuine in the context of the JWST Duplicate Observations Policy.

Fixed targets

You may search for fixed targets by entering the target coordinates and a search radius (see below). The appropriate search radius to use for duplication checking is summarized in Table 1, and depends upon the instrument and observing configuration. Figure 1 shows a search in a region near 30 Dor, which will be observed in JWST program GTO-1226.

Figure 1. Portal search results for 30 Dor



Portal search results for 30 Dor using a search radius of 180" (dashed red circle) appropriate to a NIRSpec spectrum, showing the JWST exposures listed in a table (left, with orange background), and the spatial footprint of the initial dither position (blue rectangle) superimposed on the Digital Sky Survey at this location (right). Also shown are the footprints of HST observations with ACS/F658N (green rectangles) and the F814W filter with multiple HST instruments (orange rectangles).

Primary search

Navigate to the MAST Portal, and enter the coordinates or name of your intended target and the search radius in the dialog box labelled ***and enter target****, then click the ***Search*** button:

> To search *30 Dor* for potential duplications, enter ***`30 Dor r=180s`***

After the search results are displayed, in the **Filters** panel (*far left*), find the **Mission** filter and select the ***`JWST`*** checkbox.

- Optionally, dismiss the filter panel to see more of the results table and the **AstroView** panel.
- Optionally change the color of the displayed footprints using the color selector pull-down menu.

The result will be the footprint of the initial dither/mosaic position of planned JWST observations for this target (but see the caveat below). While you can edit the columns that appear in the **List View** table, be sure to display at least the following to see important metadata:

- ***Instrument***
- ***Filters***
- ***Proposal ID***

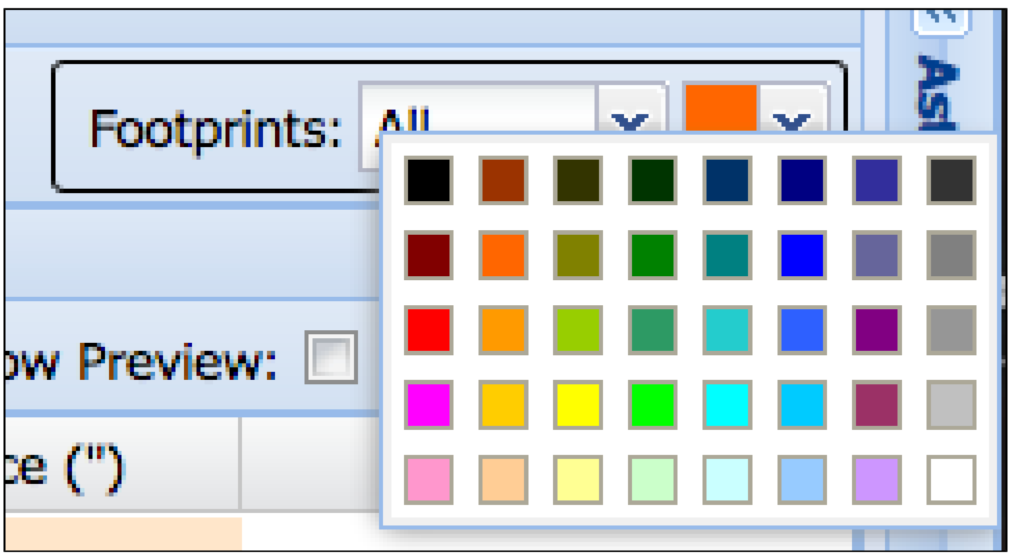
- ***Distance***

The ***Proposal ID*** text in each row is a link to the corresponding program information page, which contains a link to the program summary (.pdf) and the APT program definition (.aptx) file. You may need to slide the horizontal scroll bar to the right to see the ***Proposal ID*** column.

Supplemental searches

You may optionally show extant observations with other observatories by selecting additional missions beyond JWST. Alternatively you can conduct additional searches and (easily) display footprints for other missions in a different color:

- Enter the same coordinates (or name) and radius used in the first search and click the search button
- When the results appear, check the boxes that correspond to the mission data/instrument/filter of interest
- Modify the color of the displayed footprints using the color selector at the far right.



The **AstroView** panel displays all footprints from all search tabs.

If the observations for other missions overlap your intended target, they may prove useful for detailed observation planning (or as a pre-image).

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

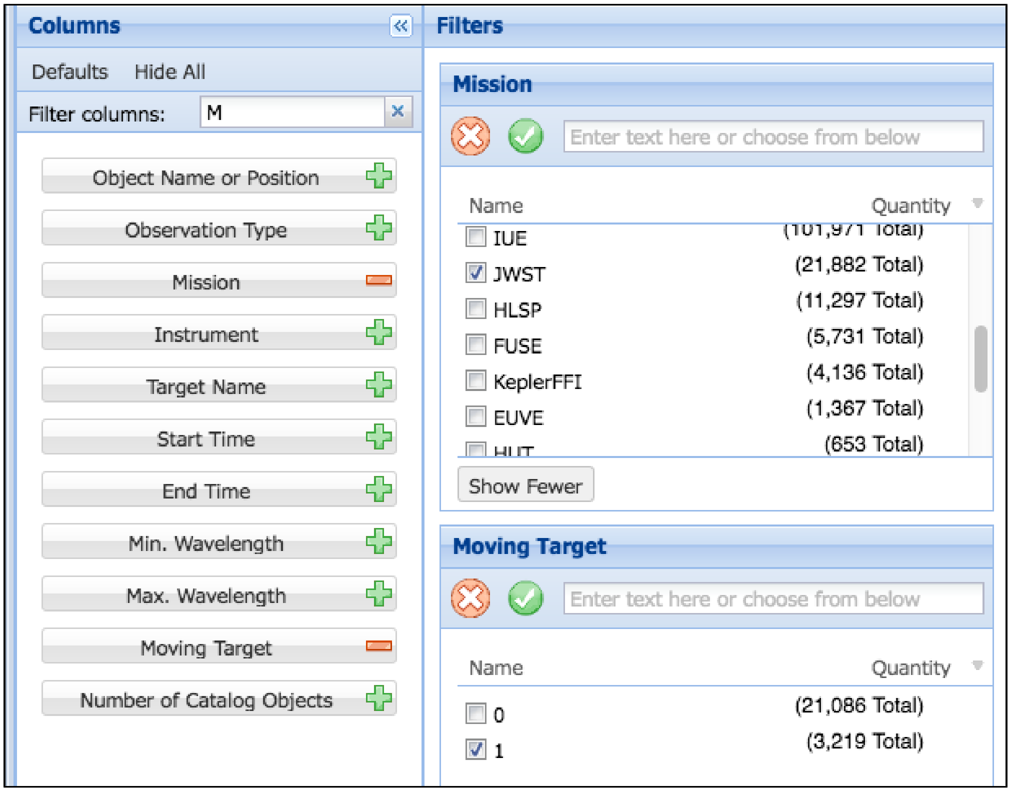
Moving targets

Searching for moving targets (mostly Solar System bodies or their satellites) is possible. Rather than entering celestial coordinates (which may not be correct until the observations are scheduled), click the ***Advanced Search*** link under the Portal dialog box. When the search panel appears,

- click ***JWST*** in the **Mission** filter
- check ***1*** in the **Moving Target** filter

as shown in Figure 2 below, then click the ***Search*** button at the top left of the page.

Figure 2. Portal moving target search



Select the desired columns in the Portal Advanced Search panel (left). Use the Mission filter (upper right) and the Moving Target filter (lower right) to initiate a search for moving targets.

Once the results appear, you may further narrow the search by entering the common target name in the **Keyword /Text** filter, as shown in Figure 3.

Figure 3. Moving target selection by name

The Keyword/Text filter for selecting a target name in the MAST Portal. In this example, where charon was entered, the filter will match any occurrence of the text including "`CHARON`" and "`PLUTO+CHARON`".

Some footprint details of moving target observations, such as the coordinates or orientations, are subject to change until the observations have actually been scheduled for execution. The **AstroView** panel is unlikely to be useful in these cases.

Brute force approach

Many moving target names in the planning database are non-standard, so a search on the target name using the ***Advanced Search*** field may not be complete. But for cycle 1, since only about 1,100 observations of moving targets are planned in the GTO and ERS programs, a simple search for JWST moving targets with no other selection criteria may suffice.

MAST API target search

As an alternative, you may use the MAST application programming interface (API) to search the archive for planned and archived observations, the mechanics for which are described in the MAST documentation Programmatic Interfaces (see also the more general MAST API Tutorial). The API allows any search that can be specified with the portal; the results will be textual rather than visual. This approach is most useful for identifying potential duplications with a large number of targets. But if planned observations are identified for fixed targets within your search radius, you will want to use the MAST Portal to visualize those results in detail. A Jupyter Notebook with example queries of the database is available.

- Download notebook: https://github.com/openSAIL/JWST_Planned_Observations

Use and adapt the examples to your specific needs.

Evaluating potential duplications

If the results of one of the above types of MAST Portal searches shows that accepted JWST observations are at or near your specified target position, there is a potential duplication. You should go on to the next step, which is to look at the accepted program's detailed information to assess the situation in detail.

The portal does not provide the full metadata about planned observations that are necessary to determine whether your intended observation is a duplication. The portal also displays only the primary footprint for an observation, but *not* those for associated dither positions or mosaic tiles. Use the process below to visualize the full footprint.

Check the APT file

You will need to examine the specifications and exact overlap of planned observing programs in order to determine in detail the nature of a potentially duplicating observation. To do this, you will need to fetch the relevant APT file(s) for the specific JWST program(s):

1. Click the ***Proposal ID*** link in the portal listing (you may need to slide the horizontal scroll bar to the right to see the ***Proposal ID*** column). Or if you prefer, use the JWST Program Search Tool) and enter the Proposal ID number to bring up the program planning page for that ID.
2. Click the link provided there to download the APT file to your local disk. Optionally, you may download the Observation Summary (*Public PDF*) file, which is a formatted readable version of the proposal.
3. Open APT and load the .aptx file like you would with any other APT file. Or alternatively, open the PDF summary file to view its contents.
4. Compare the instrument used and its configuration (imaging/spectroscopy, filters, dispersers, masks) to your intended observation. If the observation is a mosaic, visualize the footprint of dithered or mosaicked observations in APT by clicking the ***View in Aladin*** button.

Finally, review the JWST Duplicate Observations Policy carefully to determine if an apparent duplication is genuine.

For help with APT or Aladin, see the relevant tutorial videos on the JWST Observer YouTube channel.

Resolving Duplications

If there is a genuine duplication, there are a few choices for resolving it:

- Select a different target.
- Change your observation in a way that does not duplicate those already planned.
- Indicate the duplication and include a sound justification for it (e.g., observations of a time variable source) in the appropriate section of your proposal's Scientific Justification, which is part of the PDF file that must be attached to your APT Proposal Information page prior to final submission of your proposal.

Note: all observations obtained in DD/ERS programs, and observations in select GTO programs, will be publicly available as soon as they have been archived, with zero exclusive access period. Archival proposals for these data are part of the solicitation in cycle 1. See the Call for Proposals for details.

Published	10 Feb 2018
Latest updates	10 Dec 2019 Article updated for 2020 cycle 1 use.

JWST Observatory Functionality

There are many aspects of the JWST Observatory and its operations that determine if proposed observations can be carried out. The articles in this section provide various kinds of background information to help users understand some of these constraints and their impact on how observations are planned and scheduled.

Expand all Expand all Collapse all Collapse all

Published	15 May 2017
Latest updates	

JWST Position Angles, Ranges, and Offsets

Users should be familiar with JWST position angles, coordinate systems, and related nomenclature to understand the telescope’s pointing constraints.

On this page

Observations that need specific orientations for a particular instrument's field of view on the sky can run into complications due to constraints on where JWST can point relative to the sun. There are APT special requirement parameters available for specifying pointing restrictions, if needed.

Reference angle definitions

> *See also: JWST Observatory Coordinate System and Field of Regard, JWST Field of View, JWST Instrument Ideal Coordinate Systems*

The observatory coordinate system (V1, V2, V3) is used in operations (Figure 1). The V3 axis is the relevant vector for science planning. *V3PA* is the position angle (PA) of the V3 reference axis eastward relative to north when projected onto the sky.

Official reference positions and angles relative to V3PA for all defined apertures (or FOVs) are maintained in the Science Instrument Aperture File (SIAF). The SIAF is a controlled document referenced by all relevant software in the JWST operations area. It contains detailed definitions of every instrument, defined aperture, subarray, detector, and even information about transformations and distortion corrections.

A desired orientation or range of orientations for an instrument field of view (FOV) can be specified in the Astronomer Proposal Tool's (APT) special requirements. For a selected instrument (or mode, or a subarray), this orientation is expressed as the *aperture position angle* (APA), that is, the position angle for the "science y-axis" of the instrument FOV or detector being referenced (measured eastward from north).

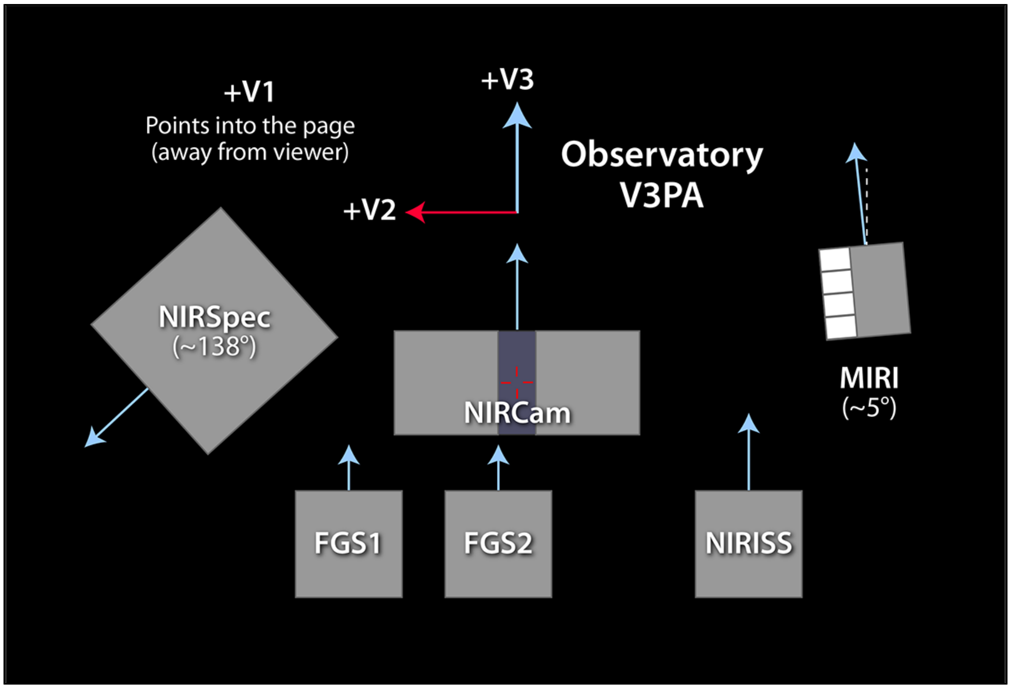
Table 1 provides information on the offset from instrument y-axis to V3PA for each science instrument. Some instruments are closely aligned to the V3 axis. Therefore, in most cases, planning tools for those instrument modes will report little difference between V3PA and APA values. Users should be aware of what V3PA means because some tools, such as diagnostics within APT, refer to V3PA in portions of the software. However, to first order, observers will deal with the APA, which is the angle specific to the instrument FOV they're using for a given proposed observation. The JWST target visibility tools provide information about both V3PA and APA (and the offsets between them, if any) for the various instruments.

Table 1. Offset angle relative to Observatory V3 axis for science instruments

Instrument	Offset angle from V3
NIRCam	0.0°
MIRI	4.45°
NIRISS	0.57°
NIRSpec	138.5°

Figure 1 shows these reference axes in the context of the JWST focal plane. Note that the two Fine Guidance Sensors are also closely aligned with NIRCam and with V3.

Figure 1. Reference axes for measuring JWST position angles



The direction of the observatory V3 reference axis is shown by the top blue arrow. The smaller blue arrows indicate the reference directions for each instrument. NIRISS, NIRCam, and the FGSs are closely aligned with V3. MIRI is rotated a few degrees counterclockwise, and NIRSpec's reference axis is at a significantly different angle, some ~138° counterclockwise.

APT special requirements controlling position angle

See also: Aperture Position Angle Special Requirements, APT Visit Planner, JWST Target Visibility Tools

See also:

Using Aladin and APT Visit Planner

In APT, after selecting an instrument, mode, aperture, etc., there are special requirements to specify the desired orientation of a JWST aperture or field of view on the sky, either at an absolute PA or within a range of PAs. Furthermore, the capability exists to specify that a given observation be placed at the same angle or at some offset angle (or within some range of offset angle) from another observation, which may be with the same or another instrument.

These position angle special requirements are specified as follows:

Aperture PA [value1] to [value2] Degrees [followed by V3 PA information]*

- a minimum and maximum value are requested by the GUI in APT. (They can be the same, but this imposes strict scheduling constraints.)

- An example GUI display would look like ***Aperture PA Range 135 to 145 Degrees (V3 356.50766 to 6.50766)***

APERTURE PA OFFSET [obs#] FROM [obs#] BY [XX] Degrees TO [YY] Degrees

- a minimum and maximum value are requested by the GUI in APT. (They can be the same, but this imposes strict scheduling constraints.)
- An example GUI display: ***Aperture PA offset 1 FROM 2 BY 10 Degrees TO 15 Degrees***

[obs#] SAME APERTURE PA AS [obs#]

- An example GUI display: ***2 SAME APERTURE PA AS 1***

The APT Visit Planner contains diagnostic plots to assess the allowed angles versus time and will flag unschedulable requests at the times they are specified. However, users with PA constraints or those who desire offsets may find it advantageous to use one of the target visibility tools prior to entering observations into APT to understand the overall schedulability and PA flexibility for a given target. Indeed, some preplanning may save significant time and possibly wasted effort downstream in APT in the event that certain desired angles or offsets are not available due to observatory level constraints.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

The effect of a target's ecliptic latitude

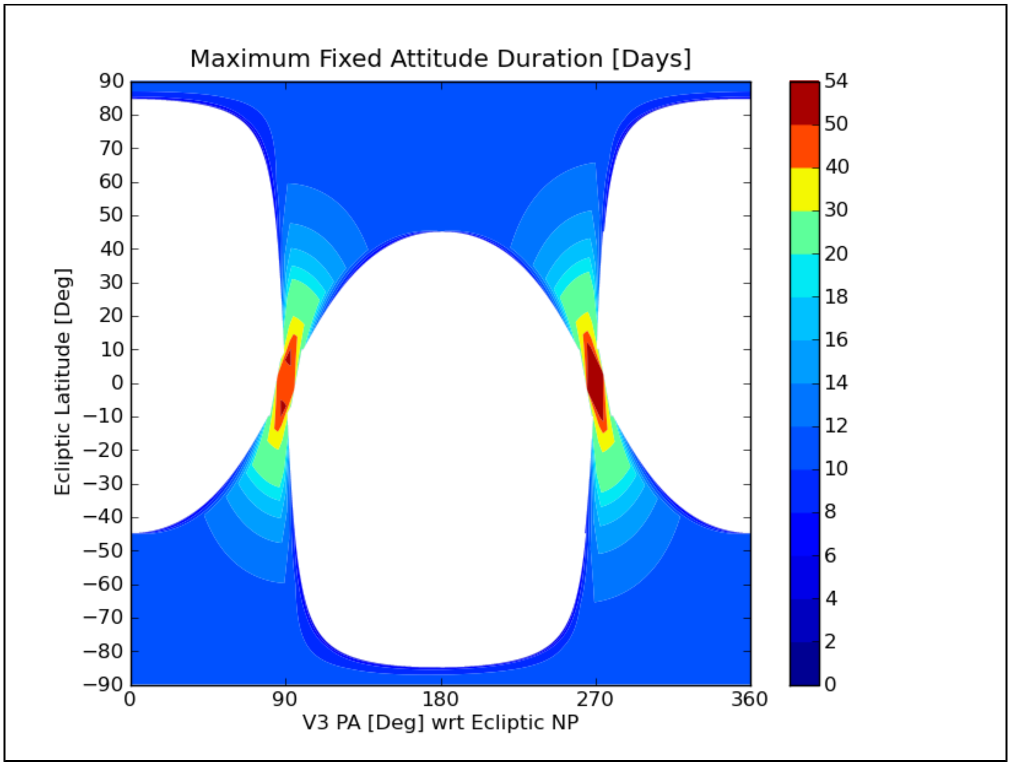
See also: JWST Target Viewing Constraints, JWST Orbit

Astronomical targets near the ecliptic plane are observable by JWST over restricted time periods; even when they're available, the *ranges* of position angles for the JWST field of view on the sky will be nearly fixed (although still allowing the nominal roll flexibility of roughly ±5°).

Targets near the ecliptic poles can be observed at nearly any time, and at any PA on the sky at some time during the calendar year. But again, at any given time, a high ecliptic latitude target will have a nominal PA with only about ±5° flexibility. This limits the length of time a target in this region can be observed *at the same PA* (for instance, a large mosaic observation).

At and below roughly 45° in ecliptic latitude, the available observing windows and PAs on the sky become more severely restricted, but the length of time one can remain at a given valid PA *increases*. Figure 2 demonstrates these restrictions graphically.

Figure 2. Ecliptic latitude plotted against V3 PA with respect to the ecliptic north pole



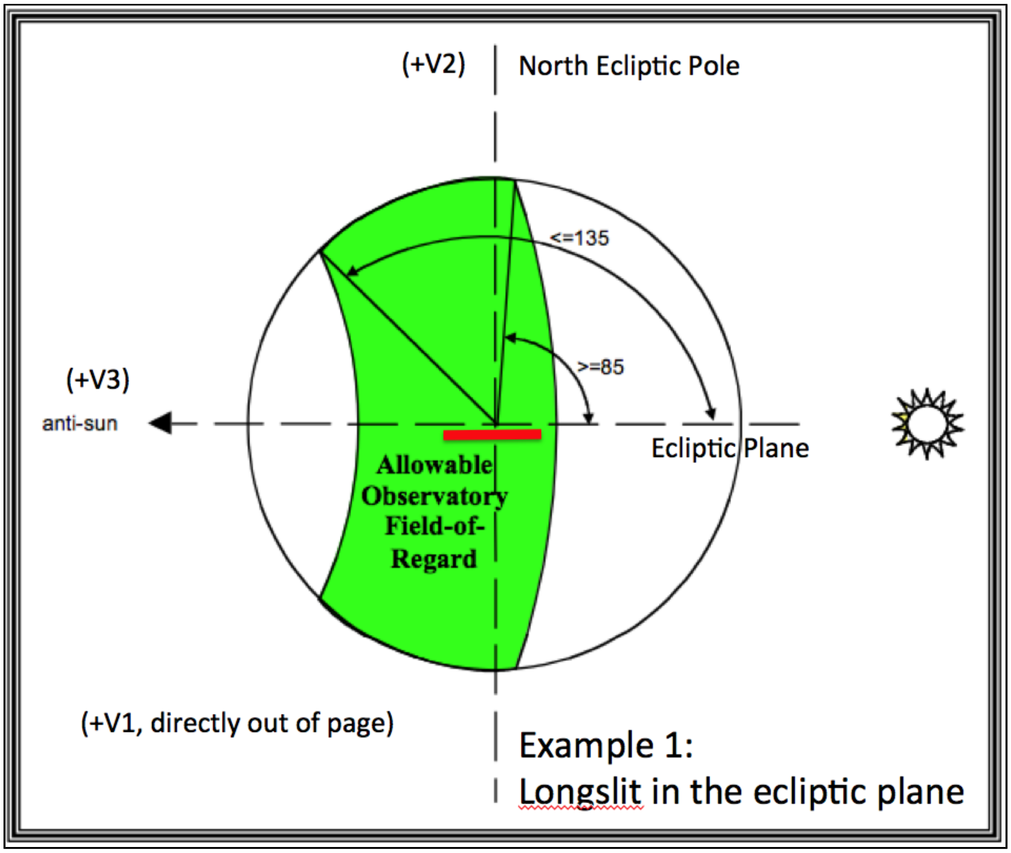
The ecliptic latitude is plotted against the V3 PA with respect to the ecliptic north pole (which by going from 0° to 360° essentially covers one year). The colorized region represents the available portion of the sky in these coordinates. This plot shows several things: the horizontal width of the colorized region as a function of latitude indicates the allowed roll range, and this is restricted at low latitudes. Additionally, the color bar indicates the maximum length of time JWST can stay pointed at a fixed attitude. Except for edge effects, no region has <10 days of visibility at given position angle. (Figure courtesy of Wayne Kinzel.)

Why do these restrictions occur?

Two extreme cases are illustrated below.

First, consider a target located in the ecliptic plane (see Figure 3). Such a target will be visible to JWST instruments for two ~50 day periods, approximately 6 months apart, as the target cuts through the projected annular JWST field of regard (FOR) on the sky. Then, consider an imaginary long slit along the [V3] axis, as shown by the red bar in Figure 3; it is essentially oriented along the ecliptic plane at all times while the target is visible to the observatory. The PA of the JWST FOV on the sky will only have an instantaneous roll flexibility of about ±5° during this time. A large range of PAs will *never be available to JWST* for targets at low ecliptic latitudes. This limitation only improves slowly with increasing (absolute) ecliptic latitude until ecliptic latitudes of about 40°–45° are reached (see Figure 2).

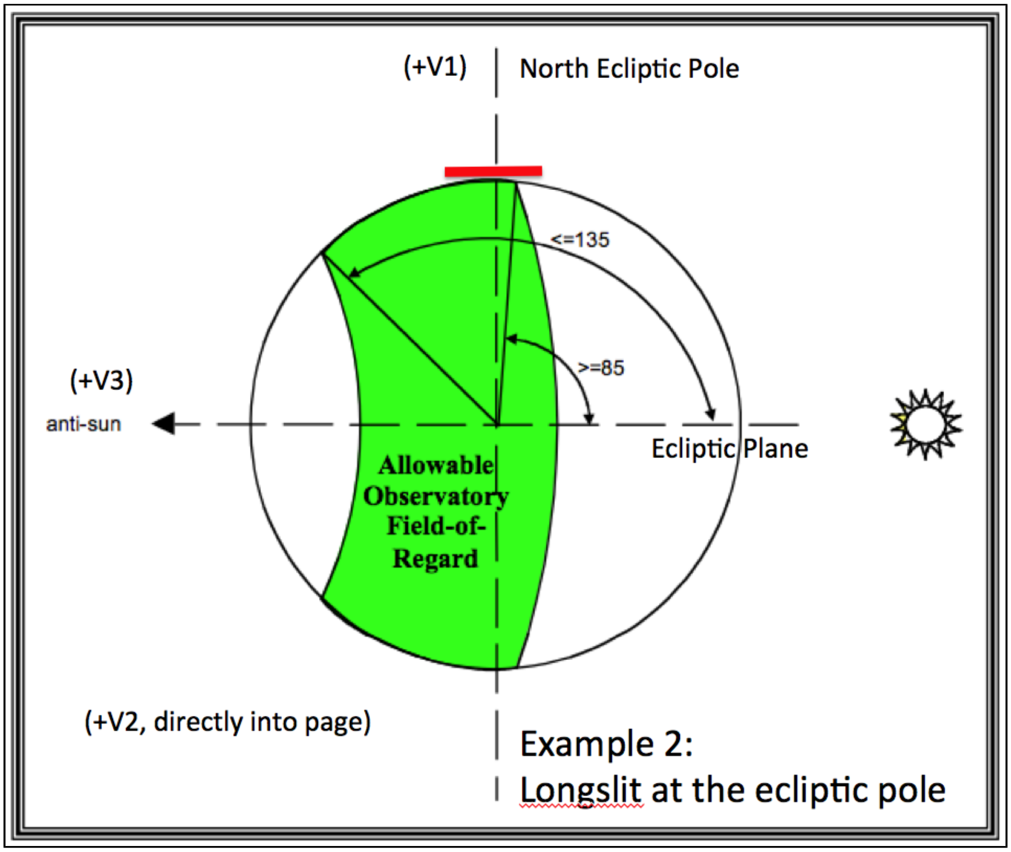
Figure 3. Imaginary long slit (red bar) shown oriented in ecliptic plane



An imaginary long slit (red bar) is shown oriented in the ecliptic plane. The observatory V1 axis is directed out of the page. As the V3 axis sweeps along the ecliptic plane, the orientation of the long slit remains essentially fixed. Referring back to Figure 2, two long windows of visibility exist during the year, but almost no roll flexibility.

Second, consider the other extreme, with JWST pointing near an ecliptic pole. An imaginary long slit is oriented, again, parallel to the observatory [V3] axis as shown in Figure 4. Imagine staying pointed in this orientation for a full year as the observatory orbits the sun. The long slit changes orientation on the sky at ~1°/day. In 90 days, the slit will be perpendicular to its starting position angle on the sky, and in 180 days the slit will be rotated 180° from its starting position angle. Hence, for targets near the ecliptic poles, although the instantaneous PA flexibility is still roughly ±5°, all PAs on the sky are available twice per year (modulo 180°). Interestingly, however, referring again to Figure 2, the *length of time* any particular PA is available is only about 10 days per instance. Such restrictions may come into play when considering large mosaics or other observations that require the same orientation on the sky.

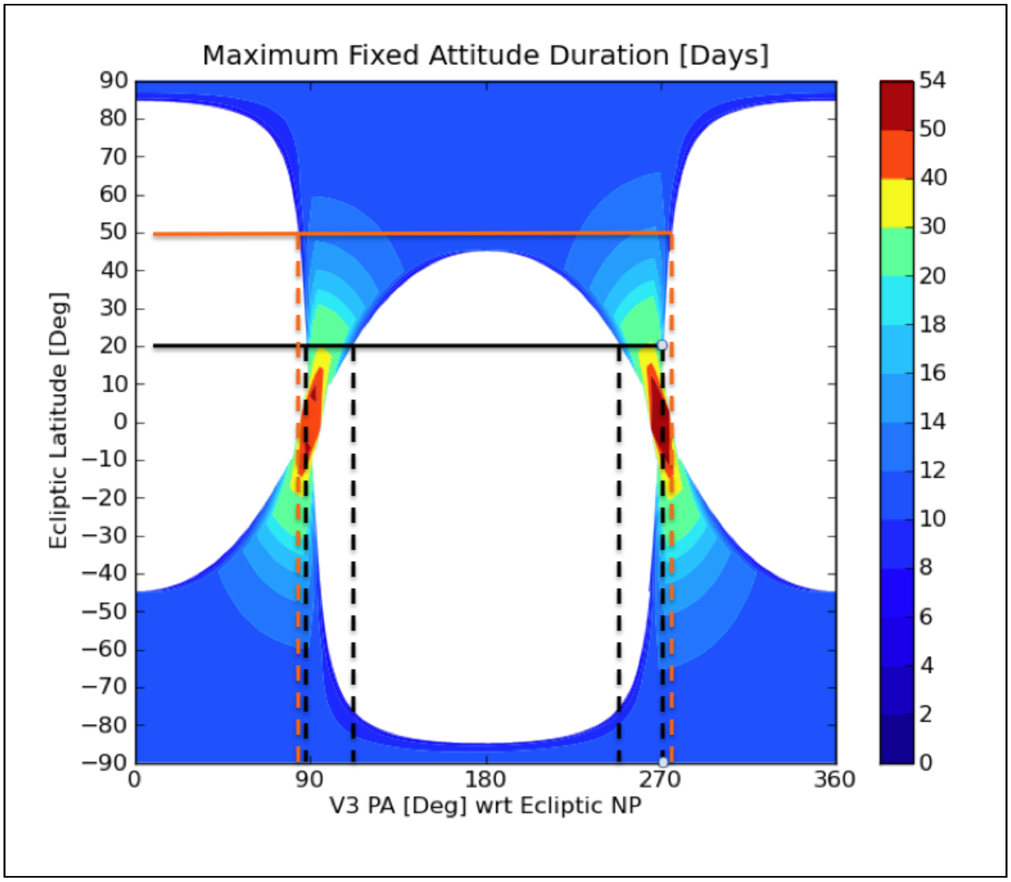
Figure 4. Imaginary long slit (red bar) pointed towards north ecliptic pole and oriented parallel to V3 axis



An imaginary long slit (red bar) is shown pointed toward the north ecliptic pole and oriented parallel to the V3 axis. As the V3 axis sweeps along the ecliptic plane, the orientation of the long slit rotates on the sky by ~1°/day, making all PAs available at some point during the visibility period.

At intermediate ecliptic latitudes, it's possible to calculate available PAs on the sky as a function of time, as was shown in Figure 2. Figure 5 shows how the range of available PAs on the sky varies with ecliptic latitude for 2 assumed targets: the black lines are for a target at 20° ecliptic latitude, and the orange lines are for a target at 50° ecliptic latitude. A target at 20° has 2 small (~25°) ranges of V3PA available. Furthermore, the 2 ranges are nearly modulo 180° from each other, so the total available V3PA range is restricted. At 50°, one large (more than 180°) range of V3PA is available, meaning that any PA on the sky (modulo 180°) is available at some time during the year. As mentioned earlier, a target at the ecliptic pole has the most PA flexibility (but also has limited time at a given PA).

Figure 5. Example of restricted V3PA ranges shown for targets at high and low ecliptic latitudes



A different take on Figure 2 showing the 2 restricted V3PA ranges for a target at 20° ecliptic latitude (black lines) and the single, much larger range of V3PA available for a target at 50° ecliptic latitude. Thus, if a user requires a specific PA on the sky for a given target, targets at low ecliptic latitudes will have much less schedulability, and in the worst case, may not be observable at the desired PA.

Examples

The schedulability of requested observations can be very limited when specifying PAs and offsets, especially if fixed angles or small ranges of allowed angles are involved. Hence, *these special requirements should only be used when truly necessary for the science*. However, there are a number of expected situations that will require this capability.

Coronagraphy

See also: HCI Roadmap, JWST Coronagraphic Visibility Tool Help

One of the most significant applications of constrained PAs and angle offset specifications will be coronagraphic observations with MIRI and NIRCam. For example, PA changes between separate coronagraphic integrations will help to identify real structure in and around a target from substructure within the point spread function (PSF). Because of concerns about changes in the PSF with time (due to thermal changes or drifts in the mirror alignments), many users will want to roll dither on coronagraphic targets at the time of their observations. Practically speaking, this will usually mean 2 back-to-back observations made at ±5° from nominal observatory roll at the time of the observations (for example, a first integration at −5° from nominal roll followed by one at +5°—note that no observation is taken at nominal roll).

Certain cases may also need follow up at some more substantial angular offset (e.g., 30° offset) relative to the first observations, which will need to be scheduled at a significantly later time. (Note also the potential impacts of targets at low ecliptic latitudes, for which this may be impossible due to the observatory roll restrictions.) Coronagraphic observers will want to assess their potential targets carefully, and when possible, select targets above 45° ecliptic latitude if they require large offsets in PA between observations. To help assess these situations quickly and easily, a coronagraphic target visibility tool is available to users.

Near and mid-IR imaging and mosaics

Some programs will want to obtain near- and mid-IR imaging, using NIRCam and MIRI, of a similar region on the celestial sphere. The use cases vary from a single field to larger mosaicked fields to covering an entire region such as the HUDF, or an extended source such as a nearby galaxy or H II region. Because the field sizes (and orientations at some level) are different between the cameras, some users will not only want to orient one of the cameras in a certain way to cover a desired region, but may also want to align (or roughly align) the 2 camera fields of view as projected onto the sky in order to maximize the overlap.

To visualize this, imagine that a single NIRCam field is obtained on an extended object, and a user wants to cover the same region with MIRI. A MIRI mosaic will be required because the MIRI field of view is smaller. If the MIRI observation is scheduled with the field rotated by 45° from the NIRCam observations, the corners of the MIRI fields in the mosaic will hang outside of the NIRCam region, and it will likely require more MIRI pointings to cover the region of interest. A user would likely want specify a PA constraint on the MIRI observation to align (at least approximately) the MIRI field of view with that of the NIRCam observation. (Note, however, there may be allowable options offset by 90° or 180° that would increase schedulability, at least for targets above absolute ecliptic latitude, |~45°|.)

Complications

There are subtleties that can arise in the JWST planning system due to the offset between the origin of the observatory coordinate system and the coordinate system based on a given instrument aperture. Considerable effort has been expended to insulate the science user from this underlying complexity, but it may still be of use to understand that it exists.

As mentioned above, the JWST planning and scheduling system itself will operate on a system of axes (V1, V2, V3) defined with respect to the observatory. Hence, while science users may specify a PA of a particular instrument/aperture on the sky for a given observation, or a relative orientation rotated around the target location, the observatory is actually referenced to (and rotated about) the V1 axis (the boresight), which *is not coincident with the target*. For most cases, the difference in angles is slight and inconsequential. However, in a worst case scenario, close to the celestial poles, a target and the V1 axis position could be at significantly different angles with respect to the pole, which is a complication that the planning system handles internally.

Another subtlety involves the ±5° guideline on the nominal roll flexibility. The ±5° is not a hard number, but rather varies from ±3° (at 85° sun angle) to ±7° (at 135° Sun angle). Thus, with careful planning, operations may be able to squeeze out an extra degree or two of roll flexibility, but it will come at the cost of making a given observation more restricted in terms of when it can be scheduled. There may be special applications, for instance, in certain coronagraphy programs, where this extra angular offset will benefit the science. Fixing observations toward the large end of this range will be very restrictive to scheduling and should only be done when scientifically justified.

Published	22 Feb 2017
Latest updates	• 11 Dec 2019 Reviewed with minor text updates for 2020 Cycle 1. • 06 Feb 2018Minor text edits for improved clarity; added more links. • 03 Aug 2017 Figure 2 updated

JWST Instrument Ideal Coordinate Systems

The locations of the JWST instruments in the focal plane and a description of instrument ideal coordinate reference frames are provided.

> *See also: JWST Position Angles, Ranges, and Offsets, JWST Observatory Coordinate System and Field of Regard, JWST Field of View*

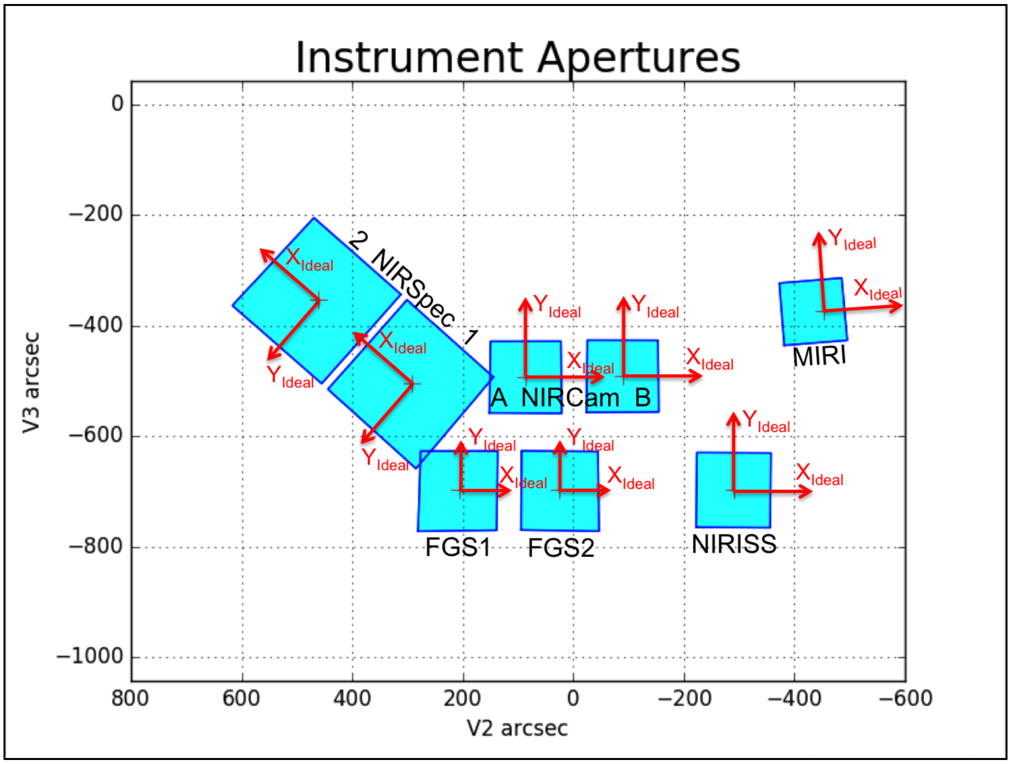
The ideal coordinate system is a distortion-removed frame used for dithers and other pointing offsets. These coordinates correspond to a functional transform of the pixel coordinates in the science frame. The orientation and parity of the ideal coordinate system are equal to the pixel coordinates.

Pixel coordinates are used in *uncalibrated* images produced by the JWST calibration pipeline. The ideal coordinate system is used in *geometrically rectified* images (e.g., the _i2d image products from the pipeline).

The ideal coordinate frame is defined locally for each aperture in the SIAF (Science Instrument Aperture File).

Figure 1 depicts the right-handed *ideal coordinate system* (X_{Ideal}, Y_{Ideal}) for one of the science apertures on each of the JWST instrument detector arrays in the JWST focal plane and its V2/V3 coordinate system. (In this figure, the +V1 axis—the telescope boresight—points into the screen.) For NIRCam, only the 2 long wavelength detectors are shown for simplicity. For the MIRI, the medium resolution spectrometer (MRS) ideal coordinate system (not shown here) is not aligned with the detector arrays (since these have a degenerate and discontinuous mapping to the sky) but is instead defined to be aligned with the V2/V3 coordinate system in the sense that $+X_{Ideal}$ lies along -V2, and $+Y_{Ideal}$ lies along +V3.

Figure 1. JWST instrument detector locations in the JWST focal plane and ideal coordinate system axes



JWST focal plane V2/V3 coordinate system with instrument detectors' fields of view shown as cyan rectangles. (For NIRCam, only the 2 long-wavelength detectors are shown.) For one SIAF[1] aperture on each detector, the right-handed ideal coordinate system is shown in red. For reference, the +V1 axis (boresight) points into the screen. Click on figure for a larger version.

[1] SIAF is Science Instrument Aperture File

Published	30 Mar 2017
Latest updates	

JWST Background Model

JWST observations will detect infrared background emission from multiple sources: the zodiacal cloud, Milky Way Galaxy, and thermal self-emission from the JWST Observatory itself. Both in-field and scattered emission are important contributors to the JWST background.

On this page

See also: Background Variability, Background-Limited Observations, Backgrounds Tool

Several components of infrared background emission will contribute to JWST observations, and these backgrounds are variable with position in the sky and over time. Furthermore, some components of the background are modeled based on pre-mission expectations, which are uncertain at some level. Many observations with JWST will be background-limited, meaning that the noise will be dominated by the level of background emission, and not by photon noise from the target or detector read-noise. The JWST proposal planning system (PPS) calculates these background levels for both planning and scheduling purposes. This page summarizes the sources of background emission that are important for JWST and their relative contribution as a function of wavelength.

A python-based Background tool for JWST is available for providing a visualization of the various background components for a given target and set of assumptions.

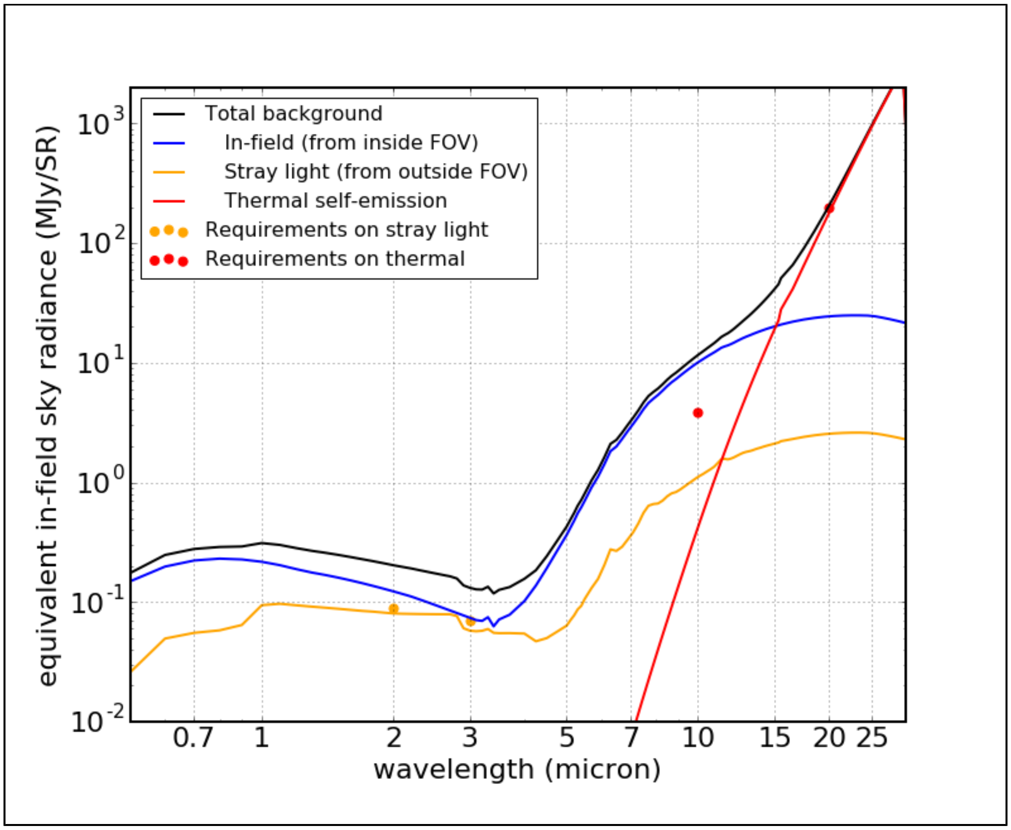
Components of the background emission

Several components contribute to the background emission that JWST will detect. The primary in-field sources of this background are the zodiacal cloud of the Solar System and the Milky Way Galaxy. In the thermal infrared (longward of ~15 μm), the background is dominated by thermal self-emission, mostly from the JWST primary mirror segments, as well as scattered thermal emission from the sunshield. Since JWST does not have a traditional optical baffle, light from the out-of-field sky can also gain access to the focal planes through scattering—this additional source of background is called "stray light."

Figure 1 illustrates the relative expected contributions of these components to the JWST background for a benchmark pointing. This pointing (ecliptic Long, Lat = 266.3°, −50.0°; RA, Dec [J2000] = $17^h26^m44^s$, −73° 19'56") has a zodiacal emission that is 20% higher than the celestial minimum. It was chosen as a benchmark because it is a stressing case for stray light. The backgrounds are expressed as equivalent units of uniform sky radiance (megaJanskys per steradian, or MJy/sr) at the JWST focal planes. Figure 1 shows that, in general, in-field zodiacal emission and scattered light are the main sources of background at wavelengths less than 4 μm; in-field zodiacal emission dominates from 4 to 15 μm, and thermal self-emission dominates at wavelengths longward of 15 μm. At 4–8 μm, the thermal emission from the zodiacal dust is particularly steeply rising, with the surface brightness well described by the Wien approximation. As a result, NIRCam imaging observations at 4–5 μm are background limited and medium filter (F410M, F430M, F460M, F480M) observations are more sensitive than wide filter (F444W) observations.

Stray light, which is out-of-field emission scattered into the field of view, is primarily due to the zodiacal cloud and the Milky Way. In the example shown in Figure 1, this stray light is less than but comparable to the in-field zodiacal emission from 1 to 4 μm. The amount of stray light depends on ecliptic latitude (pointings toward the ecliptic poles will have lower stray light) and the orientation of the Milky Way with respect to JWST for a given pointing. Since the benchmark pointing used in Figure 1 was chosen to be a stressing case for stray light, most extragalactic deep fields should have a lower level of stray light. As one example, the stray light level in the Hubble UltraDeep Field (HUDF) should be about half that indicated by the benchmark pointing.

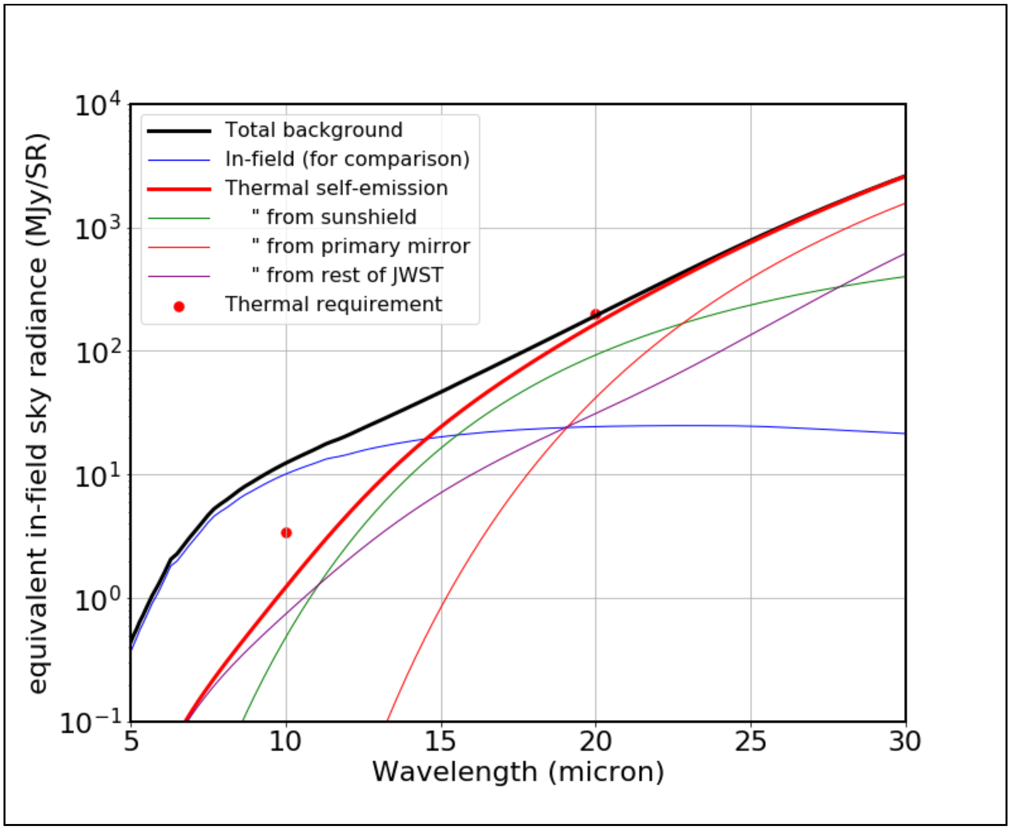
Figure 1. Contributions to JWST background emission, expressed in equivalent units of uniform sky radiance (MJy/SR) at the JWST focal plane



This example is for the benchmark pointing (ecliptic Long, Lat = 266.3°, 50.0°, RA, Dec (J2000) =17^{h}26^{m}44^s 73°19'56"), chosen to have a zodiacal emission that is 20% higher than the celestial minimum, and to be a stressing case for stray light. In this example, in-field emission from the zodiacal cloud and the Milky Way (blue curve) dominates the background for most wavelengths below 15 m. At longer wavelengths, thermal emission from JWST itself (red curve) is the dominant source of background. Stray light (yellow curve) results from zodiacal and Milky Way emission scattered into the field of view, and is a significant fraction of the total background, particularly at 1 to 4 m. The sum of all these emission components is the total background (black curve).

At wavelengths greater than 15 µm, the background seen by JWST is expected to be dominated by thermal emission from JWST itself. Figure 2 shows the expected spectrum of this thermal self-emission, and the major components that produce it. This thermal emission dominates the background at wavelengths longer than 15 µm. As Figure 2 shows, emission from the primary mirror is expected to dominate at wavelengths greater than 21 µm, and that scattered thermal emission from the sunshield will dominate from 15 to 21 µm. As discussed above and shown in Figure 1, at wavelengths shorter than 15 µm, the in-field zodiacal background dominates over thermal emission at the benchmark pointing. The thermal curve plotted in Figure 2 is a conservative estimate of likely on-orbit performance; it is incorporated into the JWST Exposure Time Calculator (ETC) and the JWST scheduling system.

Figure 2. Expected thermal self-emission from JWST



The expected level of thermal self-emission from JWST (thick red curve) is derived from extensive thermal modeling. The contribution from the primary mirror (thin red line) dominates at wavelengths greater than 23 m. Thermal emission from the sunshield dominates at 15 to 23 m. Thermal emission from the rest of JWST (purple line) is also shown. The total thermal self-emission (thick red line) is a conservative estimate of expected performance; it is what is assumed by the JWST ETC and APT. Also shown (red dots) are the JWST design requirements for thermal performance (3.4 MJy/sr at 10 m, and 200 MJy/sr at 20 m). For comparison, the total background (thick black line) and the in-field backgrounds (blue line) from Figure 1 are also shown. At wavelengths below 14 m, the in-field zodiacal background is more important than the thermal self-emission.

Uncertainty in background levels

In addition to the variability of the backgrounds, there is intrinsic uncertainty in the models used. The ETC calculates the in-field zodiacal and Galactic backgrounds using a model based on Cosmic Background Explorer (COBE) data (Kelsall et al. 1998; Reach et al. 1997), that was developed and used operationally for the Spitzer Space Telescope, with the Galactic stellar contribution refined using data from the Wide Field Infrared Survey Explorer (WISE) survey. This model agrees with the Spitzer Infrared Array Camera (IRAC) measurements at the few percent level (Krick et al. 2012). As such, the in-field backgrounds predicted by the ETC should be very reliable.

By contrast, the predicted levels of stray light and of thermal self-emission carry considerable intrinsic uncertainties. These estimates depend on extensive modeling of the scattering properties of observatory materials, estimates of the amount and properties of contaminating dust particles, knowledge of the deployed observatory configuration, and thermal models incorporating material emissivities which result in temperature estimates of all surfaces which can act as sources of thermal background.

The stray light estimates are thought to have uncertainties of order (+30%, −20%). Proposers should use the ETC to understand the extent to which stray light contributes to the total background of their observations, and bear in mind these uncertainties on the stray light predictions.

The thermal background curve (thermal self-emission in Figures 1 and 2) is a conservative best estimate based on detailed thermal modeling. It is neither a worst nor best case scenario, and is also uncertain at the (+30%, −20%) level. *Users are cautioned that, for cycle 1, exposure time estimates will be highly uncertain for background-limited observations at wavelengths longer than 15 μm until actual performance can be determined on orbit.*

Both the thermal and stray light backgrounds will be measured during the commissioning of JWST; results will be disseminated to users prior to the cycle 2 proposal deadline.

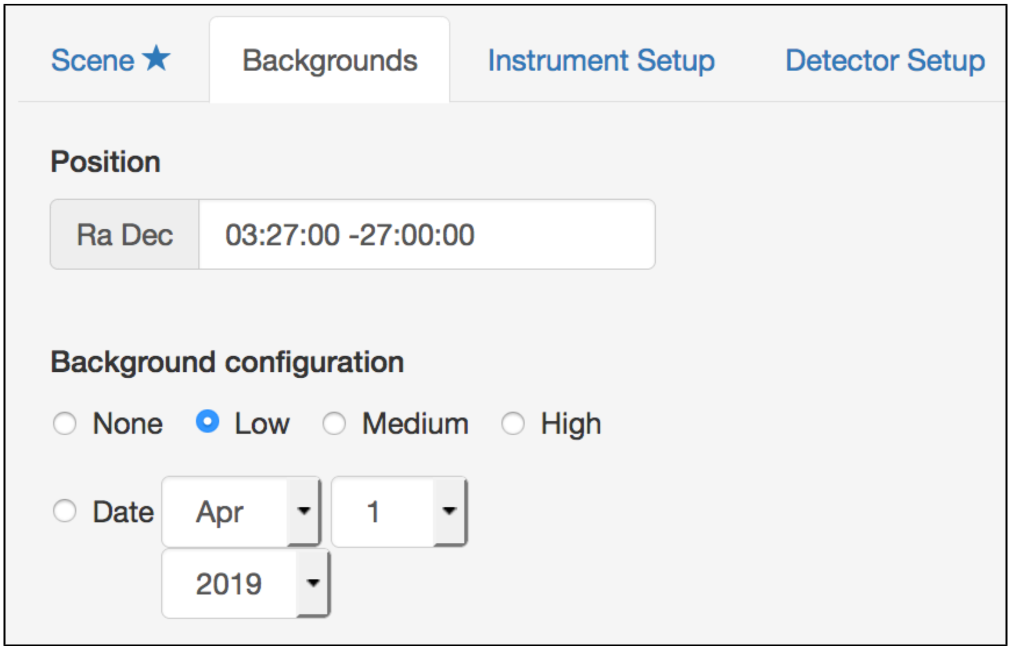
Background levels in the ETC and JIST

See also: JWST Exposure Time Calculator Overview

The JWST Exposure Time Calculator (ETC) will calculate backgrounds for a given celestial position. If the user specifies a date, the ETC will give the best estimate of background on that date. Otherwise, the user can choose a low background (10th percentile), a medium background (50th percentile), or high background (90th percentile), all calculated for the selected celestial position over the period of visibility at 3.5 microns (selected as a typical NIR wavelength of interest, noting that the time-dependent component of the background dominates only in the NIR). Figure 3 shows how to input this background information into the ETC. The computed background spectrum can be downloaded as a FITS file, and the total background can be found in the "background" section of the input.json file included in the ETC downloads, as described in the JWST ETC Outputs Overview page.

The quick-look JWST Interactive Sensitivity Tool (JIST) makes a simplifying assumption for background: JIST assumes background of 1.2 times the minimum zodiacal background.

Figure 3. ETC screenshot of the Backgrounds tab



An ETC screenshot of the Backgrounds[*] tab, selecting the background for a given position, and the 10th percentile best background (Low). If the anticipated date of the observation is known, the user can specify the background calculation to be specific to that time.

[*] ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Background Levels in the APT

See also: JWST Astronomers Proposal Tool Overview, APT Special Requirements

If your observation(s) are *not limited by background*, nothing has to be done when specifying the observation is APT. However, if your experiments with the ETC convince you that your observation is background-limited, you can set a ***Background Limited*** special requirement on the relevant observation, which can restrict scheduling to periods of lowest background.

References

Kelsall et al. 1998, *ApJ*, 508, 44
The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. II. Model of the Interplanetary Dust Cloud

Krick J. E. et al., 2012, *ApJ*, 754, 53
A Spitzer/IRAC Measure of the Zodiacal Light

Reach, W. T., Franz, B. A., & Weiland, J. L, 1997, *Icarus*, 127, 461
The Three-Dimensional Structure of the Zodiacal Dust Bands

Published	30 Dec 2016
Latest updates	• 20 Dec 2019 Thermal background component updates, and other small changes made in preparation for 2020 cycle 1. • 15 Nov 2017 The previous "Backgrounds" article was restructured into several new articles. This one now concentrates on the components that contribute to the overall infrared background. • 17 May 2017 Added more information in section “How to request low background for background-limited observations” • 25 Apr 2017 Replaced Figure 3 Added Figure 4 Added text in section "how backgrounds are treated by planning system"

Background Variability

Backgrounds in JWST observations will vary seasonally for a given sky position; the magnitude of that variation depends on the observation wavelength and ecliptic latitude.

On this page

Parent article: JWST Background Model
See also: Background-Limited Observations, Backgrounds Tool

JWST observations will include background emission from the zodiacal cloud, the Galaxy, and the observatory itself. A component of the background that varies seasonally is the zodiacal emission, due to the changing path length of Solar System dust through which JWST must look and the temperatures of that dust. This means that for a given fixed target, the JWST backgrounds will vary seasonally in a predictable way. The variation is most pronounced for wavelengths <15 μm, where zodiacal emission dominates the JWST background, and for targets at low ecliptic latitude (near the ecliptic plane). One consequence, as explained below, is that targets near the ecliptic plane may be observable with a low background for only a small fraction of their observable window. This can be a significant scheduling constraint for observations that are determined to be background limited.

JWST backgrounds will vary seasonally for a given sky position. The magnitude of its variation depends on the observation's wavelength and the target's ecliptic latitude.

APT, the ETC, and the JWST scheduling system calculate these backgrounds, using the same background model. The Backgrounds Tool can be used to calculate and visualize the seasonal variation of backgrounds for a given target.

Spatial and temporal variability of the background

Some components of the JWST background should be constant with time and telescope pointing, while others vary seasonally.

Thermal self-emission

Thermal self-emission should dominate the JWST backgrounds for wavelengths $\geq$15 µm. The pre-launch assumption is that the thermal self-emission of JWST will be constant with time and telescope pointing. This assumption is made by APT, the ETC, and the JWST scheduling system, and will be tested during on-orbit commissioning.

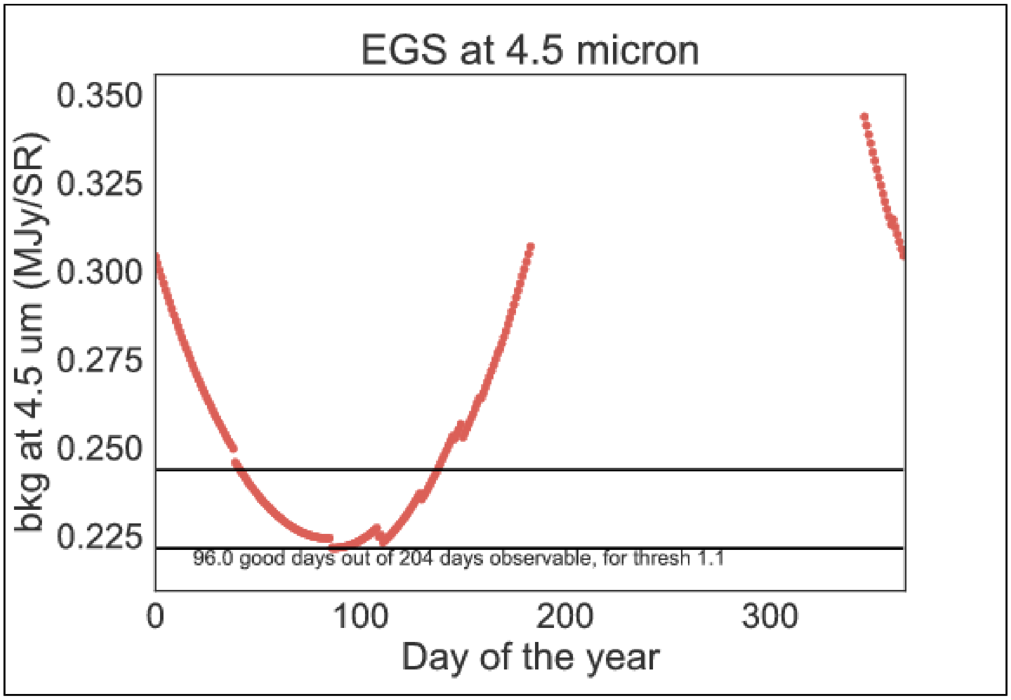
Spatial variation of in-field emission

The in-field zodiacal emission depends strongly on ecliptic latitude. The in-field *Galactic emission* depends strongly on Galactic latitude.

Temporal variation of in-field emission

JWST can observe any specified location on the sky for at least 100 days per calendar year. The length of the visibility window increases with increasing ecliptic latitude. Within a visibility window, the in-field Galactic background will be constant, while the in-field zodiacal background will vary predictably with date as JWST looks through different path lengths of dust, with different temperatures, in our Solar System. Figure 1 shows an example of the temporal variability of the background over one year.

Figure 1. Example of seasonable variation of the JWST background



The total background versus day of the year for the Extended Groth Strip (EGS), which is an extragalactic deep field. This example is for a wavelength of 4.5 m, where the background is dominated by zodiacal emission. The lower horizontal line marks the minimum background level for this RA, Dec, and wavelength. The upper horizontal line shows a background level that is 10% above the minimum background. For this example, the target is observable for 204 days per year, and 96 of those days have a background level <10% above the minimum background. Users can add the Background Limited* special requirement in APT to specify that a background-sensitive observation should be scheduled when the background is relatively low. The default for this case in APT, as shown above, is "within 10%".

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Spatial and temporal variation of stray light

Users should be aware that JWST is subject to stray light, and they should use the ETC to understand the degree to which stray light affects the signal-to-noise estimates for their planned observations.

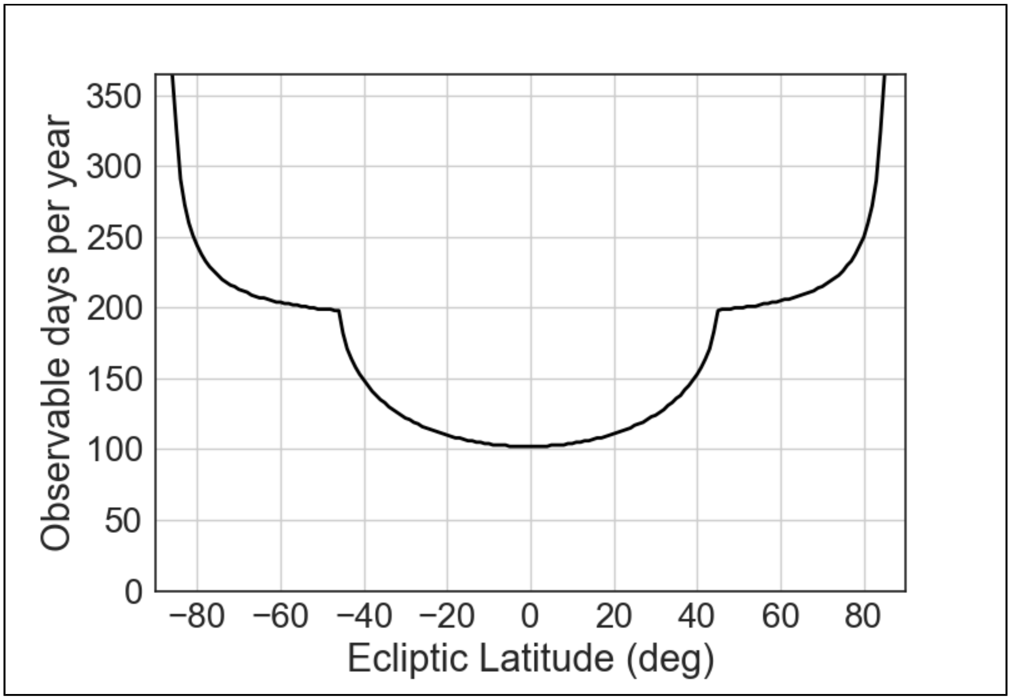
The amount of stray light depends on the pointing and the observatory V3 roll angle. Models predict a correlation of the stray light level with the in-field zodiacal and Galactic background level, since much of the susceptibility to stray light occurs within tens of degrees of the boresight (observatory V1 axis).

However, JWST is also susceptible to stray light from sources located far from the boresight. The JWST Exposure Time Calculator (ETC) uses maps that predict the susceptibility of JWST to stray light, given material properties and expected levels of dust contamination. For a given celestial position and date (which determines the nominal observatory V3 roll angle), the ETC projects the susceptibility maps onto the astronomical sky, to predict the amount of stray light at each instrument focal plane.

How the seasonal variation of the background affects schedulability

The number of days per year that a target is observable to JWST is a simple function of ecliptic latitude, as illustrated by Figure 2. The JWST backgrounds are also a function of ecliptic latitude—both the minimum background over a year, and the shape of the seasonal variability curve. This has important consequences for target observability.

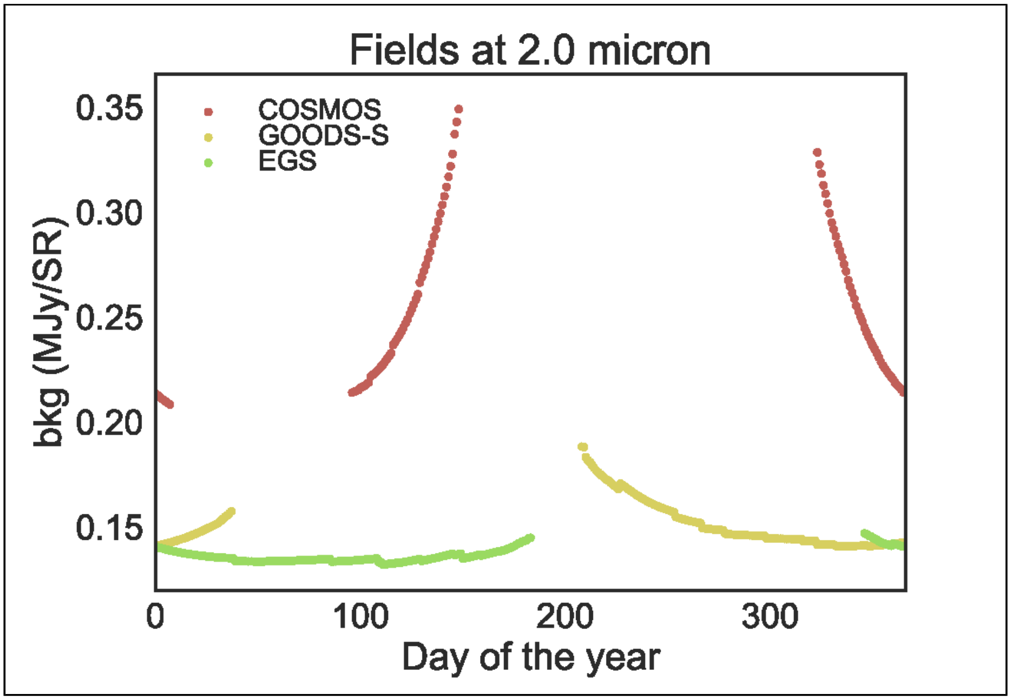
Figure 2. Number of days per year that targets are observable to JWST

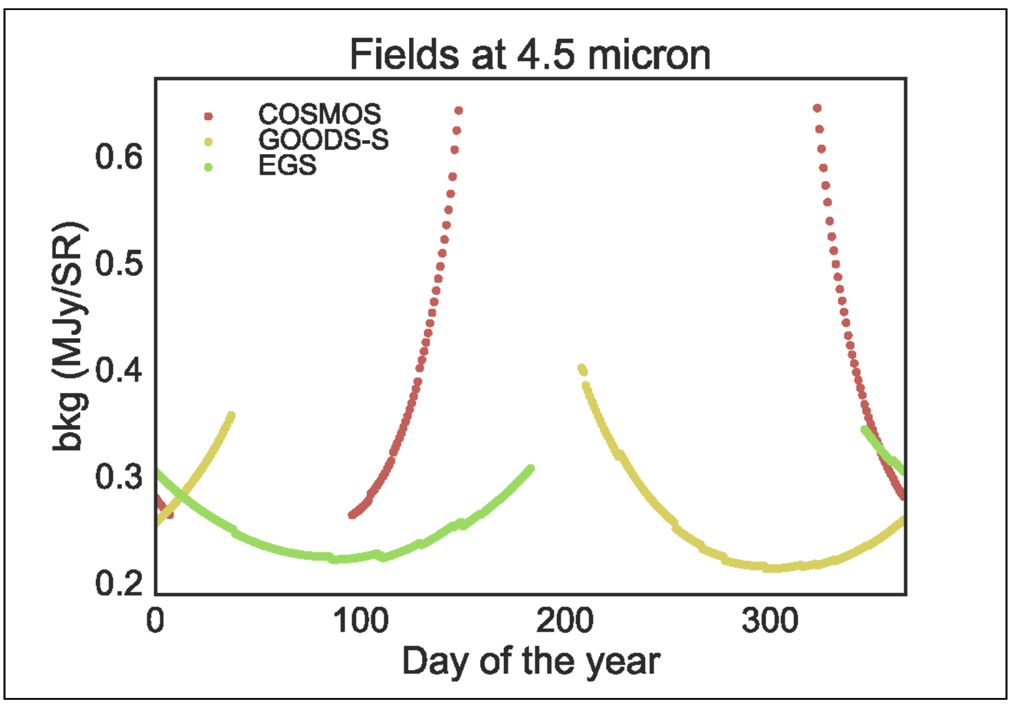


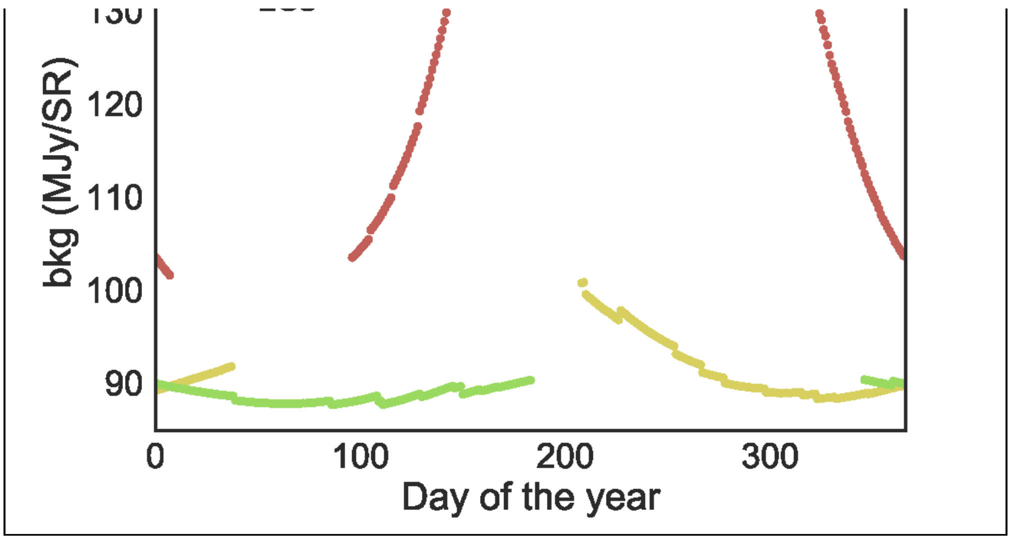
The number of days per year that targets are observable to JWST is a simple function of ecliptic latitude.

Figure 3 illustrates how the seasonal variation of the JWST background is a predictable function of wavelength and ecliptic latitude. Targets at high ecliptic latitude and high Galactic latitude will have lower background than targets near the ecliptic plane or the Galactic plane. Figure 3 illustrates this: the background is lower for the 2 fields at high ecliptic latitude, compared to the COSMOS field which is located near the ecliptic plane. Moreover, ecliptic latitude controls how steeply the background rises with time: at high ecliptic latitude the background-versus-time curves are shallow, whereas near the ecliptic plane, the curves rise steeply. As a result, targets near the ecliptic may be observable with low background at 5–10 µm for only a few days per year.

Figure 3. Total background versus calendar date for selected extragalactic deep fields



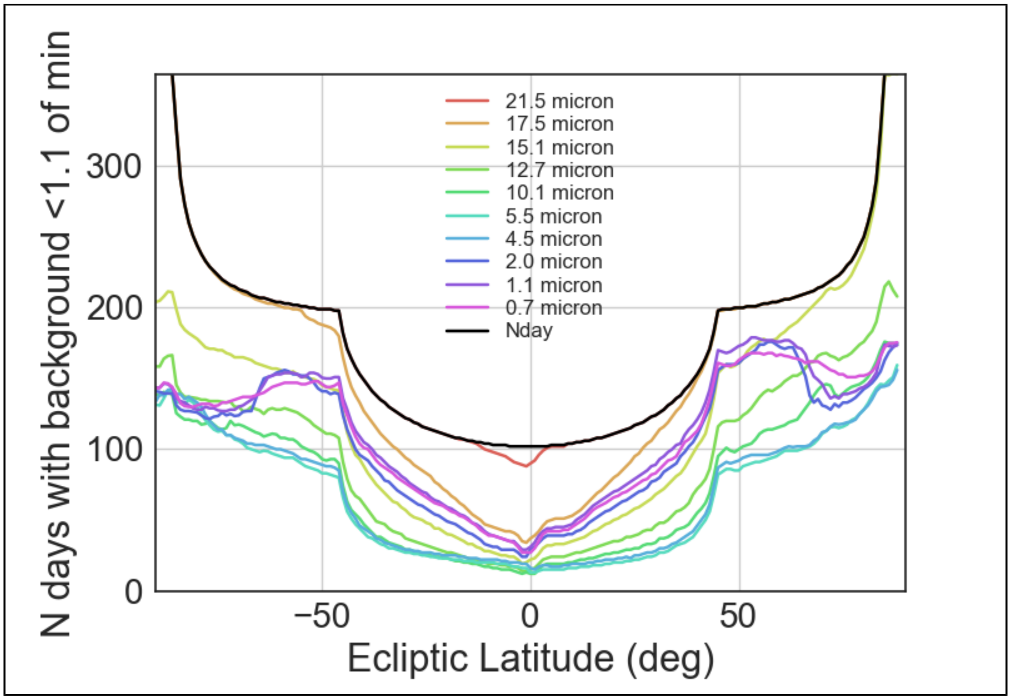




Total JWST background versus calendar date for 3 extragalactic deep fields, at 3 choices of wavelength: 2.0 m (top panel), 4.5 m (middle panel), and 17.5 m (bottom panel). The example targets are chosen to span a range of ecliptic latitude: 9° for COSMOS, 45° for GOODS-S, and +60° for the EGS.

Figure 4 expands these results for all ecliptic latitudes. Figure 4 plots the median number of low background days, as a function of ecliptic latitude, for the central wavelengths of the JWST broadband filters. Figure 4 shows that targets with low ecliptic latitude (−40° to +40°) are observable for only a few days per year with low background. For example, targets on the ecliptic have only 14 days/year with background <10% above the minimum at 5 µm.

Figure 4. Number of days that a target is observable to JWST with low background, versus ecliptic latitude



Number of days per year that targets are observable to JWST and have low background (for the default threshold of <10% above the minimum background), as a function of wavelength and ecliptic latitude. What is plotted is the median value in bins of 1° in ecliptic latitude. The thick black line, labeled "Nday," shows the number of days per year that a target is observable, at any background level, as a function of ecliptic latitude.

Advice for proposers

See also: Background-Limited Observations

The Background-Limited Observations article describes a simple method, using the JWST ETC, to determine whether the signal-to-noise ratio of a particular observation is sensitive to the time-variable background. Observations that are background sensitive should use the ***Background Limited*** special requirement in APT, so that the observation will be scheduled when the background is relatively low. This special requirement affects the schedulability of an observation.

Published	30 Dec 2016
Latest updates	

	• 06 Feb 2018 Minor text clarifications. • 15 Nov 2017 This article broken out from the old Backgrounds article into a separate article, and expanded. • 17 May 2017 Added more information in section “How to request low background for background-limited observations” • 25 Apr 2017 Replaced Figure 3 Added Figure 4 Added text in section "how backgrounds are treated by planning system"

Background-Limited Observations

Observers can assess if their observations are sensitive to background levels using the JWST Exposure Time Calculator (ETC), and then apply the ***Background Limited*** special requirement in APT to limit scheduling to when the background is relatively low. This special requirement affects the schedulability of observations.

On this page

Parent article: JWST Background Model
See also: Background Variability, Backgrounds Tool

Observers can assess the sensitivity of their proposed observations to the JWST background using the JWST Exposure Time Calculator (ETC). If the signal-to-noise ratio of an observation depends by more than 5% on the time variable JWST background levels, then users should use the ***Background Limited*** * special requirement to request that the observation is scheduled when the background is relatively low. Because this special requirement affects the schedulability of observations, it may be necessary to make a trade-off between background levels and schedulability.

Many observations with JWST will be background limited, meaning that the noise will be dominated by the level of background emission, and not by photon noise from the target or detector noise. The JWST Background Model article describes the origins of the background emission and its spectral shape, while Background Variability describes time variable aspects of the various background components.

There are multiple components to the JWST background. The one that varies seasonally is the zodiacal emission, due to the changing path length of Solar System dust through which JWST must observe, as well as the temperature and temperature range of that dust. As a result, for mid-infrared wavelengths where the zodiacal emission peaks, a target may have a low background for only a fraction of all the days when the target is technically observable. For an overview of the backgrounds at a given sky position, consider using the Backgrounds Tool to visualize the time variability.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

The *Background Limited* special requirement in APT

See also: JWST Astronomers Proposal Tool Overview, APT Special Requirements

The JWST ground system has a requirement to schedule the ensemble of background limited observations at times when the background is relatively low, within 10% of the minimum background for those targets. *Users are responsible* for identifying to the scheduling system those observations that are sensitive to the variable background level, by using the ***Background Limited*** special requirement in APT.

It is often not obvious whether a particular observation needs to use the ***Background Limited*** special requirement. Here are two non-intuitive examples:

1. MIRI imaging at 25.5 μm is background limited, but that background is dominated by emission from the primary mirrors (assumed by the ETC to be time independent), not by the time variable zodiacal emission. As a result, all observable dates for a target may have a background level that is <10% above the minimum background.

2. While sufficiently deep NIRCam imaging at 4.4 μm will be dominated by the time variable zodiacal emission, for shallower observations the SNR will instead be dominated by detector effects. The integration time where that transition occurs is a function of wavelength, brightness, ecliptic latitude of the target, and the chosen filter.

Users should not try to guess whether the ***Background Limited*** special requirement is needed for their observation**.** Users should calculate whether it is needed, using the method described below.

How to determine if an observation needs the *Background Limited* special requirement in ETC

See also: JWST Exposure Time Calculator Overview

1. In the ETC **Backgrounds** tab, specify the RA and Dec of the target (see Figure 1).

2. Select ***Low*** background. Click ***Calculate*** (bottom right of the panel, not visible in Figure 1) and make note of the signal-to-noise ratio (SNR).

3. Select ***High*** background. Click ***Calculate*** and, again, note the SNR.

4. On your own, calculate the fractional change in the SNR, X, where
   `X = [SNR(low bkg)  SNR(high bkg)] / SNR(low bkg)` (Equation 1)

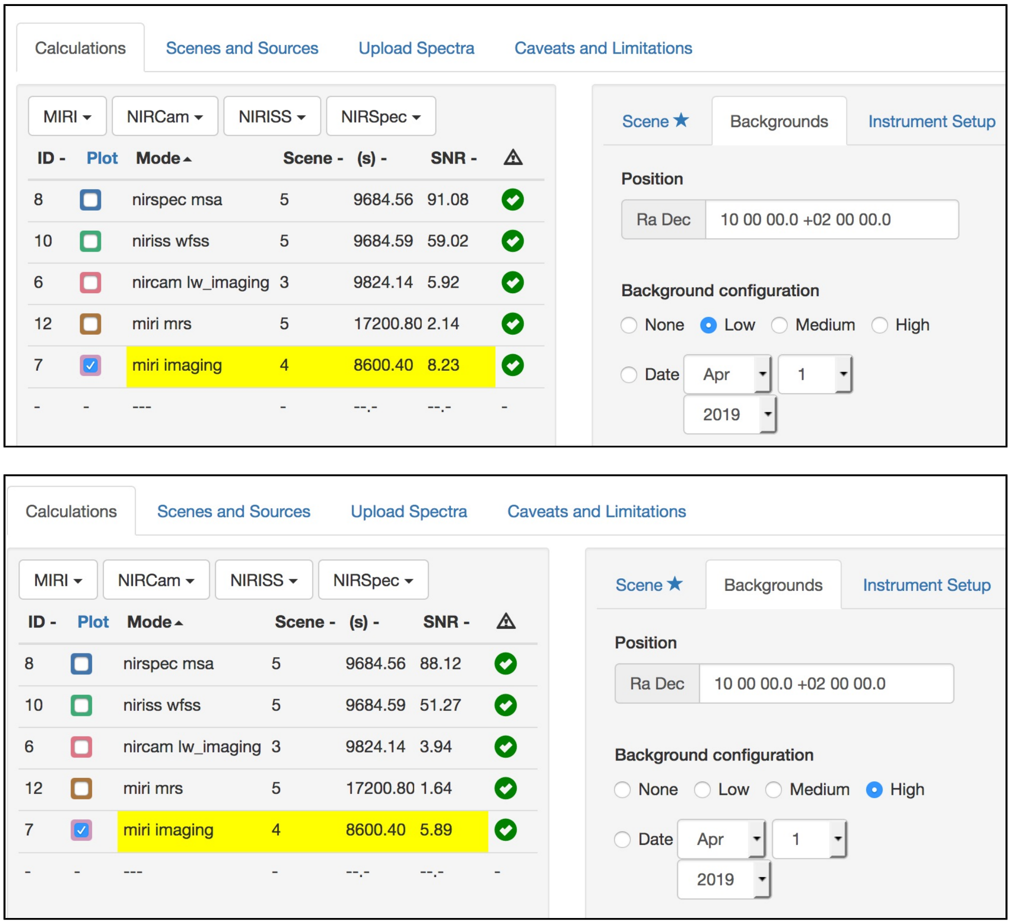
5. If X > 0.05, then the SNR of this observation depends by more than 5% on the variable background level. You *should use* the ***Background Limited*** special requirement in APT, at the default value of <10% above

the minimum background, unless you have a good reason not to do it.

6. If X < 0.05, then your observation is not sensitive to the time variable background. You *should not use* the ***Background Limited*** special requirement in APT.

The threshold value of X = 0.05 was chosen for consistency with the ground system requirements. Proposers are encouraged to mention the results of this calculation in their technical justification, especially if they select the ***Background Limited*** special requirement.

Figure 1. How to determine whether an observation needs the *Background Limited* special requirement



Screenshots showing an ETC calculation to determine whether the* Background Limited *special requirement should be used. In the upper panel, the Backgrounds tab of the ETC is open, the RA and Dec have been set (step 1), in this case for the COSMOS extragalactic deep field on the ecliptic plane. The dateless background has been set to Low (step 2). The resulting SNR column shows the signal to noise for the low background case (the 10th percentile lowest background for that target over all observable dates). In the lower panel, the SNR has been recalculated using the High background case (90th percentile highest background for that target over all observable dates).

Figure 1 shows 5 worked examples of this method. For the examples in Figure 1, calculation #8 (NIRSpec MSA) has X = 0.03, so the ***Background Limited*** special requirement should not be used. The other observations have X > 0.05, and therefore should use the ***Background Limited*** special requirement.

How to apply the *Background Limited* special requirement in APT

The ***Background Limited*** special requirement has a variable: the maximum permitted background for the RA, Dec, and wavelength of an observation. The default value is <10% above the minimum background for that RA, Dec, and wavelength. Higher values may be chosen to increase schedulability when there are competing constraints.

The APT Special Requirements page provides guidance on how to use APT to apply the ***Background Limited*** special requirement to an observation.

The *Background Limited* special requirement affects schedulability

Since the ***Background Limited*** special requirement limits the schedulability of an observation to times when the background is relatively low, it is effectively a scheduling constraint. For targets at low ecliptic latitude, the ***Background Limited*** special requirement may restrict the schedulable window to 10–20 days per year. Thus, users should apply the ***Background Limited*** special requirement only if scientifically justified.

Applying *both* the ***Background Limited*** special requirement and another scheduling requirement (for example, one of the aperture position angle special requirements) may make an observation impossible to schedule. Users will have to decide which constraints are more important to the science goals, and relax constraints until the observation becomes schedulable. Within the ***Background Limited*** special requirement, the user may select an acceptable background level higher than the default (of 10% above the minimum) to improve schedulability.

Best practices

1. Users should assess whether the signal to noise estimates of their observations are sensitive to the level of the time variable background, using the ETC method described above. If yes, then the ***Background Limited*** special requirement should be added to the observation, to request scheduling when the background is relatively low.

2. *Proposers should not use the **Background Limited** special requirement when it is not justified*. Doing so will decrease schedulability while negligibly improving the signal-to-noise ratio.

3. Users should exercise caution when adding any additional scheduling requirements to an observation that has the ***Background Limited*** special requirement. This is especially true for targets at low ecliptic latitude. Multiple scheduling requirements may make the observation impossible to schedule.

4. Users should be aware that a constraint on the aperture position angle can be incompatible with the ***Background Limited*** special requirement since both are effectively scheduling constraints.

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Latest updates	• 15 Nov 2017 New article, broken out from old Backgrounds article, concentrating on the need for and use of the new BACKGROUND LIMITED special requirement. • 17 May 2017 Added more information in section “How to request low background for background-limited observations” • 25 Apr 2017 Replaced Figure 3 Added Figure 4 Added text in section "how backgrounds are treated by planning system"

JWST Guide Stars

JWST uses a single guide star in one of the FGS fields for fine guiding during a given visit.

On this page

Fine guiding is provided by a single guide star. Roll control is provided separately by the spacecraft star trackers.

It is not the user's responsibility to pick specific guide stars to be used for their observations. JWST guide stars are selected from the GSC2.4 catalog by the guide star selection system (GSSS) based on several factors related to telescope pointing and suitability of the star. Tools and reports are available to visualize the availability of guide stars for a target.

Guide Star Catalog

See also: JWST Pointing Performance

The JWST proposal planning system currently uses Guide Star Catalog (GSC) version 2.4 for the selection of guide stars and reference stars. GSC 2.4, released for JWST use in November 2017, is a major update to the GSC used for many years for HST operations. GSC 2.4 is a merger of GSC 2.3 with data from 2MASS, Sloan Digital Sky Survey (SDSS) DR13, Gaia DR1, and VISTA[1] Hemisphere Survey (VHS) DR4. SDSS and VHS stellar data improve the quality of the GSC, particularly at the fainter magnitudes (J > 17), which significantly improves the JWST guide star availability at higher Galactic latitudes.

Improvements in the catalog that have resulted in increased guide star availability include:

1. Guide star catalog object classifications as stellar or non-stellar have been improved. Analysis has shown that SDSS and VHS are particularly helpful in this regard, especially for J > 17. Guiding on slightly extended sources can reduce guiding accuracy.

2. Additional photometric information, especially in the near-infrared, has been made available. In order to be considered a valid JWST guide star candidate, a GSC object must have photometry available in 2 or more bandpasses so interpolations or extrapolations can be made as needed. If a given star has more photometry bands, its total observed FGS count rate can be more accurately predicted, making it possible to determine if it’s a guide star that will provide successful acquisition, tracking, and fine guidance functions.

3. The Gaia DR1 catalog provides significant astrometric improvement (0.001” vs >0.1”) for essentially all stars near the galactic plane, and for about half the stars at higher galactic latitudes.

4. Coverage gaps in GSC 2.3 have been filled, for example, in areas around very bright stars and in regions of very high extinction.

[1] Visible and Infrared Survey Telescope for Astronomy

Guide star availability

Guide Star Catalog objects need to meet a number of requirements, discussed below, in order to be considered a JWST guide star candidate for a given observation. The area density of guide star candidates is strongly correlated with Galactic latitude, with the density falling sharply for regions about 35° above or below the plane of the galaxy. The FGS field of view and sensitivity, along with the depth of known stars in the Guide Star Catalog, determine the availability of guide stars for any particular pointing and orientation of the telescope. Mission requirements call for a 95% probability of acquiring a guide star and maintaining pointing stability for any permitted pointing of the telescope. The statistical availability of guide stars as a function of galactic latitude is used by APT to determine the visit splitting distance it assumes for each target/observation.

Given the GSC 2.4 content, FGS sensitivity, and operational limitations, the probability of finding a guide star is 97% or higher at all galactic latitudes. VHS southern sky coverage is nearly complete but there are small areas of the southern sky that are not yet in the catalog (see www.vista-vhs.org).

Photometric measurements of the guide star candidates contained in the GSC are used to predict the count rate of the star at the FGS detector (which is needed by the FGS to successfully acquire the guide star). This involves transforming the catalog’s optical photometric measurements into the near-infrared (if 2MASS data are unavailable), and then applying wavelength dependent telescope and FGS throughput factors over the 0.6–5.0 μm passband of the FGS.

Guide star selection criteria

JWST uses a single guide star in one of the FGS fields for fine guiding during a given visit. Roll control is provided separately by the spacecraft star trackers (see JWST Attitude Control Subsystem.) The following criteria are used to select up to 3 guide star candidates for each visit:

- Guide star candidates must be classified as point sources in the GSC; extended objects ("non-stars") are excluded.

- Guide star candidates must be in the magnitude range of $12.5 \le J \le 18.3$ (the limits vary slightly with spectral type of the star).

- No bright spoiler stars exist within 6″ of a guide star candidate. A spoiler star in this context is defined to be a star that is less than two magnitudes fainter than the guide star candidate.
- A guide star candidate must be detected in two or more of the catalog’s photometric passbands so its brightness in FGS count rate can be derived.
- Each guide star candidate may be (but is not required to be) augmented by up to 10 “reference stars,” which will be used in the guide star identification pattern matching algorithm to identify the correct guide star.
- Compact objects classified as non-stars in the GSC can be used as “reference stars” for the guide star identification algorithm.

Retrieving and visualizing JWST guide stars

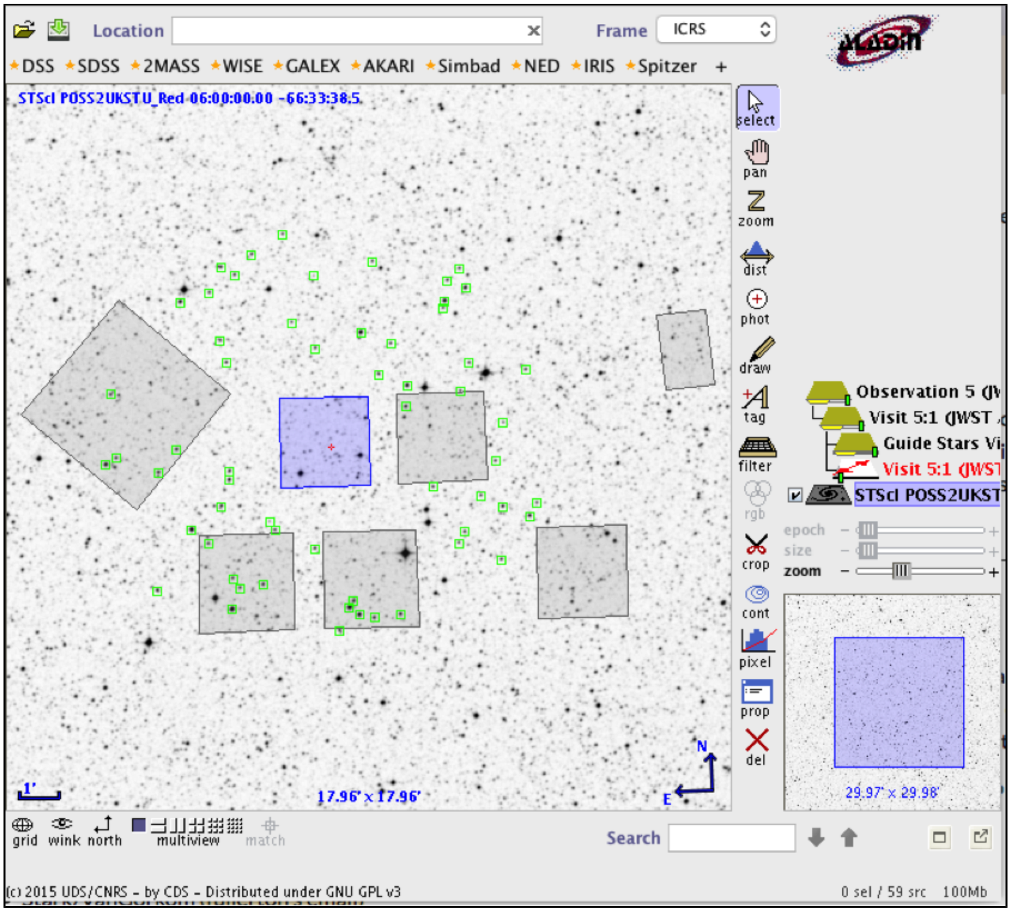
See also: APT Aladin Viewer

It is not the proposer's responsibility to pick specific guide stars to be used for observations. However, there are cases where you may want to understand the availability of potential guide stars for a particular target, and the Astronomer Proposal Tool (APT) provides a way to help you evaluate this.

At the visit level in APT, select **View in Aladin*** in the main menu. Then, in the same window, click on the ***FoV*** and ***JWST GS*** buttons in the **APT Aladin Controls**.

In the separate Aladin pop-up window, the JWST focal plane and guide star candidates are displayed. These candidates are stars that have met the constraints applied by the guide star selection system (basically the guide star selection criteria described above). An overlay of the DSS can be included by either clicking the ***DSS*** icon in the Aladin display or opening the folder icon at the top left of the window and choosing the ***DSS option***. (Note: this displays the DSS view with a dark background.) For planning observations, the former method is recommended and is shown in Figure 1, which illustrates this for a NIRCam observation. Green squares denote the guide star candidates that are available for the visit, with only those within the FGS apertures being applicable for that particular roll angle of the observatory.

Figure 1. Aladin display of the JWST focal plane overlaid with a DSS field



One potential use case for this functionality would be a situation where the user has fixed the desired position angle to some value (or a range), and run the Visit Planner only to find the observation is declared unschedulable due to lack of available guide stars. The user could view the observation in Aladin and assess the guide star situation, and determine an alternate position angle or range where a guide star would be available.

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

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	• 14 Nov 2017 New Figure 1 Major updates to text

JWST Mosaic Overview

JWST mosaic observations, a series of pointings covering an area larger than an individual instrument field of view, can be specified using parameters in the relevant APT observation templates.

On this page

See also: APT Mosaic Planning

JWST offers the capability to mosaic regions that are larger than a single field of view (FOV). This is useful not only for imaging instrument modes but also for integral field units (IFUs) in NIRSpec and MIRI MRS. A mosaic is made up of a series of pointings, called *tiles*, each of which may be dithered. These mosaics can be planned in the Astronomer's Proposal Tool (APT).

Table 1. APT science templates allowing mosaics

Instrument	Template
NIRCam	Imaging
NIRCam	Wide field slitless spectroscopy (grism)
MIRI	Imaging
MIRI	Medium resolution spectroscopy (IFU)
MIRI	Low resolution spectroscopy
NIRSpec	Integral field unit (IFU)
NIRSpec	Fixed slit
NIRISS	Imaging
NIRISS	Wide field slitless spectroscopy (grism)

Table notes:

- The MIRI MRS is a special case since the field of view sizes for the 4 MRS wavelength ranges are different from each other.
- Time series modes, coronagraphy, NIRSpec multi-object spectroscopy, and templates for observations of individual targets are not useful for mosaics; to avoid confusion, mosaics have been disallowed in those templates.

Mosaic functionality

Mosaics are defined by a single coordinate, an assumed tile footprint (size and orientation), and a designated number of rows and columns of the tile footprint. Each instrument and mode that allows mosaics have a FOV size and reference axis defined in the Science Instrument Aperture File (SIAF), which is the official repository for all defined instrument-related positional and angular definitions.

If a dither pattern is defined for a given tile, it is the combined region covered by the FOV and the dithers that define a tile footprint for a given mosaic. This is the footprint that should be considered when addressing the overlap of tiles in a given mosaic. Because the various instrument FOVs have different shapes and dimensions, it's useful to always view their defined mosaics in the Aladin viewer in APT to assess the overall shape and coverage of their mosaic.

Because the overall mosaic footprint will rotate with time, it's helpful to define your mosaic footprint to be approximately symmetrical on the sky. If a non-symmetrical mosaic is needed to cover a particular target, the user should fix the position angle of the mosaic and define the tiles to cover the region of interest.

However, it may or may not be possible to find guide stars simultaneously for all tiles in a highly constrained mosaic. Also, fixing the orientation of mosaics essentially requires fixing the time of the observations, and many such observations can overly constrain observation scheduling. Users should only fix the position angle of mosaics when necessary for science. Consider obtaining insight into the available range of position angles using one of the JWST Target Visibility Tools.

Imaging mosaics

See also: APT Mosaic Tile Splitting Activity; APT Simple Mosaic Example;, MIRI Imaging Mosaics, NIRCam Mosaics

See also:

Specifying Mosaics in APT

For imaging mosaics, it is usually the case that the separation of the tiles is large enough that each tile will be a separate visit[1] (requiring a separate guide star and GS acquisition activity). For simplicity in this discussion, assume this is the case. Because each visit (tile) requires its own guide star (and thus a guide star acquisition), part of the schedulability assessment is that *all tiles must simultaneously have guide stars available* in order to be declared schedulable. With the addition of Gaia DR2 stars to the guide star system, experiments have shown that the problem of missing guide stars for mosaic tiles has nearly disappeared, but we cannot guarantee that this problem will not occur. As a general rule, the larger the mosaic, the more likely it is that one or more tiles will be missing guide stars at the same time as the rest of the tiles, and hence there will be no time when the entire mosaic can schedule simultaneously. In such cases, APT declares the entire mosaic as unschedulable because, by definition, the entire mosaic is a single observation.

There are ways to remove a tile or tiles into separate associated observations to fill the gap(s) in the original mosaic if needed. However, another option is to consider a pattern of smaller overlapping mosaics to cover larger regions, leaving each of the smaller units free to rotate and schedule at different times when guide stars are available for that portion. Some experimentation is required to understand the effectiveness of this option.

[1] This is not always the case, as it depends on such things as the amount of overlap you specify and the visit splitting distance calculated by APT, which is a function of the target's Galactic latitude. However, since APT performs the splitting of proposed observations into visits, it is a detail that only becomes an issue when a tile needs to be removed or split from a parent mosaic.

Spectroscopic mosaics

> *See also: APT Targets, MIRI LRS Mosaics, MIRI MRS Mosaics, NIRISS Mosaics, NIRSpec FS and IFU Mosaic APT Guide*

Since grism spectroscopy with NIRCam or NIRISS uses the full FOVs of the imagers, the mosaicking of such fields directly parallels that of imaging mosaics.

For many smaller spectroscopic fields of view, such as the NIRSpec IFU and MIRI MRS (also an IFU), mosaicking is allowed but the situation is handled quite differently by APT. The footprints of most mosaics with these small FOVs will remain within a region of a single guide star's availability, and so the entire observation stays within a single visit. (Recall that the visit splitting distance changes with ecliptic latitude of the target, but even the smallest values of visit splitting distance (30"-40") would require a huge IFU mosaic to need more than a single visit.) IFU mosaics in APT take advantage of a reorganization of the activity ordering to greatly reduce mechanism motions and improve efficiency. These changes occur by default and require no special handling in APT, but you should be aware of the difference as it is more efficient than large imaging mosaics which may require multiple visits.

Mosaics versus Dithers

See also: JWST Dithering

The mosaicking capability for JWST is intended to provide users with a convenient way to cover larger regions of the celestial sphere. It should not be applied to make very small steps in position, to mimic normal dithering. While this could, in principle, result in somewhat lower overheads, in practice, it is a false gain.

Filter mechanisms have the potential to be life-limiting factors for JWST instrumentation. This is particularly the case for NIRCam, which serves as the wavefront sensing imager for the telescope. As a consequence, observers must not circumvent standard observation logic that minimizes filter wheel moves. Programs with either MIRI or NIRCam that involve dithered observations or “mini-mosaics” (that can be observed within a single visit) should step through the dither positions with a single filter before moving to a second filter. Creative alternative ordering for improving overhead efficiency will not be allowed.

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JWST Dithering Overview

JWST dithering is a data acquisition technique that enables data processing to remove various artifacts, fill gaps between detectors, and provides better sampling of the point spread function. Different dither strategies can be used for different purposes.

On this page

See also: MIRI Dithers, NIRCam Dithers, NIRISS Dithers, NIRSpec Dithers

Dithering is a technique in which an observed astronomical scene's position is moved by a small amount and then re-observed, often for multiple times. When the resulting data is processed, the scene can be reconstructed without gaps or detector artifacts.

With some exceptions, dithering is recommended for all JWST observations because of how it improves data products for both the original proposers and later archival users. Depending on the number of dither steps and their sizes, dithering can be used to fill gaps in sky coverage between detectors; mitigate against bad pixels and provide optimal sampling of the point spread function at a given wavelength to produce improved resolution for the processed data.

Data obtained from dithered observations can be processed to remove bad pixels. Depending on the number of dither steps and their sizes, dithering can also be used to fill in detector gaps, as well as sub-sample the point spread function at a given wavelength to produce improved resolution for the processed data.

Each instrument has its own strategy and the dither parameters are, by necessity, instrument-specific. Customized dither patterns have been established for coordinated parallel observations. These dither patterns improve the data quality, simultaneously, for both the prime and the parallel instruments.

Different kinds of dithers

The terms "dither" and "dithering" are applied to a range of scene motions, with offset sizes from sub-pixels to several arcseconds.

Primary dithers to fill in detector gaps

See also: NIRCam Primary Dithers

Some instruments, like the NIRCam imaging short wavelength channel, contain multiple detectors separated by small gaps. To fill in these regions of an astronomical scene, primary dithers are used; this results in small stripes or regions in the processed data with lower effective exposure times. However, with a sufficient number of dither steps, this non-uniformity can be minimized to produce an image with fairly uniform sensitivity. Gap dithers also move the scene sufficiently so that any detector features, such as bad pixels or modest flat field features, can be mitigated.

Sub-pixel dithers to improve PSF sampling

See also: NIRCam Subpixel Dithers

In certain situations where pixels are not Nyquist sampled, dithering by fractions of a pixel can produce data that recovers some or all of the diffraction-limited performance. The effectiveness of this approach depends on the diffraction limit, which is a function of wavelength, and on the telescope's actual optical performance.

Roll dithers (coronagraphy)

See also: MIRI Coronagraph Imaging Dithers

Roll dithers are different from normal dithers in that the scene is rotated about the target rather than offset. This technique is used in coronagraphy, where a target is placed in position behind a mask. Offsetting the target to move the scene would move the target from behind the mask, which is unacceptable to the science use case.

Positioning the target behind a mask but rotating the scene provides some (but not all) of the benefit of a normal dither since it is an angular rotation rather than an offset; hence, the size of the offset in pixel space depends on the distance from the point of field rotation. In this use case, rotating the scene means that a separate guide star acquisition (and hence a separate observation) must be specified for the roll dither observation. Also, a roll slew is accounted as a regular slew even though the telescope pointing stays on the same target position. For example, a 10^{o} roll maneuver takes the same amount of time as a 10^{o} movement of position on the sky. The maximum roll dither is 14^{o}, but may be limited to even lower values depending on the solar elongation angle of your target at the time of the observation. These angles can be assessed versus time using the Coronagraphic Visibility Tool.

Coronagraphic sequences are groupings of observations that normally include 2 science target observations (including a roll dither) plus a PSF reference star observation, all done in a non-interruptible sequence (to minimize changing thermal or other conditions). Hence, roll dithers are implemented in a completely different manner from normal offset dithers. Roll dithers are not restricted to coronagraphy, but it is the primary example identified for its use.

Small grid dithers (Mainly but not exclusively coronagraphy)

See also: NIRCam Small Grid Dithers

Small grid dithering is a technique for making *very small offsets* in position (<60 mas). This technique uses the fine steering mirror on JWST to make very small, precise motions of the scene relative to a selected instrument.

Its primary application is in coronagraphy and high-contrast imaging. Because the JWST control system cannot place a given target at a given position with absolute accuracy, observations that require a target to be placed behind a coronagraphic mask will have some positioning error. Hence, observations of a science target and a PSF reference star cannot be aligned precisely.

In order to maximize the matching of a PSF reference star observation to a given science observation, the PSF reference star can be observed at a number of small offset positions relative to the mask. Post-processing of the data then allows the modeling and matching of the PSF reference star to the science target. Of course, the exposure time is being multiplied by the number of grid steps, so this improvement does not come for free. However, for science cases needing the highest quality PSF matching, the cost may be worth the price. In principle, other specialized applications may also benefit from the use of this technique.

The allowable options for small grid dithers are selectable simply by choosing the appropriate dither pattern in a given template where it is defined. The details of the implementation (e.g., use of the fine steering mirror) are hidden from the user. See the individual instrument dither articles listed at the top of this article (also listed next) for details.

Dithers and spectroscopy

See also: NIRCam WFSS Dithers, MIRI LRS Dithers, MIRI MRS Dithers, NIRISS WFSS Dithers, NIRSpec Fixed-Slit Dithers, NIRSpec IFU Dithers, NIRSpec MOS Dithers

Some spectroscopic modes allow dithering. In these cases, the user decides whether to step in the spatial direction, the spectral direction, or both, and by how much.

The NIRSpec multi-object spectrograph, however, is a special case where integral full shutter steps are used in the offsets, and a large step is sometimes needed to obtain full spectral coverage due to the separation of the detectors. In some documentation, the motion by integral shutters are referred to as *nods* rather than dithers. There are also some MIRI motions, such as offsets to a nearby background region, that are referred to as nods, but the intent of those motions is different from a dither. The nomenclature is unfortunately ambiguous, but can usually be understood from the context.

Interplay between dithers and mosaics

See also: JWST Mosaics

When defining mosaics, users should be aware that the footprint of a given mosaic tile will include any dither steps defined at each tile location. This may come into play when deciding on the amount of tile overlap to specify in APT, and on considerations about the uniformity of coverage desired. See the APT Mosaics article for more information.

Dithering in the ETC and APT

See also: Astronomer's Proposal Tool Overview, Exposure Time Calculator Overview

Each dither step produces a separate exposure as specified in the APT template. Hence, one needs to be clear about this when using the ETC to calculate the S/N for a given exposure or for the entire observation (all of the dither exposures combined). To approximate the total SNR expected, set the number of exposures in the ETC calculation to be the number of dither steps anticipated. But in transferring the ETC observation specifications into the APT template, users should make sure they are entering the values for an *individual exposure*. Selecting a given dither pattern in APT then automatically increases the number of exposures.

Exceptions

Pure parallel observations are not allowed to impact the primary observation. Therefore, they will either not be dithered or dithered with the primary observation's pattern (which would be non-optimal for the parallel observation). This is different from the situation for coordinated parallels, where dither patterns can be chosen to optimize dither step sizes that work for both instruments.

Time-series observations are cases where continuous time coverage with the target in a constant position on the detector is more important than improving the overall data quality. Hence, the relevant time series templates in APT do not allow a dither pattern to be selected.

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	• 30 Oct 2019 Clarified roll dither section.

JWST Observing Overheads and Time Accounting Overview

JWST proposers will use the Astronomer's Proposal Tool (APT) to estimate the total time required to achieve their observing program science goals, including science time and overheads.

On this page

JWST operations will be event-driven, where events will occur sequentially in time as soon as the previous event is complete. This fact drives the JWST single stream proposal process. In contrast, HST events are typically driven by orbital viewing periods with breaks for Earth occultations.

Observations by JWST are broken into one or more visits**.** A visit is a grouping of activities scheduled together as a unit by APT**.** The JWST schedule is constructed from an optimized sequencing of visits from all JWST programs. Unless special requirements are specified for the observations, there is no guarantee that the visits in a given multi-visit observation (or all the observations in a given proposal) will be executed in a contiguous manner.

Details of the actual timelines that would execute for a proposed set of observations are not available at the time of proposal submission. Therefore, the estimate for the total time requested for a given proposal must be based on a statistical model of JWST operations. This model is used in the Astronomer's Proposal Tool (APT) where calculations for a proposal's total time allocation request is based on a set of assumptions, rules, and inputs for deterministic and statistical overheads for various operations activities. APT reports both the total science time and an estimate of the total time allocation request in the APT proposal's **Proposal Information** cover page, which, upon submission, becomes the official time allocation request for a proposal.

Different kinds of observing overheads

Overheads for JWST observations occur in 3 major categories:

- *Observatory direct overheads* are activities directly associated with a given observing program, such as major slews, mechanism motion times, guide star acquisition times, small angle maneuvers (SAMs; i.e., motions between dither points), and target acquisitions.

- *Observatory indirect overheads* are related to activities performed for the general support of science observations. This includes calibrations, momentum management, wavefront sensing and control, as well as other observatory maintenance. By NASA and STScI policy, a pro-rated fraction of indirect overhead time is assigned to each proposal. Indirect overheads are calculated statistically (currently assumed to be ~16% of JWST's time).

- *Instrument overheads* are activities directly associated with each instrument, such as filter changes, detector readout, and operations script compilation.

The time assumed for each overhead activity is calculated either deterministically or statistically.

- *Deterministic time estimates* are those with times known *a priori* and are typically associated directly with the sequence of activities within a visit. For each visit, the deterministic direct overheads include guide star acquisition, target acquisition (when appropriate), any mechanism motions, and SAMs.

- *Statistical time estimates* are those with times that depend on the exact sequence of scheduling events for JWST observations and cannot be calculated deterministically during the proposal submission process. Statistical overheads include the assumed major slew time from a previous target to the first visit of each target in the proposal; the value APT assumes comes from practice scheduling exercises where this statistical overhead was assessed. Because the primary scheduling unit used by the scheduling system is a visit, and because a given proposal's visits may be interleaved with those from other proposals and activities, the actual slew prior to each visit cannot be precisely known until it is scheduled (and eventually executed on orbit).

Estimating total time allocation request for a JWST program

See also: JWST Observing Overheads Summary, Slew Times and Overheads

APT provides an estimate of the science time (time spent actually acquiring data) and total (including overheads) time charged for each visit, observation and proposal. These values are estimated using the sequence of JWST activities for each observation, based on visit-breaking rules in APT, the APT pointing model to sequence visits within an observation, and the sequence of activities within each visit.

In general, the largest source of overhead for a JWST observing program is the number of major slews executed, and the overheads associated with each visit (e.g., guide star acquisition, visit clean-up activities).

An APT observation is made up of one or more visits, but APT decides when multiple visits are required. If needed, APT will break an observation into multiple visits according to the following rules:

- The total pointing change is large enough that it is no longer feasible to use a single guide star for all exposures. For moving targets, this distance assumed is 30". For fixed targets, this distance is a function of galactic latitude and is based on the density of available guide stars. The visit splitting distance is shown in each observation template in APT after a target is selected.

- The total duration of the visit exceeds a maximum of 24 hours. This limit is imposed for efficiency (because very long visits are hard to schedule efficiently) and to preserve flexibility to insert engineering visits where needed.

- Different instrument templates are used, and separate observations are required (which is automatically a new visit).

An observation template defines an observation of the specified target (or target group). The visits within that observation are ordered by the APT pointing model using the following strategy. (Think of these steps as a set of nested "do" loops.)

- For each target in the observation (only more than one if the target is specified as a target group)...
- If a mosaic observation, for each mosaic tile...
- For each filter/grating/exposure specification...
- For each dither point (primary and secondary dithers are expanded first, then the pointing list is iterated. Visits will not be split between secondary dither points, but may be split at a primary dither break point)...
- Generate the pointing information for the visit (to be passed downstream to scheduling).

Note that because of the APT pointing model's sequencing of activities, all pointings within a dither pattern will execute for a given filter, and then repeat after a filter wheel change. In contrast, a given mosaic tile pointing will be observed in all requested filters before the pointing is changed to the next mosaic pointing. Some primary dither patterns have pointing offsets large enough to require new guide star acquisitions that will "break visits" and incur additional overheads associated with a new guide star acquisition and visit clean-up activities.

A visit's duration is the sum of the time it takes to execute all science exposures and the time for other associated activities (including initial slews, guide star acquisitions, mechanism motions, frame resets, small angle maneuvers, and visit clean-up activities).

Special observations that incur additional time to configure have additional overheads. For example, a disruptive target of opportunity observation needs to account for the inefficiencies caused by disrupting the nominal JWST schedule. Likewise, given the normal event-driven scheduling (where scheduled events may slip forward of backward against a fixed timeline due to real time events), any "fixed time" observation requests can cause forced dead time in the schedule which must be accounted for.

Smart accounting

See also: APT Smart Accounting

APT initially assumes one major slew for every new observation specified in a proposal. In some cases, this will be approximately correct, but in others, it may significantly overestimate or underestimate the overall resources needed. For example, proposals that include targets with largely overlapping visibility windows (or even multiple observations of the same target with different position angles or instruments) may be observed in temporal proximity, and hence not require a large “average” slew for each new observation.

The goal of the total time request estimation is to produce realistic and fair overhead assessments for the whole range of potential proposals and observation types that will be received. The way APT accomplishes this goal is the following: once a proposal's full complement of observations has been specified and the visit planner has been run to demonstrate schedulability, the user will invoke the proposal planning step called "smart accounting," which looks through the targets and observations specified in the proposal and formulates what are called *same scheduling sets*, that is, subsets of the requested observations that will likely be schedulable together. APT then reduces the number of major slews and other overheads it was initially charging to the proposal, thus reducing the total overhead charges for the proposal to a fair and equitable value.

It should be noted that these same scheduling sets are non-binding; that is, *there is no guarantee that the observations of a given same scheduling set will actually be scheduled together* unless appropriate special requirements have been specified that tell APT to do so. Rather, the same scheduling sets assess the probability that observations will be grouped if and when they are ultimately accepted and put into the scheduling system. After executing the smart accounting step, the revised total time allocation request is finalized and reported on the proposal information cover page by APT.

Modifying APT time allocation requests

The APT time estimates will be the official time allocation requests shown to the TAC panels and ultimately used in planning and scheduling for accepted proposals. The only exceptions identified to date are:

- certain target of opportunity proposals that may need to specify proposed observations where the details are unknown at the time of the initial submission, and
- pure parallel proposals, where proposers simply request representative observations in APT and do not know the full allocation they may eventually receive.

In this or any other special case that may arise, APT provides the ability to specify a different proposed allocation for the proposal on the proposal information cover page, followed by the opening of a text box for the user to provide an explanation. It is expected that this option will be used extremely infrequently and only for such special cases.

How to improve the efficiency of JWST programs

Because of the pre-configured sequences of activities associated with APT observation templates for a given instrument/observing mode, users have limited options for modifying the sequence of observing activities and total overheads. The largest contribution to JWST observing overheads are the number of major slews associated with a JWST program, and the activities associated with each visit (including initial slews, guide star acquisitions, mechanism motions, frame resets, small angle maneuvers, and visit clean-up activities). Programs that minimize the number of major slews and the number of visits will typically achieve a higher efficiency (science time/total time) than programs with large numbers of slews and visits.

To the extent possible, select targets that can schedule together. Smart accounting tries to gather observations that can schedule together and thus reduce the major slew charges. This is the largest overhead reduction that APT can assess, and so the more grouped the proposed observations are, the more the reduction in overhead that will be gained.

Pay attention to the visit splitting distance reported by APT. For the most part, users specify observations in APT, and APT then decides on the splitting of the observations into visits (i.e., the “scheduling units”). The visit splitting distance assumed by APT is tied to the Galactic latitude of each target because the density of potential guide stars drops off away from the Galactic plane.

APT reports the visit splitting distance along with the assessment of the number of visits required for the observation on the instrument/observing mode observation template GUI where one enters the exposure and dither specifications. Many observations are accomplished with a single visit, but other common observations may involve many visits. Each visit of an observation requires a guide star acquisition, which incurs an additional overhead charge. Hence, anything a user can do that reduces the number of visits will reduce total guide star acquisition overheads.

A specific example where this might come into consideration would be NIRCam or MIRI imaging mosaics. The fields of view of these instruments are large enough that each new tile of the mosaic is usually in a separate visit. Depending on the size of the mosaic (i.e., the number of tiles), the size of the object or field to be observed, the dither pattern selected (for uniformity of coverage), and the visit splitting distance reported for a given observation, it may be possible to adjust the amount of overlap in the mosaic tiles so that their separation is less than the visit splitting distance. If so, then APT can observe more than one tile in a given visit and thus reduce the total number of visits (and guide star acquisitions) required.

A special case of this idea would be an observation of a target group. If one has a set of target positions that are so close together that they could be scheduled within a single visit (i.e., on a single guide star), the overheads for that set of observations can be greatly reduced from what would otherwise be estimated. Since a typical visit splitting distance is of order 30"– 80", this is indeed a special case (perhaps a set of closely spaced IFU pointings, for example). Not only would such a set only require a single major slew, but a single guide star acquisition (and possibly target acquisition) would be needed. See the APT Targets article for more details on target groups.

Published	30 Dec 2016
Latest updates	• 12 Dec 2019 Reviewed and minor updates for 2020 Cycle 1. • 16 Aug 2019 Minor text updates; removed references to dated technical documents.

JWST Observing Overheads Summary

The Astronomers Proposal Tool, APT, charges users time and overheads for their observing programs. Overheads consist of slews, instrument overheads, observatory overheads, and direct scheduling overheads. These overheads may be viewed in APT at the proposal level, the visit level, and in the exported times report.

The total charged time consists of the following components. Terms in **bold** are as given in APT:

- **Science** observing time
- **Slew** to begin each visit
- **Instrument Overheads** consist of the following:
    - **SAMs**: small angle maneuvers for dithers, mosaics, target acquisition, etc.
    - **GS Acq**: guide star acquisition(s)
    - **Targ Acq**: target acquisition, if any
    - **Exp Ovhd**: some instruments require an initial reset
    - **Mech**: mechanism movements, including filter wheels
    - **OSS**: Onboard Script System compilation
    - **Visit Ovhd**: visit cleanup activities
    - **MSA**: NIRSpec MSA configuration
    - **IRS2**: NIRSpec IRS^2 Detector Readout Mode setup
- **Observatory Overheads** = 16% of the total of everything above. This charged time supports observatory activities including calibration, station keeping, and momentum management.
- **Direct Scheduling Overheads**, if any, for very tight timing constraints or rapid turnaround Targets Of Opportunity (TOOs).

For further explanation, see the JWST Observing Overheads and Time Accounting Overview.

For quantitative details on slews and SAMs, see Slew Times and Overheads.

For a brief overview of instrument overheads, see Instrument Overheads.

For complete quantitative details of all JWST overheads, see Visit Overheads Timing Model.

Published	11 Jul 2017
Latest updates	

Slew Times and Overheads

The Astronomer's Proposal Tool (APT) charges time to JWST observations for telescope slews of various kinds as a function of slew distance. Some slew times are calculated deterministically and others are charged statistically. Keeping dithers and offsets within the visit splitting distance for your target can reduce these overheads.

On this page

Slew and overhead times in this page are based on model expectations and are subject to change. The values listed here are as used in APT 2020.1 (pre-release).

See also: JWST Pointing Performance, JWST Attitude Control Subsystem
See also: APT Graphical Timeline

JWST observing programs are charged time and overheads for slews by the Astronomer's Proposal Tool, APT. The slew overheads model in APT includes discrete jumps at certain distances (see Figure 1) based on current assumptions for JWST attitude control subsystem operations. Slews include:

- Initial slew to the target
- Examples of subsequent slews:
  - dithers/nods (for improving data quality or obtaining background)
  - mosaics (for observing a wider field)
  - move from target acquisition to the science target (if the pointings are offset or an offset target is used)
  - move a science target behind a coronagraphic occulting mask or within a spectroscopic slit or shutter
  - roll the telescope from one position angle to another

Initial and subsequent slews are charged differently as quantified below. The initial slew distance from the target observed previously cannot be known prior to scheduling. Therefore, initial slew times are charged statistically (based on the average expected slew distance), and subsequent slews are charged deterministically (given each known slew distance). The charged times are shown in APT for the entire proposal (on the **Proposal Information*** page) and at the individual observation and visit levels. The *times report* exported by APT (via **File** → **Export**) also provides an ASCII listing of charged times that may be useful. Small slews are referred to as small angle maneuvers (SAMs).

Note that telescope rolls are charged identically as slews. So, for example, a 10° roll is charged the time of a 10° slew; even though the boresight (optical V1 axis) does not move, the observatory is being rotated by 10°. If 2 observations are offset by a range of position angles (e.g., 10°–14°), then the midpoint (12°) will be used to calculate the time charged for the roll.

Each slew (or roll) requires time for 3 operations:

- Slew to target
- Wait for observatory to settle
- Acquire (or reacquire) guide star

[*] ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Initial slew

See also: APT Smart Accounting

The distance slewed from a previous target to start your observation of each of your targets cannot be known prior to actual scheduling, so a fixed average time is charged to all users, based on statistical expectations. Practice scheduling exercises indicate a value of 1,800 s (corresponding to a slew distance of 53°) will be typical, and so this initial slew charge is applied to each new observation (or first visit of a multiple visit observation). In APT, this initial slew time is accounted as ***Slew*** in each ***Visit Duration***. The article on Smart Accounting has further details.

Guide star acquisitions are charged separately for the initial visit and all subsequent visits: 284 s (4.7 m). Guide star reacquisitions within a visit are charged as described in Table 2.

Subsequent slews

After the initial slew to the target, subsequent slews (e.g., for dithers, mosaics, or target acquisitions) are charged times as a function of actual distance moved, as plotted in Figure 1. These are included among the ***Instrument Overheads*** in each ***Visit Duration***. The slew itself is charged as in Table 1. Guide star acquisition and settling times are given in Table 2 and described in more detail below. Note that "slews" <0.06" do not actually involve slewing the telescope; instead they are executed by moving the fine steering mirror.

> ⓘ The times below are charged in APT using models that may differ from actual slew and overhead times.

Table 1. Slew time vs. distance

Slew distance	Slew time (s)
0"–0.06"	0
>0.06" to 15"	20.48
15"–25"	20.48–26.112
>25" to 3°	109.312–825.6
>3° to 180°	521.216–3840.512

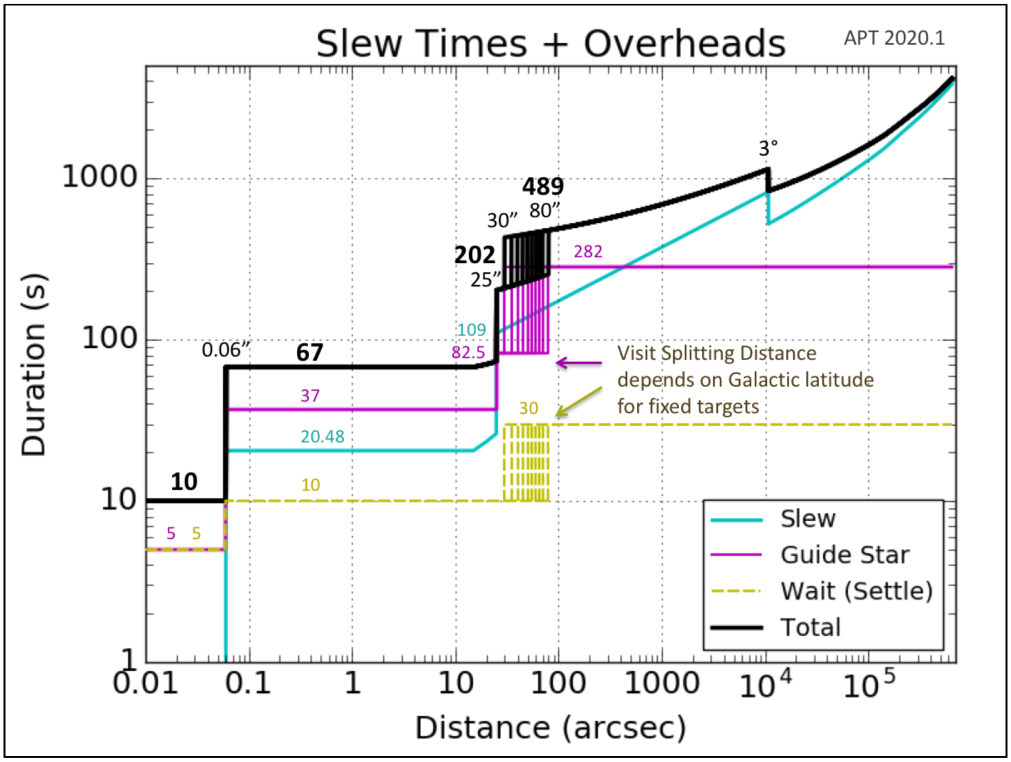
Slew time expectations do not have sub-second precision, but values with such precision will be charged by APT.

Table 2. Wait (settling) + guide star acquisition time vs. distance

Slew distance	Wait (settling time)	Guide star acquisition time	FGS operation required (plus subsequent steps; see below)
0"–0.06"	5 s	5 s	#4. Fine Guide
>0.06" to 25"	10 s	37 s	#3. Track
>25" to Vist Splitting Distance	10 s	82.5 s	#2. Acquisition
Vist Splitting Distance –	30 s	284 s	#1. Identification

Table 2 applies only to fixed (stationary) targets. Moving target overheads will be higher; please see Moving Target Overheads and Moving Target Acquisition and Tracking for more details.

Figure 1. Slew time plus overhead versus slew distance



Slew times are charged in discrete units based on the slew distance. The total time charged (black) consists of the time to slew (blue), time to acquire the guide star (cyan), and time for the telescope to settle (red dashed). The guide star acquisition time increases to 284 s when a new guide star is required, beginning a new visit. This is governed by the visit splitting distances. Note that slew times and overheads are reported in APT under Instrument Overheads, unless they begin a visit, in which case they are reported under Slew. Also note a slower slew speed is used for distances between 25" and 3° to minimize propellant sloshing. Motions <0.06" do not actually involve slewing the telescope, but rather shifting the pointing using the fine steering mirror. Not included here are 2 s charged to every SAM for OSS event messages.

Visit splitting overhead

See also: APT Visit Splitting

Some slews are large enough (individually or in combination within an observation) to require acquisition of a new guide star, which requires a new visit and incurs a larger overhead. The visit splitting distance used by APT is between 30"–80" depending on the Galactic latitude of the target. (Larger areas are serviceable by a single guide star at lower Galactic latitudes where more stars are available.) Any observation with a pair of pointings separated by a greater distance will require visit splitting and incur a new guide star acquisition overhead.

Guide star overheads

See also: Guide stars, Fine Guidance Sensor (FGS)

Guide star acquisition and settling times are given in Table 2. A new guide star is required for slews greater than the visit splitting distance. In this case, the guide star acquisition time is reported separately by APT. For smaller slews, the guide star acquisition time is included in the time charged for SAMs.

The Fine Guidance Sensor (FGS), performs a sequence of 4 operations to lock onto a guide star for fixed target observations:

1. Identification
2. Acquisition
3. Track
4. Fine Guide

Once in "Fine Guide" mode, very small slews may be performed with the fine steering mirror (see Table 2). Larger slews require returning to earlier steps in the sequence, which takes more time. The largest slews require identification of a new guide star and repeating all the steps.

Moving targets are observed using FGS "Track" mode. Only the first 3 steps are performed.

Effect of Multiple slews

In some cases, a sequence of slews may incur overheads larger than expected for individual slews if the sum of the motions causes the overall motion to cross a threshold. For example, consider a series of 6 slews, 15" each, all in the same direction along a line 90" long. Though all slews are <25", a larger overhead will be charged for exceeding the visit splitting distance; a new guide star will be required. For this threshold, APT considers the maximum distance between all pairs of pointings.

However, consider a series of 7 slews, 4" each, along a line 28" long. The total distance is not considered in this case. Each 4" slew is charged the smaller overhead for being <25". In this case, the threshold depends only on the pointing accuracy of each individual slew.

For smaller pointing shifts <0.06", multiple shifts must again be considered. In this case, in order to remain in fine guiding mode, all pointings must remain within ±0.06" of the initial pointing in both axes of FGS ideal coordinates. Otherwise, the guide star will stray too far within the FGS subarray, and the FGS will have to perform "Track" mode again before resuming fine guiding.

These rules are summarized in the table below.

Table 3. Distance considerations for multiple slews

Distance threshold	Rule

0.06"	Must stay within ±0.06" of initial pointing in FGS ideal coordinate axes
25"	Consider only individual slew distances
Visit splitting distance	Consider maximum distance between all pairs of pointings

As of APT version 27.1 and later, APT contains a graphical timeline that provides a visualization of the overheads for a selected visit or observation. The timeline does not break out the overheads in as much detail as given above, but it can still provide insight for understanding the sequence of activities and overheads that are being charged to your observations.

Published	30 Jun 2017
Latest updates	• 20 Dec 2019 Updated guide star acquisition times to APT 2020.1 (pre-release) • 21 Mar 2019 Added links to APT Timeline; other minor wording changes and updates. • 02 Nov 2018 Updated for Nov. 5, 2018 release. Visit splitting section shortened and a separate article, APT Visit Splitting, was opened. Other minor updates as needed for APT 26.1 consistency. • 06 Nov 2017 APT 25.4 values (previously APT 25.1.1)

Instrument Overheads

The JWST overhead times are adopted by the Astronomer's Proposal Tool for each overhead activity.

The Astronomers Proposal Tool (APT), charges users time and overheads for their observing programs (see overview and summary). Instrument overheads are charged for operations performed during the use of each instrument. Approximate typical examples are given in Table 1; actual overheads will vary depending on observing parameters. Complete details are provided in Instrument Specific Overheads. Details for your observing program are available by exporting the times report from APT.

The JWST Astronomer's Proposal Tool and the model for calculating overheads is under development and subject to change. The following values are approximate guides of overheads in APT 25.4.

Table 1. Typical instrument overheads (in seconds) for common operations

Operation	NIRCam imaging	NIRSpec MSA	NIRISS WFSS	MIRI imaging	FGS
Onboard Script System (OSS) compilation (per exposure)	40	65	30	25	5
Exposure overhead† (full frame, single integration)	69	74 (IRS^2 readout) 41 (normal)	31	34	40
Filter/grism change	110–190	200	84–140	50	N/A
Visit cleanup‡	105	170	62	50	50

† Exposure overhead is overhead charged ("Exp Ovhd" in the APT times report), not the exposure time itself.

‡ Visit cleanup is charged in addition to the 284 s to acquire a guide star at the beginning of each visit.

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Latest updates	

JWST Data Rate and Data Volume Limits

JWST can store at least 58.8 Gbytes of science data. Downlinks for recorded science data occur in 4-hr contacts twice a day, with each contact transmitting at least 28.6 Gbytes. APT simplifies these limits to 58 Gbytes and 29 GBytes, respectively. Users must be mindful of these limits when designing their observations.

On this page

See also: Solid State Recorder

Data rate defines the speed with which science data can be written to the solid state recorder (SSR), which is ultimately regulated by the ISIM Command and Data Handling subsystem (ICDH). The Astronomer's Proposal Tool (APT) prevents observations from breaking the ICDH data rate limits.

Data volume defines the total amount of data (58.8 GBytes) that can be stored on the SSR at any given time. JWST downlinks science data to Earth in 2 contacts per day, where each contact can transmit at least 28.6 GBytes of recorded science data to the ground.

Managing data volume

APT places some limits on data volume, and users are encouraged to abide by the following limits for each visit:

- <58 GB (exceeding it generates an APT error)
- <29 GB (exceeding it generates an APT warning)
- <0.65 MB/s (no warning issued if rate is exceeded)

The first limit prevents the SSR from exceeding capacity. The second limit ensures the data volume can be downlinked in one contact. The third limit may be required for schedulability. Users are encouraged to check the ratio of ***Data Volume*** to ***Total Charged Time*** in APT for each observation and for the total program. If this ratio exceeds 0.65 MB/s for a total time of ~12 hours or more (thus exceeding 28 Gbytes), then the program will be difficult or impossible to schedule. APT does not issue a warning in this case.

Users should keep in mind that data volume and data rates issues can only be fully identified downstream; the visit scheduling subsystem and the visit planning subsystem are designed to take these issues into consideration. Accepted programs may have to be modified to comply with data volume and data rate limits. Proposers should understand the data rate of their program, and if necessary, take steps to reduce the data rate.

General advice for reducing data volume

The amount of data is typically driven by both the number of detectors used simultaneously and the detector exposure parameters. If a proposer finds that they exceed the permitted data volume, they should consider some of the following options as a first attempt to reduce the total volume for their program.

Reduce the number of groups and integrations

See also: Understanding Exposure Times

Many of the observing modes that exceed the data volume limit are only problematic if executed for long periods of time (e.g., >12 hours). The simplest method for reducing your program's total data volume in a 12 hour period is to minimize the total number of groups per integration and number of integrations per exposure.

Select a different readout pattern, mode, and/or subarray

Using different readout patterns can enable longer exposures with a reduced amount of saved data. For example, choosing a larger numbers of frames averaged per group reduces data volume (and yields a more precise average). For MIRI, this can be achieved using either fast or slow modes.

Use overheads to your advantage

See also: JWST Observing Overheads and Time Accounting Overview

Factor in potential overheads that will decrease your observing efficiency, but at the same time potentially alleviate any data volume concerns.

Instrument-specific considerations

There are known scenarios for each instrument that may exceed the data volume limit. Some of these scenarios and suggested solutions are described below.

NIRCam

See also: NIRCam Detector Readout Patterns

A raw 2048 × 2048 pixel detector frame is ~8 MB. Near-Infrared Camera (NIRCam) has 10 detectors, so this implies at least ~80 MB of data for each group within an exposure depending on the readout pattern. Neglecting all overheads and assuming 24 hours of continuous data taken with all 10 detectors (both short- and long-wave channels), these are the limiting cases for the 9 readout patterns:

Table 1. Data volume per day generated by NIRCam using all 10 detectors

Readout pattern	Time between groups	Data Volume	
DEEP2, DEEP8*[*]*	~200s	~34 GB/day	0.39 MB/s
MEDIUM2, MEDIUM8	~100s	~68 GB/day	0.79 MB/s
SHALLOW2, SHALLOW4	~50s	~136 GB/day	1.6 MB/s
BRIGHT1, BRIGHT2	~20s	~340 GB/day	3.9 MB/s
RAPID	~10s	~680 GB/day	7.8 MB/s

* ***Bold italics*** style indicates words that are also parameters or buttons in software tools (like the APT and ETC). Similarly, a **bold** style represents menu items and panels.

Note that for long programs of ~12 hours or more, only the ***DEEP*** readout patterns abide by the 0.65 MB/s limit.

In addition to the steps outlined above, NIRCam observers may want to also consider the following options for reducing their data volume.

Use only one NIRCam module: It is possible to use only one module for an observation as a method to reduce data volume by selecting a single module in APT rather than ***ALL***. The module options in APT will vary depending on the observing mode (e.g., module A for coronagraphy or module B for imaging).

Change the number of outputs: In the case of grism time-series observations, a proposer may want to change the number of output amplifiers. Readout of the full NIRCam detector (2048 × 2048 pixels) is performed with 4 outputs simultaneously ($N_{outputs}$ = 4), each delivering a stripe of data (2048 pixel rows × 512 pixel columns), and taking 10.7 s altogether. Smaller subarrays are read out more quickly, and most are read out through a single output ($N_{outputs}$ = 1). $N_{outputs}$ is pre-defined for most subarrays, but observers are given a choice between $N_{outputs}$ = 1 or 4 in the grism time-series observing mode. Choosing one output reduces the frame rate by a factor of 4.

MIRI

See also: MIRI Detector Overview, MIRI MRS Simultaneous Imaging

The Mid-Infrared Instrument (MIRI) has only 3 detectors, but obtaining simultaneous imaging with both the imager and spectrograph can potentially exceed the data volume limit. MIRI observers should consider the general advice described above if their planned observations exceed the data volume limit.

NIRSpec

See also: NIRSpec Detectors, NIRSpec Detector Recommended Strategies

The Near Infrared Spectrograph (NIRSpec) has 2 detectors, which have 4 readout patterns spread out split over 2 readout modes. The IRS^2 ***NRSIRS2RAPID*** readout mode (~1.95 MBytes/s) results in higher data volume than the traditional ***NRSRAPID*** readout mode (~1.56 MBytes/s) because interspersed reference pixels and outputs are also saved. We recommend the use of these ***RAPID*** readout patterns (number of frames per group equal to one) for cases that have no data volume issues reported in APT because of the improved performance of cosmic ray rejection. Despite the higher data volumes, the IRS^2 patterns are also to be generally preferred over the normal modes due to the reduction in correlated read noise.

NIRSpec observing options that could result in APT data volume errors include:

- Deep, full frame FS/IFU/MOS long exposures with ***NRSRAPID*** or ***NRSIRS2RAPID*** readout (with exposure times beyond about 500 s).
- NIRSpec MOS + NIRCam parallels (data volume mostly driven by NIRCam).

The general solution is to use one of the group averaging patterns ***NRS*** or ***NRSIRS2***. Both the traditional and IRS^2 grouped NIRSpec patterns with 4 (***NRS***) and 5 (***NRSIRS2***) frames averaged per group have significantly smaller data rates and will be within limits.

NIRISS

See also: NIRISS Detector Overview

Since the Near Infrared Imager and Slitless Spectrograph (NIRISS) has only one Hawaii 2RG detector, it is not expected to exceed data volume or data rate limitations when it is used as the “prime” instrument. The wide field slitless spectroscopy or imaging modes of NIRISS can be used in parallel with other instruments. In these cases, the full frame readout format will generally be used with the NIS readout pattern to produce data at a rate of 0.195 MBytes/s. In rare cases (e.g., with bright targets), the ***NISRAPID*** readout pattern could also be used, producing 0.782 Mbytes/s. These rates and the accumulated data volumes are typically small compared with the other instruments, but must still be considered.

This article uses the S.I. definitions of gigabyte and megabyte: 1 Gbyte = 10^9 bytes, and 1 Mbyte = 10^6 bytes.

Published	28 Nov 2017
Latest updates	• 20 Dec 2019 Added APT warning for visit exceeding 29 GB • 22 Feb 2018 Updated APT warning conditions to 58.8 GBytes per 24 hours

JWST Observatory Hardware

The JWST Observatory includes the spacecraft bus and sun shield, Optical Telescope Element (OTE), and Integrated Science Instrument Module (ISIM). These articles provide details on the various pieces of observatory hardware.

Expand all Expand all Collapse all Collapse all

Observatory Hardware

- JWST Observatory Overview
- Coordinate System and Field of Regard
- JWST Field of View
- JWST Orbit
- JWST Pointing Performance
- JWST Telescope
- JWST Wavefront Sensing and Control
- JWST Momentum Management
- JWST Integrated Science Instrument Module
- JWST Solid State Recorder
- Fine Guidance Sensor

  JWST Spacecraft Bus
- JWST Target Viewing Constraints

Published	01 Nov 2018
Latest updates	

JWST Observatory Overview

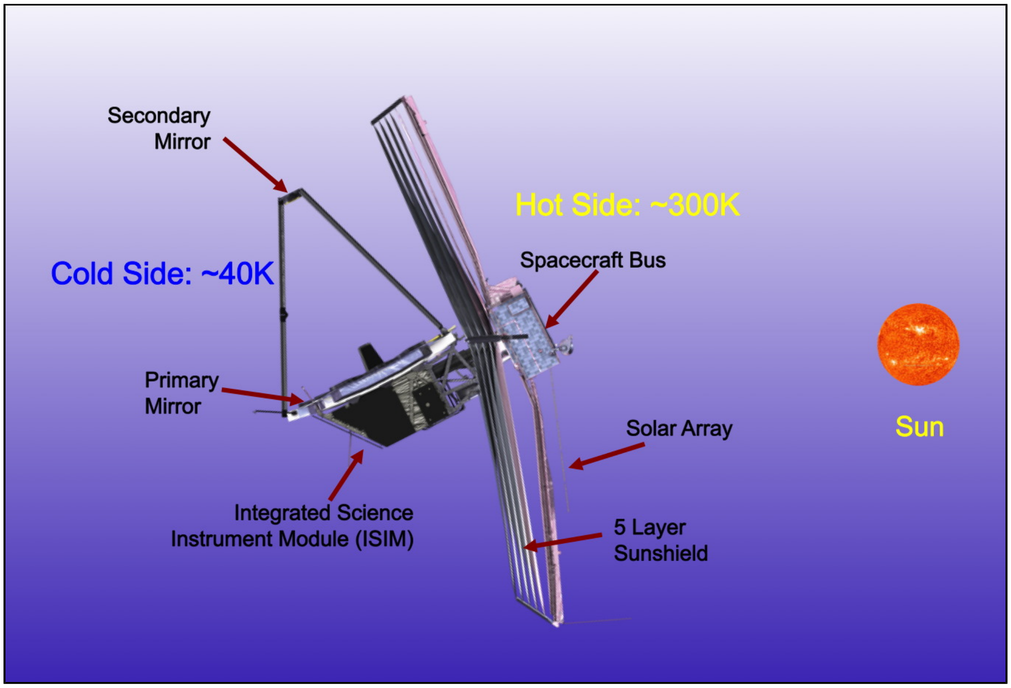
The JWST Observatory is comprised of the spacecraft bus, the sunshield, the Optical Telescope Element (OTE), and the Integrated Science Instrument Module (ISIM).

On this page

The JWST Observatory is comprised of the spacecraft bus, sun shield, Optical Telescope Element (OTE), and Integrated Science Instrument Module (ISIM), as shown in Figure 1. JWST will orbit the Sun-Earth second Lagrange point.

JWST has 2 distinct thermal regions: the sun-facing 300 K hot side and the 40 K cold side. The spacecraft bus is located on the hot side. The OTE and ISIM are located on the cold side. The hot and cold sides are separated by a sun shield that intercepts over 200,000 W of radiant energy from the Sun and transmits only about 1 W to the OTE and ISIM. By radiating the Sun's energy to space, the sun shield allows the OTE and ISIM to passively cool to cryogenic temperatures, without the use of expendable cryogens.

Figure 1. JWST Observatory



Overview of JWST, showing the 300 K spacecraft bus, which is separated by the sun shield from the 40 K Optical Telescope Element (OTE) and Integrated Science Instrument Module (ISIM).

Spacecraft bus

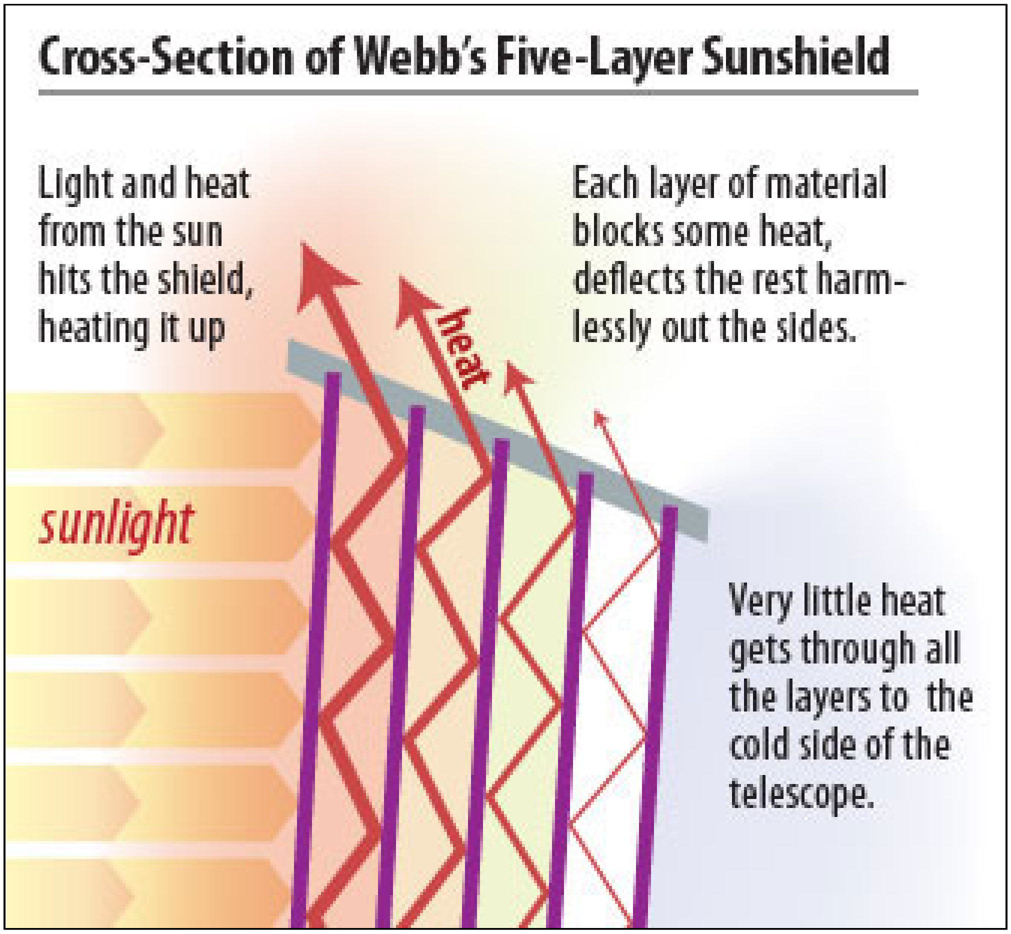
The JWST spacecraft bus provides electrical power, communications, attitude control, thermal control, health and safety functions, command and data handling, and communications services, as well as propulsion for orbit insertion, orbit maintenance, and momentum unloading. The spacecraft bus is located on the sun-facing side of the observatory and operates in a temperature of about 300 K.

Sun shield

In order for JWST to detect the infrared light from faint objects, the telescope and science instruments must be cooled to ~40 K. This cooling is done passively by a tennis court-sized sun shield; its purpose is to isolate the telescope and science instruments from the energy of the Sun, Earth, Moon, and the JWST spacecraft bus.

The sun shield is a diamond-shaped system of 5 layers of an aluminum-coated polyimide film called kapton. The dimensions of each layer are approximately 21 m long and 14 m wide. Each successive layer of the sun shield is cooler than the one below. The heat radiates out from between the layers, as shown in Figure 2.

Figure 2. JWST sun shield



The JWST sun shield redirects the Sun's energy away from the telescope and science instruments, allowing them to cool passively.

Where JWST can point

JWST must maintain an attitude such that the telescope and science instruments are protected by the sun shield from the sun. This basic constraint, combined with the geometry of the sun shield, sets the field of regard, which is the region of the sky where JWST can safely conduct science observations at a given time. The field of regard and when targets are visible will be described in JWST Target Viewing Constraints.

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Latest updates	

JWST Observatory Coordinate System and Field of Regard

The JWST Observatory, as a whole, has a reference coordinate system used by operations to define the pointing of the telescope within the field of regard (FOR), including defining the continuous viewing zone (CVZ) available to the observatory.

On this page

See also: Target Viewing Constraints
See also: JWST Position Angles, Ranges, and Offsets

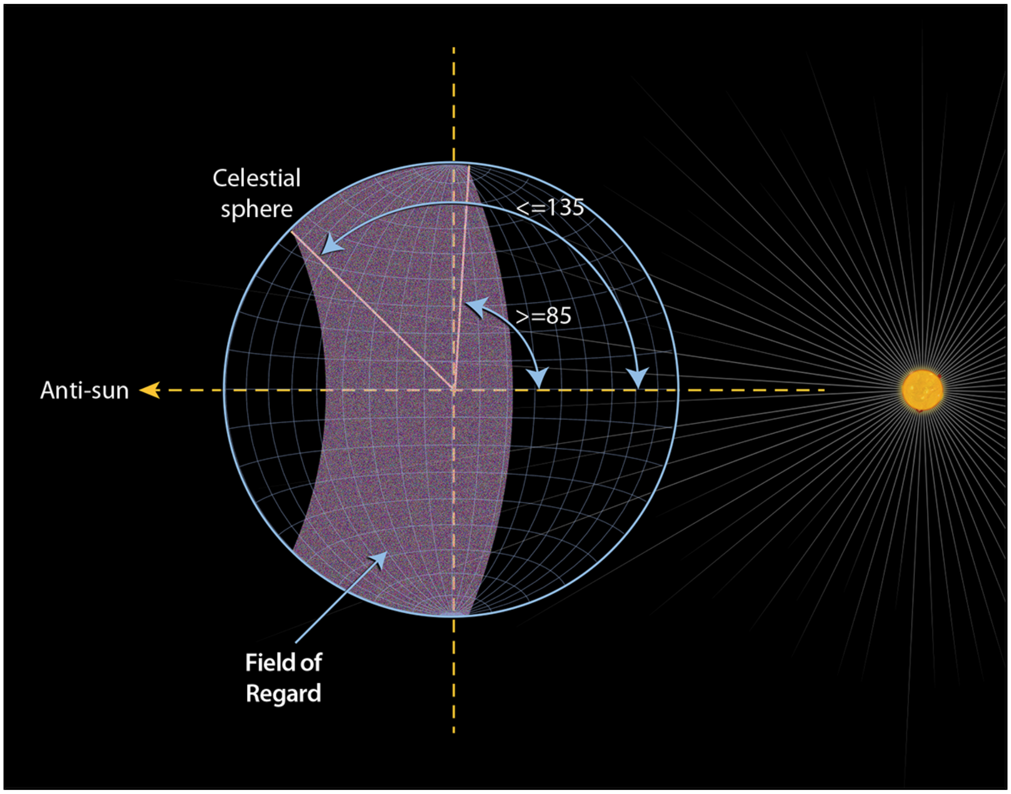
The JWST Observatory V1, V2, V3 coordinate system is primarily used in operations, but there are a number of instances where users may want to understand the orientation of the focal plane or one of the science instruments in the context of the observatory's pointing. Also, there are a number of places, for example, in various APT diagnostic plots, where the V axes are used to provide an instrument-independent reference frame.

This article provides information to link the V axes definitions to other JWST software and systems. Furthermore, the JWST field of regard (FOR) defines the instantaneous region of the sky that is available for safe JWST pointing of the telescope boresight (the V1 axis).

JWST field of regard (FOR)

The JWST field of regard (FOR) is the region of the sky where scientific observations can be conducted safely at a given time. The FOR is defined by the allowed range of boresight pointing angles for the observatory relative to the sun line, which must remain in the range 85° to 135° at all times to keep the telescope behind the sun shield. Thus, the FOR is a large torus on the sky that moves roughly 1° per day in ecliptic longitude, following the telescope in its path around the sun. Over time, this annulus sweeps over the entire celestial sphere. As a result of the FOR, JWST can observe about 39% of the full sky on any given day and can access 100% of the sky over 6 months. Figure 1 shows a schematic of the FOR.

Figure 1. The JWST field of regard

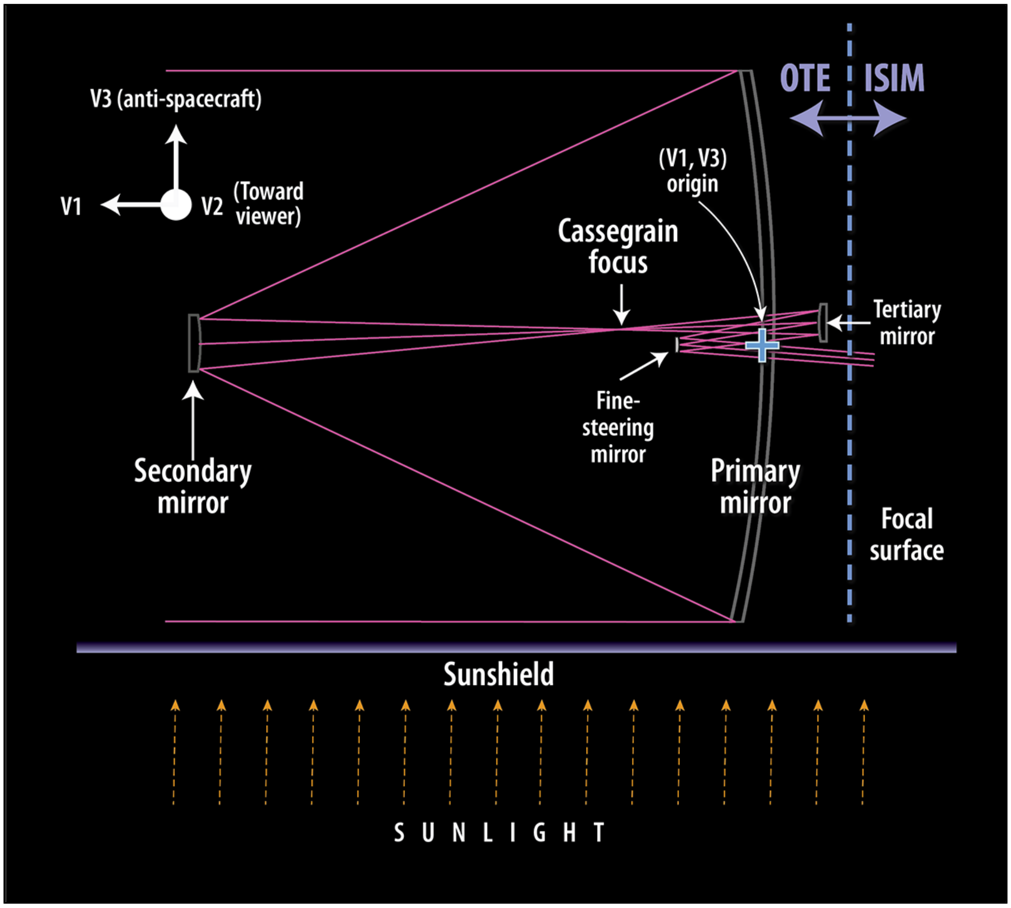


The JWST field of regard extends from a solar elongation of 85° to 135° and changes over time as the observatory orbits the sun. (Adapted from: JWST Mission Operations Concept Document, Figure 4.10.)

JWST Observatory coordinate system

The observatory V axes are defined with respect to the telescope, as shown in Figure 2. +V1 is the boresight of the telescope, +V3 points away from the sun shield, and +V2 is orthogonal to both of these, forming the "thumb" of a right-handed coordinate system. In the context of Figure 2, the V2 axis is pointing towards the reader (out of the screen). The +V3 axis projection onto the sky, referenced eastward from north, is used within the APT diagnostics (for example in the Visit Planner) as an instrument-independent reference frame.

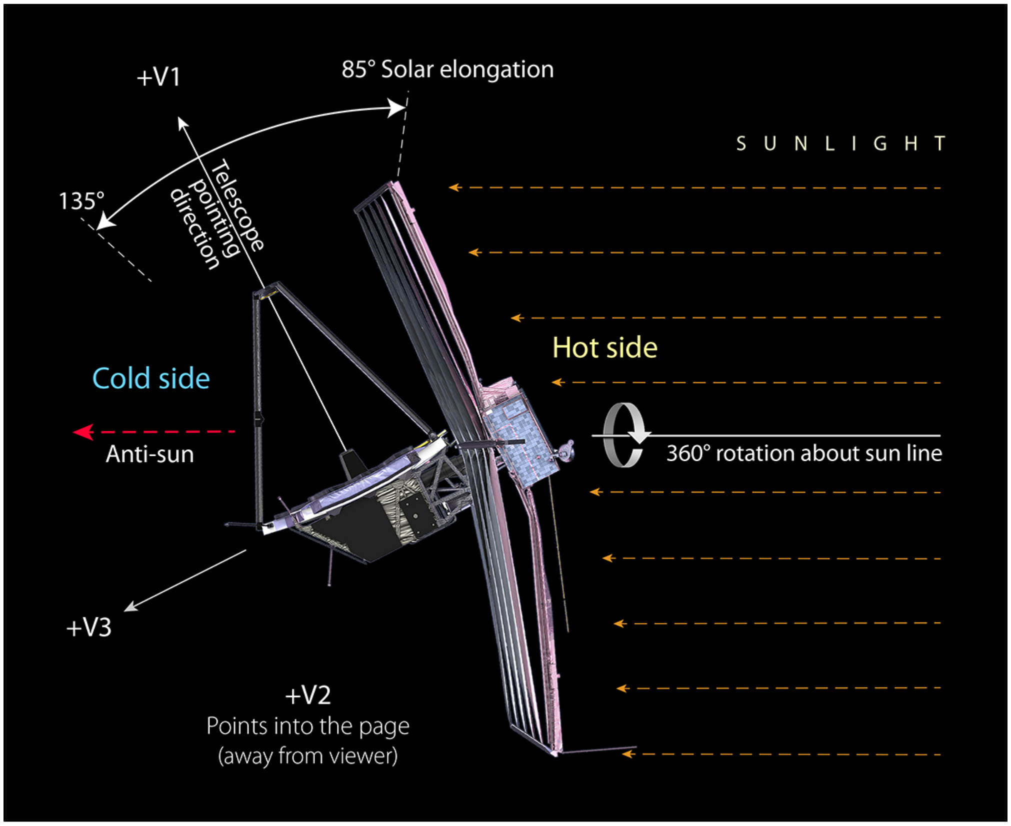
Figure 2. Schematic of the JWST V1, V2, V3 coordinate system



This schematic shows the JWST Observatory coordinate definitions. The sun shines from below in this figure, and the V2 axis points out of the screen toward the reader.

In Figure 3, the JWST coordinate system is shown in the context of the FOR. If the observatory is pointed at 90° solar elongation, the +V3 axis points toward the anti-sun, but as the boresight points elsewhere in the FOR, V3 moves away from the anti-sun direction. In the view shown in Figure 3, the +V2 axis is pointing into the screen.

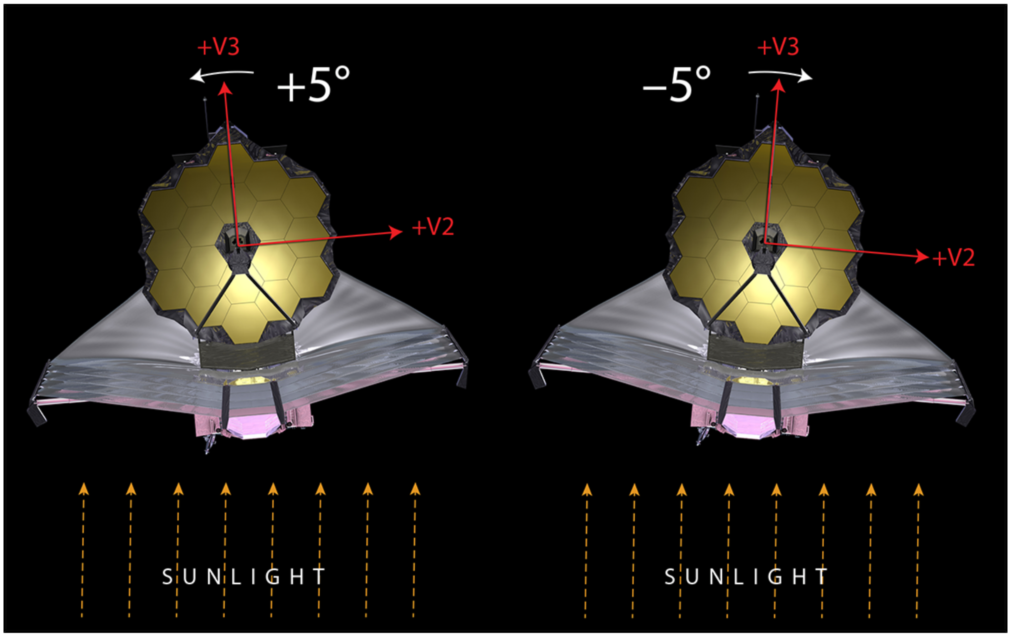
Figure 3. The JWST Observatory coordinates in the context of the field of regard



This figure shows the JWST Observatory coordinates where V2 points into the screen. Note that the observatory can rotate around the sun line and stay within the field of regard.

Figure 4 shows another view to highlight the restrictions on instantaneous roll about the boresight (+V1 axis). The amount the observatory can roll about the V1 axis is very limited due to the requirement to keep the telescope completely behind the sun shield at all times. The ±5° value shown in the figure is only approximate as the amount of off-axis roll allowed is actually a function of the V1 solar elongation (ranging from approximately ±3° to ±7° as V1 moves from 85° to 135° solar elongation). The limitation on roll comes into play for the so-called "roll dithers" used in many coronagraphic programs. (See the JWST Dithering Overview article for more information.)

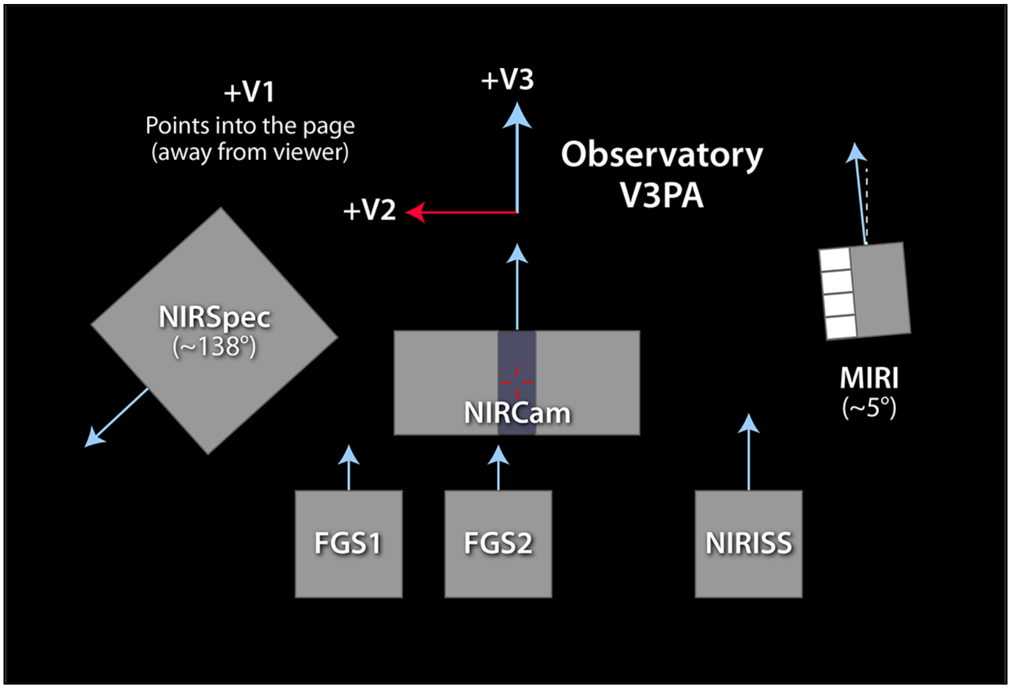
Figure 4. The JWST Observatory coordinates in the context of the roll angle



This figure shows the JWST Observatory coordinates in context of the roll angle. V1 points toward the reader (out of the screen). Note that the sunlight comes from the bottom of this figure, and the ±5° shown is only approximate.

Figure 5 shows the connection between the V axes and the JWST focal plane. The V3 axis is the primary observatory reference axis used in APT and in operations to connect the individual instrument reference axes (blue arrows) in the planning and scheduling system to the celestial sphere. This is especially important for any observations where the positioning of the instrument fields of view on the sky is important. See the JWST Position Angles, Ranges, and Offsets article for more information. This figure can also help users understand the output from the JWST Target Visibility Tools, which typically report both V3PA and individual instrument reference position angles. Note that NIRCam and NIRISS are very nearly aligned with V3PA, while MIRI is offset slightly. Only the NIRSpec reference axis is offset by a large amount relative to V3PA.

Figure 5. The JWST Observatory coordinates in the context of the focal plane

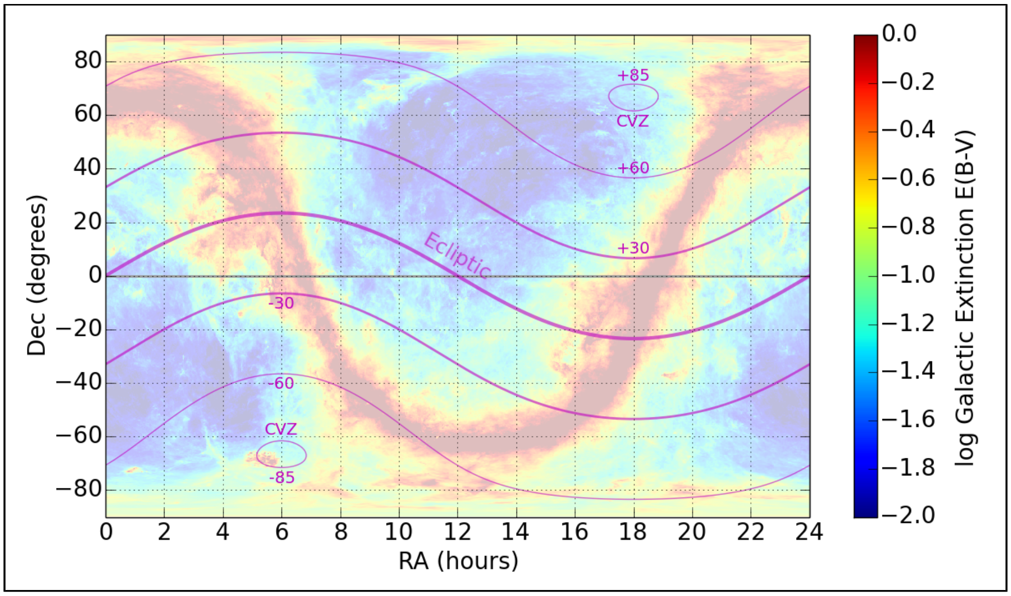


This figure shows the JWST Observatory coordinates in the context of the focal plane. The +V1 (boresight) points into the screen. The blue arrows indicate the reference axes of the individual instruments and the observatory V3 position angle is shown at the top..

Continuous viewing zone (CVZ)

Because JWST operates in an ecliptic coordinate framework, there are 2 small continuous viewing zones (CVZs) centered at each of the ecliptic poles (see Figure 6). The 85° solar exclusion zone then determines the radius of the allowed CVZs to be essentially 5°, although any observation approaching the 85° limit will have additional limitations due to safety considerations.

Figure 6. An all-sky map showing the location of the CVZs relative to galactic extinction



Magenta lines show the ecliptic plane (b = 0°) and latitudes b = ±30°, ±60°, and ±85° vs. equatorial coordinates (RA and Dec). The b = ±85° ovals enclose the JWST CVZs, the areas within 5° of the ecliptic poles (b = ±90°). The background color map shows Galactic extinction measured by Schlegel, Finkbeiner, and Davis (1998). Note the higher extinction and SMC visible within the southern CVZ.

In standard J2000 equatorial coordinates, the CVZs are centered at the following coordinates:

N-CVZ: $18^h00^m00.00000^s$ +66°33'38.5520" (or 270.00000000° +66.56070889°)

S-CVZ: $6^h00^m00.00000^s$ −66°33'38.5520" (or 90.00000000° −66.56070889°)

The S-CVZ encompasses a portion of the Large Magellanic Cloud.

References

Schlegel, D. J., Finkbeiner, D. P., Davis, M. 1998, *ApJ*, 500, 525
Maps of Dust Infrared Emission for Use in Estimation of Reddening and Cosmic Microwave Background Radiation Foregrounds

Published	02 Mar 2017
Latest updates	

	• 02 Jan 2020 Updated with additional links for 2020 Cycle 1. • 07 Feb 2018 Added Figure 6 to CVZ definition • 18 Oct 2017 Added short section on CVZ definition

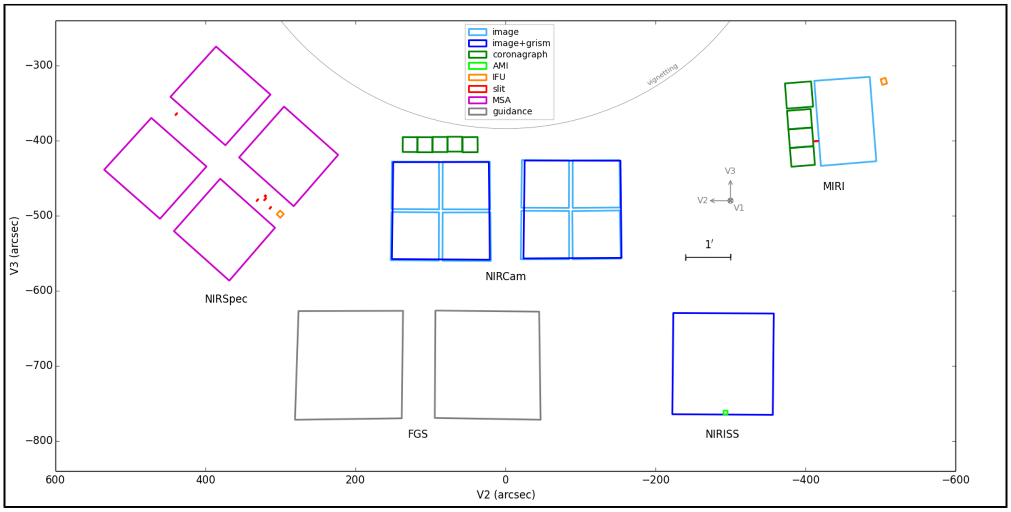
JWST Field of View

Each JWST instrument observes an area on the sky bounded by the coordinates given in the telescope's (V2, V3) coordinate system.

Figure 1 shows NIRSpec, NIRCam, MIRI, NIRISS, and FGS fields of view in the JWST focal plane. Figure 2 shows illustrations of data to be obtained with various JWST observing modes.

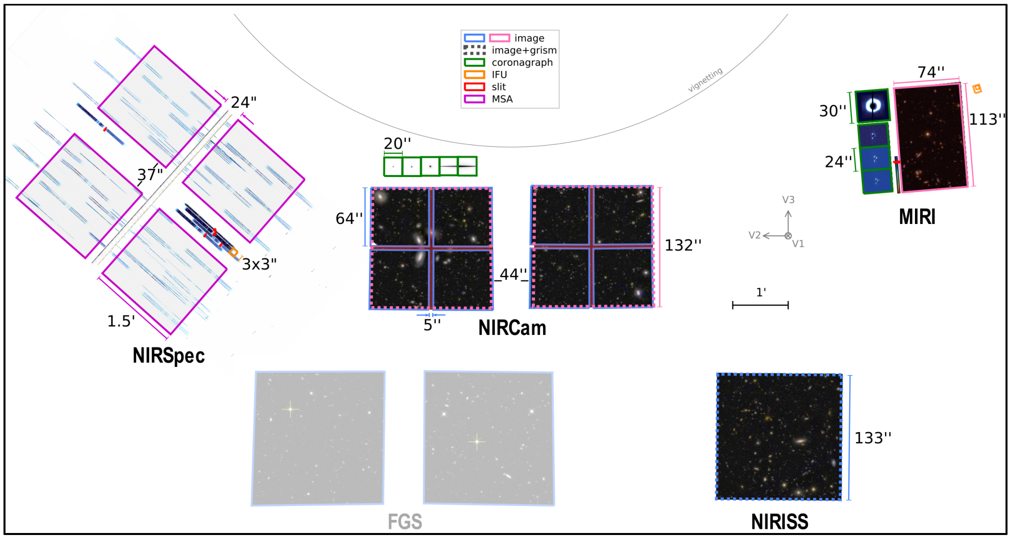
Table 1 provides the vertices of each region in the observatory's coordinate system (V2, V3). This is a small excerpt of data from the JWST Science Instrument Aperture File (SIAF). SIAF is a reference file used in operations that contains the official information on all apertures (e.g., NIRCam Apertures) and internal instrument coordinates.

Figure 1. The JWST field of view



Each JWST instrument observes an area on the sky shown here in (V2, V3) coordinates. Colors indicate observing modes: imaging, coronagraphy, grism spectroscopy, slit spectroscopy, NIRISS AMI, NIRSpec MSA, NIRSpec IFU, MIRI MRS (IFUs), and guidance with FGS.

Figure 2. Illustration of observations in the JWST field of view



Example illustrations of the types of data that can be obtained with many (not all) JWST observing modes.

The SIAF excerpt table below provides the following information for various apertures defined for each instrument:

- (V2_Ref, V3_Ref) is the reference position in (V2, V3) coordinates (arcsec); some of these entries are used to define telescope pointings.
- V3_IdlYAngle is the rotation (in degrees, counterclockwise) of the aperture's ideal Coordinate System Y-axis relative to V3.
- (V2_1, V2_2, V2_3, V2_4), (V3_1, V3_2, V3_3, V3_4) are the vertices in the (V2, V3) coordinates (arcsec) of the quadrilateral defined by each aperture.

For a few of the instruments, larger bounding box apertures are excluded from the plot above but included in the table below (marked with *).

The coordinates given below are approximate and subject to frequent minor revisions. More significant revisions are expected after launch based on flight data.

Table 1. Approximate coordinates (V2, V3) of select instrument apertures

Scroll right and down to view the full table.

Instrument	Aperture	V2_Ref	V3_Ref	V3_IdlYAngle	V2_1	V2_2	V2_3	
NIRCam	NRCALL_FULL*	-0.32	-492.59	-0.03	153.16	-153.74	-152.07	1
NIRCam	NRCAS_FULL*	81.35	-498.23	-0.10	153.16	19.49	20.80	1
NIRCam	NRCA1_FULL	120.67	-527.39	-0.57	153.16	88.90	88.69	1

NIRCam	NRCA2_FULL	120.11	-459.68	-0.21	151.95	88.56	88.68	1
NIRCam	NRCA3_FULL	51.93	-527.80	0.19	84.05	19.49	20.15	8
NIRCam	NRCA4_FULL	52.28	-459.81	0.06	84.00	20.39	20.80	8
NIRCam	NRCA5_FULL	86.10	-493.23	-0.09	151.45	20.88	22.23	1
NIRCam	NRCBS_FULL*	-82.29	-496.21	-0.06	-20.32	-153.74	-152.07	-
NIRCam	NRCB1_FULL	-120.97	-457.75	0.38	-89.59	-152.82	-152.07	-
NIRCam	NRCB2_FULL	-121.14	-525.46	0.83	-89.55	-153.74	-152.37	-
NIRCam	NRCB3_FULL	-53.12	-457.78	-0.49	-21.05	-84.57	-84.75	-
NIRCam	NRCB4_FULL	-52.82	-525.73	-0.34	-20.32	-84.82	-84.77	-
NIRCam	NRCB5_FULL	-89.39	-491.44	-0.01	-23.98	-154.75	-153.25	-
NIRCam	NRCA2_MASK210R	127.23	-405.24	-0.24	137.11	117.44	117.39	1
NIRCam	NRCA5_MASK335R	107.51	-405.52	-0.19	117.56	97.59	97.55	1
NIRCam	NRCA5_MASK430R	87.25	-405.19	-0.01	97.27	77.29	77.32	9
NIRCam	NRCA4_MASKSWB	67.61	-404.67	-0.08	77.46	57.75	57.76	7
NIRCam	NRCA5_MASKLWB	47.20	-405.44	0.35	57.20	37.13	37.29	5
NIRISS	NIS_CEN	-290.10	-697.50	-0.57	-222.43	-356.38	-357.71	-2
NIRISS	NIS_AMI1	-293.74	-762.31	-0.57	-290.73	-295.96	-296.02	-2
NIRSpec	NRS_FULL_IFU_IFU	300.15	-498.12	138.89	295.63	300.55	304.96	3
NIRSpec	NRS_S200A1_SLIT	332.14	-479.22	138.76	329.66	329.82	331.90	3
NIRSpec	NRS_S400A1_SLIT	321.87	-477.94	138.78	319.10	319.48	321.91	3
NIRSpec	NRS_S200A2_SLIT	314.98	-489.45	138.83	312.42	312.65	314.73	3
NIRSpec	NRS_S1600A1_SLIT	321.53	-473.68	138.77	319.11	320.26	321.30	3
NIRSpec	NRS_S200B1_SLIT	440.48	-364.52	138.16	437.76	437.92	440.10	4
NIRSpec	NRS_FULL_MSA*	378.77	-428.16	138.49	223.34	385.55	534.72	3
NIRSpec	NRS_FULL_MSA1	466.48	-436.16	138.24	398.68	472.27	535.09	4
NIRSpec	NRS_FULL_MSA2	381.89	-340.89	138.30	313.41	385.93	446.75	3
NIRSpec	NRS_FULL_MSA3	375.82	-516.37	138.74	307.26	380.36	442.15	3
NIRSpec	NRS_FULL_MSA4	291.77	-420.64	138.69	223.11	295.32	355.24	2
MIRI	MIRIM_FULL*	-453.36	-374.07	0.08	-381.41	-494.97	-486.22	-3
MIRI	MIRIM_ILLUM	-453.36	-374.07	0.08	-420.52	-494.42	-485.67	-4

MIRI	MIRIM_MASK1065	-393.11	-421.18	0.08	-381.24	-412.55	-410.66	-3
MIRI	MIRIM_MASK1140	-391.12	-396.53	0.08	-379.18	-410.64	-408.74	-3
MIRI	MIRIM_MASK1550	-389.22	-372.03	0.08	-377.24	-408.75	-406.82	-3
MIRI	MIRIM_MASKLYOT	-389.09	-337.61	0.08	-375.11	-410.13	-407.44	-3
MIRI	MIRIM_SLIT	-414.33	-400.69	4.36	-411.99	-416.72	-416.68	-4
MIRI	MIRIFU_FULL_SHCH1CNTR_CH4	-504.48	-321.06	17.00	-502.41	-508.81	-506.55	-5
FGS	FGS1_FULL	207.19	-697.50	-0.02	280.66	138.36	136.62	2
FGS	FGS2_FULL	24.43	-697.50	0.00	94.31	-46.78	-44.86	9

Published	09 Feb 2018
Latest updates	23 Dec 2019 Reviewed and updated for Cycle 1 Call for Proposals release.

JWST Orbit

JWST will orbit *around* the Sun-Earth L2 Lagrange point, located about 1.5 million km from Earth.

On this page

JWST will be placed in an orbit about the Sun-Earth L2 Lagrange point located about 1.5 million km from Earth, which is four times the distance between the Earth and the Moon.

It is incorrect to say that JWST "will be at L2." Rather, *JWST will orbit around L2*.

The distance of JWST from the L2 point varies between 250,000 to 832,000 km, as shown in Figure 1. The period of the orbit is about 6 months. The maximum excursion above or below the ecliptic plane is 520,000 km. The maximum distance from the Earth is 1.8 million km, and the maximum Earth-Sun angle is <33°.

L2 is a saddle point in the gravitational potential of the Solar System. Because saddle points are not stable, JWST will need to regularly fire onboard thrusters to maintain its orbit around L2. These station-keeping maneuvers will be performed every 21 days.

To maintain solar power, the orbit is designed such that JWST is never in the shadow of the Earth or the Moon during the mission.

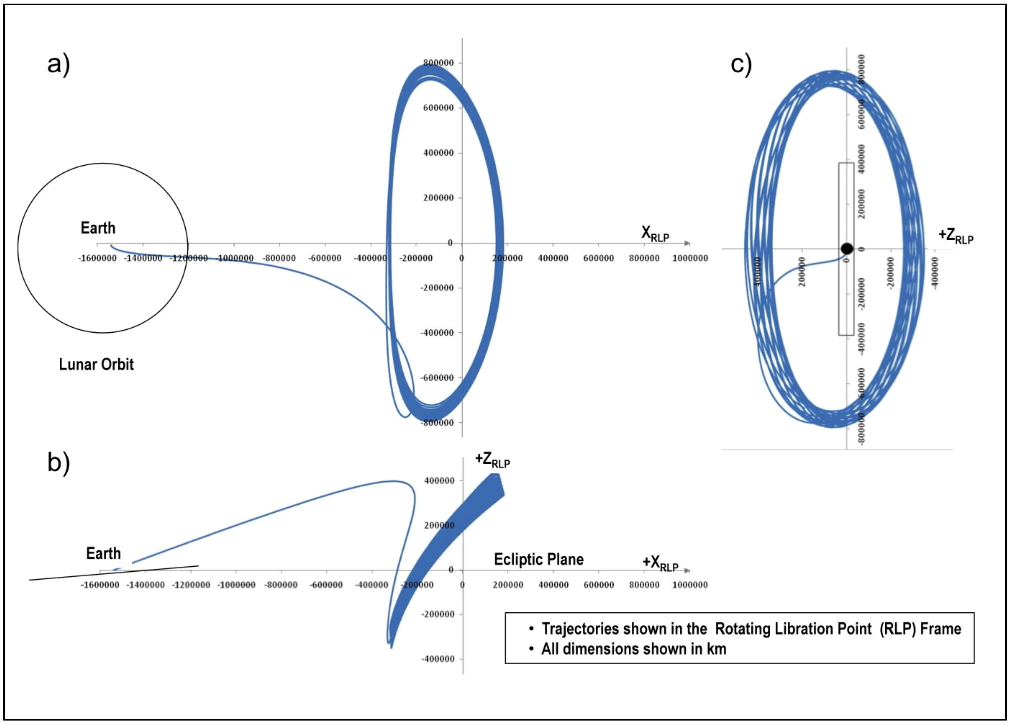
Rationale for the orbit dimensions

A larger orbit makes it easier to get the spacecraft to L2, as well as maintain its orbit. However, larger orbits can also permit stray light from the Earth or Moon to get past the sun shield and strike the primary or secondary mirrors. In addition, a larger orbit reduces communication contact opportunities.

Because JWST is solar powered, it cannot pass through the Earth's shadow during the mission. Orbits are selected that avoid shadow crossings, by selecting the launch time for a given launch day.

The L2 orbit shape is not constrained, so torus orbits, halo orbits, or Lissajous orbits are acceptable and are determined primarily by the launch's time of day and day of year. This freedom in the L2 orbit design allows for multiple launch opportunities for most months and minimizes the velocity needed to get to orbit. A trajectory can be fashioned so that JWST ‘falls into orbit’ about L2 rather than having to forcibly inject itself into a set orbit using its propulsion subsystem; this saves propellant and makes for simpler orbit maintenance.

Figure 1. JWST trajectory and orbit



A representative example of a valid JWST trajectory and orbit. Panel a is the view of the orbit projected onto the ecliptic plane; panel b is the view in the ecliptic plane, and panel c is the view along the Earth-Sun line.

Orbit maintenance

The L2 orbit has an orbit period of 6 months. While orbits about the L2 point are inherently unstable, the orbit size is large and the orbital velocity is low (~1 km/s), so the orbit "decays" slowly. However, JWST's large sun shield, roughly the size of a tennis court, is subject to significant solar radiation pressure which results in both a force and a torque. The direction of solar force varies as the observatory's attitude changes from observation to observation. The solar torque is balanced by reaction wheels, but periodically, the accumulated momentum is dumped by firing thrusters. Because JWST operations are event-driven, the observatory attitude profile and momentum dumping cannot be accurately predicted months in advance. These 2 perturbations increase the acceleration of JWST from its orbit about L2, and necessitates more frequent orbit maintenance (station keeping) maneuvers than other Lagrange orbit missions (which are typically 3–4 times per year). Accurate orbit determination will require daily tracking measurements over a period of 19 days, so station keeping will be performed every 21 days.

Orbit perturbations along the Sun-L2 axis have the greatest impact on orbit stability. Thrusters are mounted on the spacecraft bus (located on the side of the sun shield facing the Sun); those used for orbit correction are oriented as far away from the sun shield as possible. The sun shield can support a larger sun-pitch angle[1] for orbit correction than that allowed for science operations. This architecture allows thruster firing at angles up to 90° from the Sun consistent with Sun avoidance restrictions, which is sufficient to provide orbit correction in all cases.

The orbit will be biased to compensate for mean outward forces associated with gravitation of the planets and radiation pressure on the sun shield.

[1] The angle between the pointing direction and the satellite-Sun line. The "pointing direction" is the "boresight" of the telescope, also called the V1 axis of the observatory.

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Latest updates	

JWST Pointing Performance

JWST's in-orbit predicted performance for slewing accuracy and pointing stability are based on structural, thermal, and optical models. Actual values will be obtained during commissioning activities.

On this page

See also: Slew Times and Overheads

The spacecraft's attitude control system (ACS) controls the pointing and slewing of JWST. This page summarizes the *predicted* pointing performance, based on structural, thermal, and optical models of the JWST Observatory Hardware. Actual performance will be characterized after launch during the commissioning period.

Definitions and units

Pointing accuracy is expressed as the 1-σ uncertainty per axis, meaning the 2 orthogonal axes in the plane of the sky. However, the 1-σ radial uncertainty, which is larger than the per-axis uncertainty by a factor of 1.41, is often more relevant to users. In either case, the units are arcseconds or milliarcseconds (mas).

Absolute pointing accuracy

The absolute fine pointing accuracy, without a science target acquisition, is expected to be 0.10" (1-σ error, per axis). This uncertainty is dominated by guide star catalog position errors and pointing errors due to roll control. Target acquisitions, which are needed for spectrographic fixed slits, coronagraphic observations, and in some cases IFUs (depending on the desired accuracy of source placement within the IFU field of view) will further refine the pointing to the level of accuracy for offset slews, as shown in Table 1.

Pointing stability

For fixed targets, the pointing stability is evaluated as the root-mean-square (RMS) error in the guide star position in any 15 s interval, compared to the mean position over a 10,000 s observation. The predicted stability varies slightly from instrument to instrument, from 6.0 mas (NIRCam and NIRISS) to 6.7 mas (MIRI), 1-σ error per axis. The pointing stability includes several forms of "image motion" that determine the overall optical image quality and the telescope point spread function.

For Solar System (i.e., moving) targets, the line-of-sight pointing stability is evaluated as the RMS mean over a 1,000 s observation, for a linear rate of motion of 3.0 mas/s. This is estimated to be 6.2 to 6.7 mas, 1-σ per axis, depending on the instrument. This is much better than the required stability (16.7 mas, 1-σ per axis). At the maximum permitted rate of motion, 30 mas/s, models indicate that the pointing stability will be very similar to the slower 3.0 mas/s case.

Offset slew accuracy

Instrument field-of-view offsets, after guide star reacquisition, are predicted to be very accurate, generally less than 5 mas, 1-σ, per axis. This type of offset is used for dithers and target acquisitions.

Table 1. Offset angle uncertainties

Offset angle (arcseconds)	Uncertainty (mas, 1-σ, per axis)	Uncertainty (mas, 1-σ, radial)
0.0–0.5	4.0	6.1
0.5–2.0	4.2	6.4
2.0–20	4.6	7.0
20–45	5.3	8.1

Published	19 May 2017
Latest updates	• 31 May 2017 Added radial uncertainties

JWST Telescope

The Optical Telescope Element (OTE) of JWST consists of the primary, secondary, tertiary, and fine steering mirrors. The wavefront of the OTE is monitored and actively controlled.

On this page

See also: Wavefront Sensing and Control

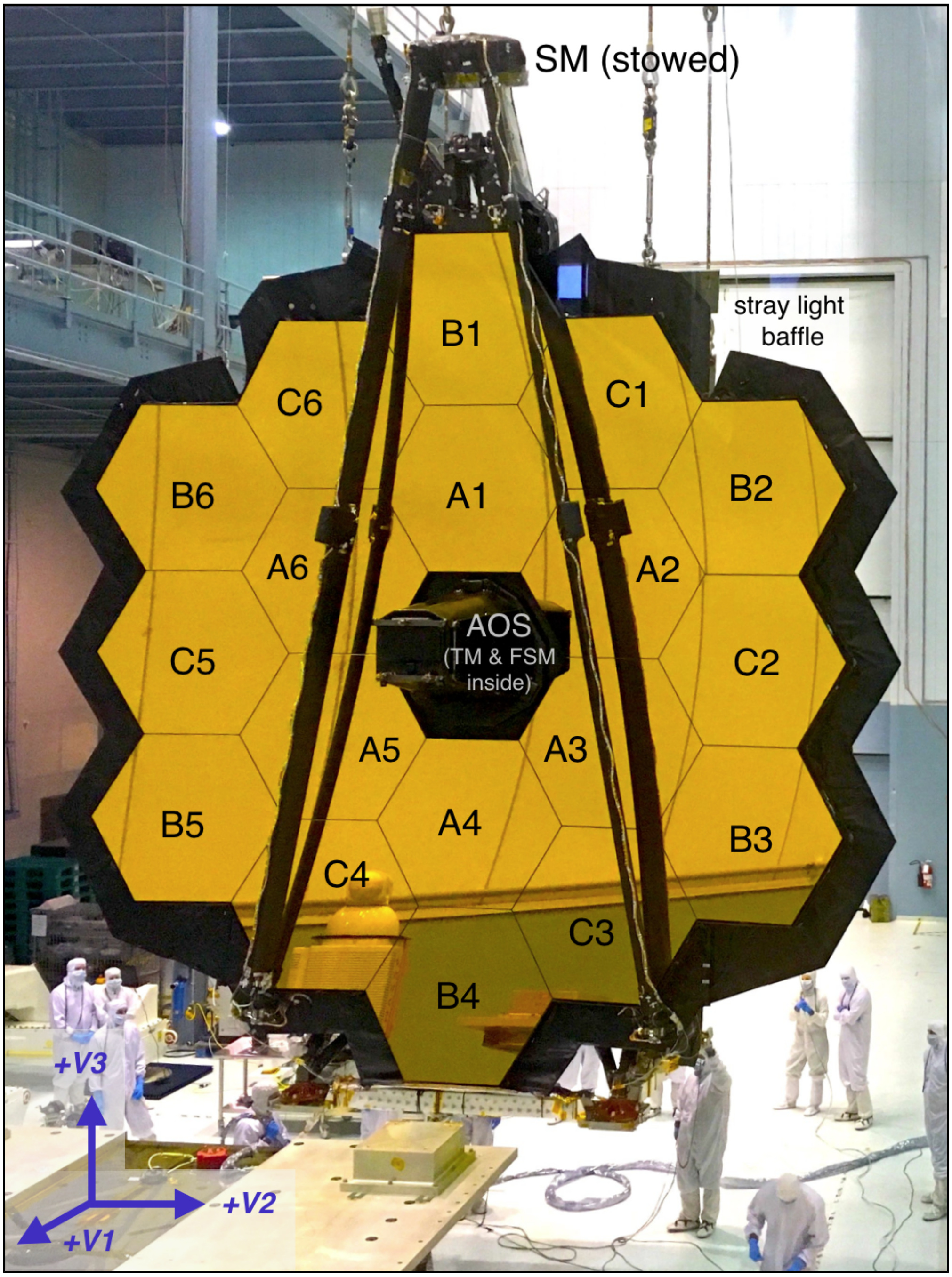
The mirror system that collects and focuses light for JWST is referred to as the optical telescope element (OTE). It has a 3-mirror anastigmat design, consisting of primary, secondary, and tertiary mirrors. A 4th flat mirror, called the fine steering mirror (FSM), is used for pointing stabilization and very small offset maneuvers. The effective focal ratio of the OTE is f/20, and the effective focal length is 131.4 m.

The mirrors are made of beryllium, which is both lightweight and very stable to temperature variations over the range of 30–80 K. The mirrors are coated with gold to provide high reflectivity from 0.6 to just beyond 28 μm.

Optical design and components

Details on the optical design, manufacturing, and testing of the JWST OTE can be found in Lightsey et al. (2012) and Lightsey et al. (2014).

Figure 1. JWST Optical Telescope Element (OTE) with components labeled



The main components of the JWST OTE are labeled above. Unseen on the back side are the mechanisms and electronics for active control of the optics, plus the primary mirror backplane support structure providing a rigid framework. This photo shows the OTE in the large cleanroom at NASA Goddard in October 2016, being positioned prior to the start of the center of curvature tests. The telescope (V1,V2,V3) coordinate system is indicated; +V1 is the telescope boresight.

Primary mirror

The primary mirror is comprised of 18 hexagonal segments, each ~1.4 m in diameter, which, when properly phased together, act as a single mirror ~6.5 m in diameter. The individual segments have, on average, better than 25 nm rms surface figure error. The primary mirror serves as the aperture stop for most JWST observing modes, with the exceptions of coronagraphy and aperture masking interferometry (AMI). The unobscured collecting area of the primary mirror is 25.4 m^2. (The total polished area is slightly greater, 26.3 m^2, but the secondary mirror support struts obscure a small portion.) An opaque border around the outer edge of the primary helps minimize stray light.

Each primary mirror segment has actuators on the back that allow control of the 6 spatial degrees of freedom with a precision better than 10 nm. A 7th actuator on each segment controls its radius of curvature, allowing correction for slight manufacturing variations to ensure all 18 segments' focal lengths are very closely matched. Two segments needed larger radius of curvature corrections than the rest, and as a result, have somewhat higher surface residuals. These segments were positioned in the primary in locations blocked by the Lyot stops and aperture mask, specifically positions A1 and C3, thus minimizing the wavefront error for the coronagraphy and aperture masking modes which are most sensitive to such residuals.

Secondary mirror

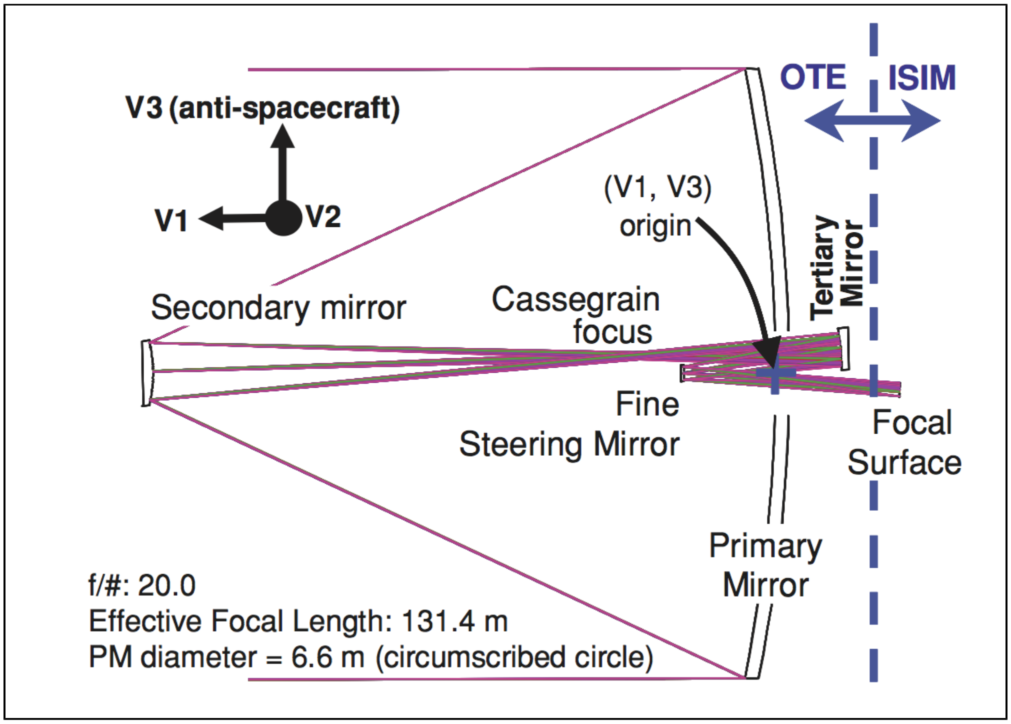
The secondary mirror is a convex circular mirror 0.74 m in diameter. A set of 6 actuators allows control of the mirror's position and orientation, similar to the control of the primary segments. The primary and secondary first bring light to an initial Cassegrain focus just before the entrance aperture of the aft optics system, where a fixed baffle also helps to block stray light.

Aft optics

The aft optics system contains a fixed tertiary mirror and movable FSM. The tertiary mirror is a concave aspheric mirror with an elongated shape roughly 0.73 × 0.52 m in size. It re-images the primary aperture onto the FSM, while canceling out aberrations to provide excellent image quality over the full field of view. Like the primary and secondary mirrors, the tertiary mirror surface figure is better than 25 nm rms. Because the tertiary is at an intermediate focal plane, in-between a focal plane and pupil plane, images taken at different field positions will see different pieces of that surface figure. This will be one of the factors contributing to field dependence of point spread functions. See Lightsey et al. (2014) for more details.

The FSM is a high quality flat mirror used to stabilize the image during science observations. During observations, it will be continuously adjusted in X- and Y-axis tilts based on measurements made by the attitude control system as part of the fine guidance control loop. The OTE exit pupil is the image of the primary that reflects off the fine steering mirror towards the ISIM focal plane and instruments. A mask around the outer edge of the fine steering mirror helps further minimize stray light.

Figure 2. Schematic of the OTE from the side



The tertiary and fine steering mirrors are located within the aft optics system as shown here. Light exiting the OTE converges to the ISIM focal surface, where several pickoff mirrors redirect portions of the field to the science instruments. (From Gardner et al. 2006)

Deployments and wavefront control

The telescope will be phased during on-orbit commissioning; the wavefront will be periodically monitored during science operations and corrected as needed to maintain alignments.

The primary mirror segments are mounted on a graphite-composite backplane structure that is designed to be very stable. Two "wings", each supporting three mirror segments (B2, C2, B3 and B5, C5, B6 in Figure 1 above), are folded at launch, and will deploy once on orbit and then latch firmly into their permanent positions. The secondary is supported by a deployable tripod support structure which also latches into position following deployment. These large deployments happen within the first few weeks after launch while the observatory is en route to L2.

Bringing the mirrors from their initial deployed positions into fine alignment requires a long series of small iterative adjustments that makes use of several different variations of wavefront sensing and control. This process will begin about 40 days after launch and is expected to take about three months to complete.

Several OTE electronics boxes support the use of actuator mechanisms and related sensors for position, and to handle telemetry. An actuator drive unit in the spacecraft interfaces with these electronic boxes. Notably, the actuator drive unit can either run the FSM control loop, or send adjustments to the primary and secondary actuators, but not both tasks at once. Thus, during science observations when the fine steering loop is active, the other mirrors will always be static and fixed in position. The OTE electronics system is fully redundant for robust fault tolerance in flight.

Predicted performance

The OTE is required to be diffraction limited for wavelengths $\lambda \geq 2$ µm, and should deliver excellent performance over its full wavelength range down to 0.6 µm. Detailed optical alignment budgets and Monte Carlo simulations are used to model the deployment and alignment process to produce predictions for performance along with statistical confidence intervals. With 95th percentile confidence, the full observatory wavefront error level (telescope plus instrument plus dynamics) should achieve better than 100 nm rms WFE for NIRCam after completion of the WFSC process. The mean predicted performance is even better, <75 nm rms with 50th percentile confidence for NIRCam. NIRISS and FGS will see similar performance; NIRSpec and MIRI have optical budgets designed to tolerate slightly higher levels of wavefront error and this is reflected in the predicted performance. See Lightsey et al. (2014) for more details.

References

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The James Webb Space Telescope

Lightsey, P. A. et al. 2012, *Optical Engineering*, 51, 011003
James Webb Space Telescope: Large deployable cryogenic telescope in space

Lightsey, P. A. et al. 2014, *SPIE* 9143, 914304-1
Status of the Optical Performance for the James Webb Space Telescope

WebbPSF tool (converts predicted OTE performance and related data into simulated JWST point spread functions as seen by each of the instruments)

Published	13 May 2017
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JWST Wavefront Sensing and Control

The precise optical alignment of the telescope optics for JWST is achieved and maintained using wavefront sensing imagery from the science instruments, particularly NIRCam.

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Periodic wavefront sensing and control (WS&C) will keep the primary mirror segments aligned and in phase, so that their wavefronts match properly and the segments act like one large telescope, rather than 18 individual telesopes.

A telescope commissioning process after launch will proceed through several stages of iterative sensing and alignment correction over several months to establish the initial best on-orbit alignments. Routine monitoring observations and occasional corrections during science operations will subsequently maintain the mirror alignment. Wavefront sensing results will be made available in the archive for use by observers for any data calibration or analysis purposes.

Active optics system overview

Because of the unique circumstances of the stable space environment, the wavefront sensing system architecture on JWST is different from large active telescopes on the ground. Most significantly, JWST is free from atmospheric disturbances and gravity-induced deformations, which are the dominant factors requiring rapid correction for active and adaptive telescopes on Earth. Instead, JWST only needs corrections for wavefront aberrations that change much more slowly than the durations of typical science observations. In particular, the need for wavefront corrections during science operations will be mostly due to temperature changes that cause slight thermal expansion and contraction of portions of the observatory, typically on timescales of several days. This allows the use of the science instrument imaging detectors for periodic measurements, rather than requiring dedicated wavefront sensor detectors or continuously active segment edge sensors.

All instruments will be used for a portion of wavefront sensing during observatory commissioning, but NIRCam is the primary wavefront sensor for JWST and contains several components in its pupil wheels that are used to measure wavefront information. Because of its importance to overall observatory operations, NIRCam is comprised of 2 fully redundant modules. Weak lenses in the NIRCam filter wheels defocus the images to provide wavefront information. Analysis and determination of the wavefront error is performed on the ground using downlinked image data, and the necessary mirror commands are then uplinked to JWST to correct the alignments.

Each primary mirror segment has actuators on its back that provide 6 degrees of freedom, as well as control over the radius of curvature. The secondary mirror is also controlled in its 6 degrees of freedom. Thus, there are a total of 132 degrees of freedom in the telescope that need alignment, plus the focus mechanisms in each of the science instruments apart from MIRI. Other alignments, such as the tertiary and fine steering mirror, have been established during observatory assembly on the ground and are sufficiently rigid to not need correction after launch.

During commissioning

After launch and deployment, the primary mirror segments, secondary, and science instruments will be misaligned relative to each other by up to several millimeters. An iterative process using several types of wavefront sensing and control will bring these mirrors into alignment within tens of nanometers. The large dynamic range (millimeters to nanometers) means that several distinct stages and types of sensing are necessary. This commissioning process is necessarily iterative, due to finite sensing precision and also to mechanism uncertainties inherent to the coarse stage actuator design. As a result, Optical Telescope Element (OTE) commissioning will be iterative at both small scales (a given step may need to be performed several times to converge) and at much larger scales (mechanism uncertainties will likely require looping back to repeat entire sections of the commissioning plan).

The deployment of the secondary mirror, the 3-mirror folded side sections of the primary mirror, and initial deployments of segments from their launch restraints will take place starting around 16 days after launch. The wavefront sensing and correction process will begin once the telescope and instruments have cooled sufficiently toward their operating temperatures, expected around 40 days after launch. This process will intersperse individual wavefront sensing and control tasks, initial activation and checkouts of the science instruments, and observatory-level calibration tasks that involve many subsystems across the whole observatory, such as the guider and attitude control system. The main stages of the process are (1) segment location and identification, (2) segment level wavefront control, (3) segment co-phasing, and (4) multi-instrument sensing and control. This process, expected to take several months, comprises a large portion of the 6 month-long commissioning phase. Because NIRCam is the main wavefront sensing sensor, high quality images will first be achieved on NIRCam prior to any of the other instruments, about halfway through telescope commissioning. The multi-instrument sensing process then adjusts secondary mirror alignment to optimize image quality over the full instrument suite.

Shortly after the telescope is fully aligned, a stability characterization assessment will characterize the observatory's response to changes in spacecraft attitude with respect to the sun. This will begin quantifying stability in flight, and will better inform subsequent wavefront maintenance.

For more information on OTE commissioning, see Acton et al. (2012) and Perrin et al. (2016).

During science operations

During routine science operations, the wavefront will be monitored periodically, and alignment corrections made as needed. Nominally, the wavefront will be measured every 2 days using NIRCam weak lenses. Corrections are expected to be relatively infrequent, no more often than every 2 weeks and perhaps only a handful of times per year. The sensing and control processes together will take about 1%–2% of observatory time, which is accounted for as part of the observatory calibration overhead.

The cadence for sensing and control measurements may be adjusted in later cycles based on achieved performances in flight. This will happen as part of developing the calibration plan for each cycle, alongside the planning of the instrument calibration programs. The 2-day sensing cadence has a loose tolerance; the goal will be to schedule wavefront sensing observations so as to accommodate any time-critical observations, to not disrupt part way through any long mosaic or time-series observations, etc.

Note that the intent of corrections is to maintain the telescope alignment, not to intentionally change it. That is, the effect of corrections should be to bring the OTE back to the nominal aligned state that it had at the end of the commissioning period, and ensures it continually remains near that state. There is no plan for "campaign" style observation plans in which the OTE would be temporarily optimized for one instrument over another. Nor is there any need for observers to request scheduling their observations with any particular timing constraints relative to wavefront sensing. However, to mitigate any possible impacts of thermal changes to the point spread function during certain high-contrast imaging observations, *cycle 1 users are directed to force back-to-back observations of science targets and PSF reference star observations*. Pending assessment of on-orbit performance, this restriction may be relaxed in future cycles.

The wavefront sensing image data from NIRCam and the derived wavefront maps will be available from the MAST archive interface, similar to other calibration program data.

References

Acton et al. 2012, *SPIE* 8442, 84422H
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Perrin et al. 2016, *SPIE* 9904, 99040F
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JWST Momentum Management

The JWST Observatory's momentum is managed both predictively and in real time by the attitude control system to keep the observatory under control at all times.

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During science observations, solar photon pressure causes angular momentum to build up within the reaction wheels. This angular momentum must be dumped periodically by firing thrusters.

How momentum builds up

During science observations, the observatory will be pointed at a target, in an orientation at which the sun shield center of pressure is not aligned with the observatory center of mass. As solar photons hit the large sun shield, they place a torque on the observatory as a whole. The attitude control subystem (ACS) counteracts this torque by appropriately changing the spin rate on the reaction wheels, with the consequence that angular momentum accumulates in the reaction wheels. Momentum accumulation depends on the solar pitch angle, the roll orientation of the telescope, and the visit duration at a particular pointing position. The angular momentum (spin rate) of the reaction wheels must be managed to be kept within operational limits.

Managing momentum

The planning and scheduling system predicts the momentum profile for a given section of the schedule delivered to the observatory, based on an assumed starting momentum and schedule of observatory pointings. Momentum changes can be managed at some level by the way a sequence of observations is planned; this is done by observing at an orientation that builds momentum in a particular reaction wheel, followed by an observation at an orientation that removes momentum from that wheel.

However, managing momentum is only one of a number of planning constraints. At some point, one or more wheels will need to be adjusted to stay within operational bounds. The planning and scheduling system inserts planned momentum unloads into the schedule as needed, based on the modeling of expected momentum buildup, currently expected to be 1–2 times per week. Each unload activity takes a few hours, in which the observatory slews to a particular orientation to minimize the impact on the orbit and then fires thrusters as needed to allow the spin rate of the reaction wheels to be adjusted. The observatory then rejoins the preplanned observing timeline.

Because loss of pointing control from saturating one or more reaction wheels could endanger the entire observatory, an important safeguard is built into the ACS. Since JWST operations are event-driven, the actual sequence of activities can differ from what was planned. For example, if a guide star acquisition fails on one observation, that observation is dropped and the observatory moves on to the next planned observation. This will obviously make the real momentum profile different from what was planned.

The onboard operating system checks the current momentum state before starting each visit. If the momentum state is judged not to be sufficient to safely complete that visit, it will autonomously request a momentum unload be performed before the visit begins. Also, while margins are built into the planned timeline, if for any reason one of the reaction wheels approaches its saturation limit, the ACS will autonomously terminate the science activities, unload momentum at the current pointing, and put the observatory into a "safe mode." Recovery from safe mode would not occur until the next ground contact when real-time communications can be established. Operating system checks prior to each visit should prevent this safety net from ever being needed, but the safety net is there as a stop gap against a dangerous situation for the observatory.

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Latest updates	

JWST Integrated Science Instrument Module

The Integrated Science Instrument Module (ISIM) is the part of JWST that contains 4 science instruments, the Fine Guidance Sensor, and the data-handling computer.

It also houses electronics that (1) control the instrument detectors and mechanisms, (2) maintain the thermal environment, and (3) provide command and data processing for the science instruments and the FGS. See Figures 1 and 2.

Figure 1. The JWST Integrated Science Instrument Module (ISIM)

The JWST ISIM is shown in final preparation for thermal vacuum testing at NASA/GSFC, in spring 2016.

Figure 2. The completed ISIM

The ISIM, complete with thermal blankets, on its way to the thermal vacuum chamber at NASA/GSFC, in spring 2016.

The ISIM Command and Data Handling (ICDH) subsystem provides the commanding, telemetry routing, and processing functions for all of the science instruments, including the Fine Guidance Sensor. The ICDH manages the event-driven science operations of the observatory and coordinates ISIM and spacecraft activities. It performs readout mode processing of the science data, that is, formatting of the science data for each exposure before transfer to the spacecraft's solid state recorder. Software resident on the ICDH analyzes portions of the data for target acquisition purposes.

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Latest updates	

JWST Solid State Recorder

JWST can store at least 58.8 Gbytes of science data. Science data downlinks occur in two 4-hr contacts per day where each contact can transmit at least 28.6 Gbytes of recorded science data.

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The solid state recorder (SSR) onboard JWST can hold at least 58.8 Gbytes of recorded science data.

JWST downlinks science data in two 4-hr contacts per day; each contact can transmit at least 28.6 Gbytes of recorded science data to the ground.

Limits on data rates and data volume

APT calculates the expected data rate for observations and warns users if planned observations may exceed the data volume limits. When constructing the weekly observation plan, the JWST planning system verifies that the data rates within each visit are acceptable, and that the data volume to be accumulated between contacts will not exceed the downlink capacity or the SSR capacity.

Sending science data to Earth

During normal science operations, JWST will downlink data in 4-hour contacts, nominally occurring twice per day, approximately 12 hours apart. *In one contact, JWST can transmit at least 28.6 Gbytes of recorded science data.* If a contact is missed, science observations can continue without filling the recorder, and the ground can catch up on the next contact.

Data rate limits within ISIM

The rate at which science data can be written to the SSR is regulated by the ISIM Command and Data Handling subsystem (ICDH). The maximum ICDH sustained data rate is about 48 Mbits per second, including data packetization overheads. This corresponds to about six 2048 × 2048 full frame image files every 10.7 s. The actual data rate depends on the number of detectors simultaneously in use, their exposure parameters, and the precise timing of when their exposure readouts arrive in the ICDH for processing. The number of detectors in use at any one time could be as large as 14. For example, observations with both NIRCam modules (10 detectors), along with parallel NIRSpec observations (2 detectors), and the FGS for guiding would be sending data from 13 detectors to the ICDH. The relative timing of the arrival of data packets is unpredictable, and this uncertainty is factored into the 48 Mbps limit.

To prevent the loss or corruption of packets, the APT templates set the number of detectors in use and the rate at which data is generated. For example, in the NIRCam rapid readout mode, only one NIRCam module (five 2K × 2K detectors) can be used with N_{groups} = 1. To use both modules (ten 2K × 2K detectors) in rapid readout mode requires N_{groups} = 2. Combinations using multiple instruments must stay within the 48 Mbps limit.

This article uses the S.I. definitions of gigabyte and megabyte: 1 Gbyte = 10^9 bytes, and 1 Mbyte = 10^6 bytes.

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Latest updates	

Fine Guidance Sensor

JWST's Fine Guidance Sensor (FGS) provides data for science attitude determination, fine pointing, and attitude stabilization using guide stars in the JWST focal plane. Absolute pointing and image motion performance is predicted on the JWST Pointing Performance page.

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JWST's Fine Guidance Sensor (FGS) is a near-infrared (NIR) camera residing in the Integrated Science Instrument Module (ISIM). It has a passband from ~0.6 to 5.0 μm and operates at a temperature of ~37 K, similar to near-infrared science instruments. The FGS has 2 channels, each with 2.3′ × 2.3′ field of view (FOV) and a pixel scale of ~0.069".

The FGS functions are:

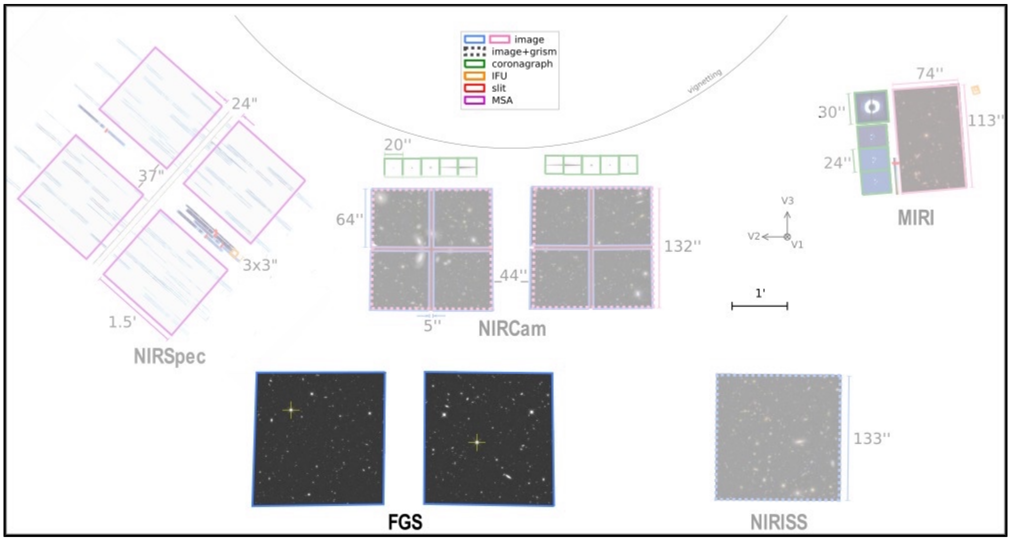
- to identify and acquire a guide star, measure its position in one of the 2 guider channels, and provide this data to the JWST attitude control subsystem (ACS) for attitude determination.

- to provide fine pointing data to the ACS for attitude stabilization. The FGS can provide this data for both fixed target pointings and for moving target observations.

Guide star position data is used by the ACS for absolute (right ascension and declination) pointing knowledge and pointing control in the plane of the sky (pitch and yaw). ACS uses the data from off-axis star trackers to control the spacecraft’s roll orientation.

In addition to its critical role in executing observations, the FGS also serves as an integral part in the commissioning of the JWST Observatory, and in observation planning. FGS pointing data are archived for every science observation and may be valuable for post-observation data analysis.

Unlike on HST, the Fine Guidance Sensors on JWST are expected to be used for guiding and calibration exclusively. Thus, at this time they are *not available* for science proposals by general observers.



Observational capabilities

The FGS has an unfiltered passband from ~0.6 to 5.0 μm. Each focal plane array is a 2048 × 2048 HgCdTe sensor chip assembly that has a 2.3’ × 2.3’ FOV after correcting for internal field distortions. The central 2040 × 2040 pixels are light sensitive; the 4 outermost rows and columns are reference pixels for bias measurements. However, the usable FOV for guide star identification and guiding is 2.20' × 2.20' in order to provide sufficient light-sensitive pixels for flat field corrections for potential guide stars near the edge of the FOV.

The FGS has neither a shutter nor a filter wheel; therefore, its detectors are always exposed to the sky.

The JWST proposal planning system currently uses the Guide Star Catalog (GSC) version 2.4.1, which was updated in the fall of 2017. The Guide Star Selection System has been updated to use this new catalog, with improvements to astrometry, photometry, and number and distribution of stars that are available—for additional information, please refer to the JWST Guide Stars article.

FGS optical design

The optical assembly of the FGS is shown in Figure 2. Light from the telescope is focused onto the pick-off mirror (POM), collimated by the 3-mirror assembly (TMA), and focused by an adjustable fold mirror (fine focus mechanism) onto the 2 focal plane arrays. The fine focus mechanism allows tuning of FGS focus.

Figure 2. Layout of the FGS optical components on the optical bench

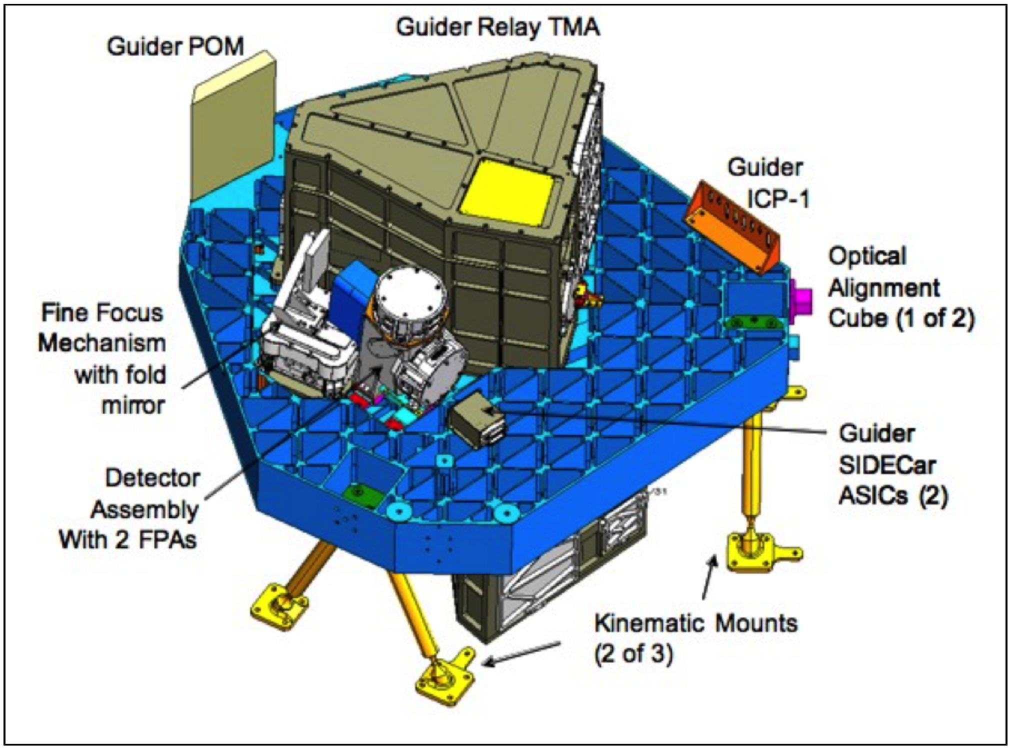


Figure courtesy of Honeywell.

FGS operations

FGS has 3 operating modes: "OFF", "STANDBY",[1] and "OPERATE". In operational mode, it has 5 software functions: calibration, identification, acquisition, track, and fine guide. The calibration function allows the FGS to obtain necessary data for calibration by the ground system, while the remaining functions enable the identification, acquisition, and tracking of a guide star. These flight software functions are briefly described below.

Calibration

In order to be able to calibrate the FGS, the ground system requires data collected with the "calibration" function. In this mode, the FGS acts like a camera, obtaining full frame or subarray images with one guider while the other tracks a guide star. These data are then used to measure and correct for geometric distortion, intra-pixel non-uniformity, flat field response, bias, bad pixels, and other performance characteristics. The "calibration" function is only available for commissioning and calibration.

Identification

At the conclusion of a spacecraft slew, the telescope is pointing at the sky such that the selected guide star is near the center of one of the FGS detectors and the science target is in the desired science instrument, though not yet at the precise attitude for the scientific observation. To assure that the correct guide star is acquired, the FGS obtains an image of the sky and compares the observed positions of stars (and any other luminous objects) to a catalog of objects using a pattern-matching algorithm. To minimize smearing, the "identification" images are obtained in a sequence of "strips": 36 subarrays of 2048 × 64 pixels with an effective integration time of 0.3367 s each.

Acquisition

The approximate location of a guide star on the FGS detector is measured using the flight software "identification" function, or is determined at the end of a small angle maneuver that offsets the guide star from a previously known location in the FGS FOV. This is followed by executing the "acquisition" function. A 128 × 128 pixel (8.8” × 8.8”) subarray is centered at the expected position of the guide star. Images of the guide star within this subarray are obtained and autonomously analyzed by the FGS to locate the star. A second set of measurements using a 32 × 32 pixel (2.2" × 2.2") subarray, centered on the guide star position, is obtained. The FGS reports the position and intensity of the guide star to the ACS; this information is used by the ACS to update its knowledge of the spacecraft’s current attitude, and to bring the pointing of the telescope to within 0.45" (1-σ radial) of its commanded position.

Track

Following the successful completion of the "acquisition" function, and ACS’s corrective maneuver of the observatory pointing, the FGS executes the "track" function. The FGS places a 32 × 32 pixel (2.2" × 2.2") subarray on the expected location of the guide star. High cadence subarray images are obtained from which the guide star’s position centroid is determined and reported to ACS every 64 ms. Once the guide star is within ~0.06" of its desired location, the FGS can transition to "fine guide" mode.

In "track" mode the FGS will adjust the position of the 32 × 32 pixel subarray on the detector to remain centered on the guide star if the guide star moves. Thus, "track" mode is used for moving target observations.

Fine guide

When the FGS transitions from "track" to "fine guide," a fixed 8 × 8 pixel (0.5" × 0.5") subarray is centered on the guide star position. The guide star centroid is computed from each subarray image and sent to the ACS every 64 ms, controlling the observatory pointing in a closed loop. In "fine guide" mode, the subarray location is fixed and cannot be changed without transitioning through the operating mode "STANDBY"[1], which requires exiting fine guidance control and starting over in "track" mode.

Once in fine guide control, the absolute pointing accuracy of JWST with respect to the celestial coordinate system will be determined by the astrometric accuracy of the Guide Star Catalog and the calibration of the JWST focal plane model.

[1] In "STANDBY," the operations scripts subsystems (OSS) software is running and the guider is waiting, ready to transition to the operating mode "OPERATE" and execute a commandable function such as "identification." The FGS flight software (FSW) controls the physical and electrical conditions to which the guider's performance is sensitive. In "STANDBY," the FGS flight software will be capable of sending and receiving commands, data, and software updates.

Subarrays

Each of the operational modes uses a different sized subarray and readout pattern. The frame readout time for each subarray can be calculated using the following equation:

$$t_{frame} = \left(\frac{N_{columns}}{N_{outputs}} + C_{overhead}\right) \times (N_{rows} + 1) \times 10\mu s.$$

where $N_{outputs}$ is the number of amplifiers used in the subarray, equal to 4 for CAL full frame and ID and 1 for CAL subarrays and other functions; where $C_{overhead}$ is a constant that accounts for electronic overhead, equal to 12 for ACQ1 or 6 for all other functions; and where the number of rows and columns N_{rows} and $N_{columns}$are as specified in the table below.

FGS data utilizes correlated double sampling (CDS) to correct for detector effects within integrations, a method in which the 0th read is subtracted from the 1st read. The time between reads, or CDS time, is a function of the readout pattern and the frame readout time:

$$t_{CDS} = (N_{DROP} + 1) \times t_{readout}$$

where N_{DROP} is the number of dropped frames between reads and $t_{readout}$ is the frame readout time.

Table 1. Subarray and readout definitions for each function

Name	Abbreviation	Subarray	Integration readout pattern	Frame readout time (s)	CDS time (s)
Calibration	CAL	Variable[2]	RESET READ DROP x n READ[2]	Variable[2]	Variable[2]
Identification	ID	2048 x 64 x 36 (strips)[3]	RESET READ READ READ READ	0.3367	0.3367
Acquisition 1	ACQ1	128 x 128	RESET DROP READ DROP READ	0.1806	0.3612
Acquisition 2	ACQ2	32 x 32	RESET DROP READ DROP x 3 READ	0.01254	0.05016

Track	TRK	32 x 32	RESET READ DROP READ	0.01254	0.02508
Fine Guide	FG	8 x 8	RESET READ x 4 DROP x 39 READ x 4	0.00126	0.05418

[2] In CAL, images can be taken either as full-frame (2048 × 2048) or as certain subarrays (128 × 128, 32 × 32, or 8 × 8) at fixed positions on the detector. Furthermore, the readout pattern in CAL can be modified to produce images with different integration times. The frame readout time is determined by the subarray size; for full frame images it is 10.7368 s, and for all other subarrays the readout times are as listed in Table 1. As explained above, the CDS time depends on both the readout pattern and the subarray readout time.

[3] The strips are read out as 36 subarrays with 64 rows by 2048 columns, with an overlap between rows of 8 pixels. This configuration means that the bottom 12 pixels and top 12 pixels of the detector are not read out during ID.

Acknowledgements

The Canadian Space Agency (CSA) has contributed the FGS to the JWST Observatory. Honeywell (formerly COM DEV Space Systems) of Ottawa, Canada, is CSA's prime contractor for the FGS.

Published	19 Apr 2017
Latest updates	• 20 Nov 2019 Clarified notes regarding $N_{outputs}$ • 15 May 2018 Added documentation of CAL function, subarrays, and readouts • 26 Sep 2017 FGS pointing accuracy changed from 0.68" to 0.45" • 31 May 2017 Replaced 1" requirement (each axis) with 0.68" estimate (radial)

JWST Spacecraft Bus

The JWST spacecraft bus provides the telescope with electrical power, attitude control, thermal control, command and data handling, communications services, and propulsion.

Its solar array provides 2,000 W of electrical power for the life of the mission.

The attitude control subsystem (ACS) provides attitude determination and control for all mission phases and modes of the observatory. The ACS interfaces with the Fine Guidance Sensor (FGS), located in the Integrated Science Instrument Module (ISIM), and with the telescope's fine steering mirror (FSM) for fine pointing control during observations.

JWST's propulsion subsystem provides the means to correct the telescope orbit, control the observatory attitude in certain modes, and unload reaction wheel momentum. Thrusters are used for orbit maintenance, momentum unloads, and some attitude control functions. The observatory carries enough propellant for at least 10 years of science operations.

The spacecraft Command & Data Handling (C&DH) subsystem supports command processing for the spacecraft bus, command routing to the ISIM and Optical Telescope Element (OTE), as well as telemetry recording and routing to the communications subsystem.

The spacecraft's solid state recorder (SSR) provides at least 58.8 Gbytes[1] of storage for science data. The ISIM Command and Data Handling (ICDH) computer creates science data files as the detectors are read out, and transfers these files to the SSR where they are staged until they can be transmitted to the ground.

[1] This article uses the S.I. definition of gigabyte: 1 Gbyte = 10^9 bytes.

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Latest updates	

JWST Attitude Control Subsystem

Pointing control and slewing of JWST is performed by the attitude control subsystem (ACS). Fine guiding additionally involves the Fine Guidance Sensor (FGS).

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See also: JWST Pointing Performance, Slew Times and Overheads

Pointing and slewing of JWST is done by the spacecraft flight software, which processes data from attitude sensors, instructions from the Integrated Science Instrument Module (ISIM) and the JWST ground system, and issues commands to actuators. The attitude control subsystem (ACS) is responsible for maintaining attitude and pointing, slew maneuvers, momentum unloading, Delta-V (orbit correction) maneuver control, high gain antenna pointing, observatory safe modes, and ensuring that the observatory remains within Sun avoidance constraints.

This page provides a functional summary how JWST controls pointing and slewing to conduct science operations. Related pages describe the predicted pointing stability and slew accuracy, as well as the predicted slew times and overheads.

Functional overview

The ACS uses sun sensors, star trackers, and gyroscopes to sense the observatory orientation and movement, as well as reaction wheels and/or thrusters to apply force or torque to the observatory for pointing control or maneuvers. The reaction wheels provide the control torques needed to maintain attitude and pointing as well as to slew. The spacecraft's star trackers provide stellar inertial attitude reference for 3-axis coarse pointing control. The ACS points the telescope boresight to within 8″ (1-σ, per axis) of the commanded position prior to guide star acquisition, without any position reference or input from the Fine Guidance Sensor (FGS).

Control of the roll orientation about the telescope's optical axis is provided by input from the spacecraft's 2 star trackers. The star trackers each have a ~16° diameter FOV, projected on to a 512 × 512 pixel CCD detector. They are oriented over 45° from the telescope boresight and each other. The star trackers compare the observed positions of bright stars ($V < 6$) to an internal star catalog. This allows the use of a single star for fine guidance within the FGS field of view (FOV) while still maintaining roll control.

The duration of slews is a function of the length of the motion. The rate of motion is determined in part by the need to keep settling times within certain limits as well as the desire to reach the new pointing as soon as possible. For slews between 25" and 3°, the slew rate is slower than for shorter or longer slews, to avoid exciting slosh modes of the propellant in the tanks. Once excited, propellant slosh can take a long time to damp (more than 20 minutes in some cases).

Fine guiding

Fine guidance is a closed loop system, in which a guide star in the FGS FOV is used to stabilize the observatory during science exposures. The FGS makes measurements of the guide star position in the plane of the sky and sends these to the ACS every 64 ms. Using the FGS data, the ACS determines the telescope pointing error to be removed, using a combination of the fine steering mirror (FSM) and the spacecraft's reaction wheels.

Each science visit uses a single guide star. Pointing changes within the FGS FOV (dithers, target acquisition motions, etc.) are specified to the spacecraft in terms of the change in the guide star location (Delta X, Delta Y) in the FGS FOV, and the change in the position angle (Delta PA) about the guide star's position.

For stationary targets, the ACS controls the FSM and reaction wheels so that the guide star remains at a fixed location in the FGS detector.

In order to change the telescope pointing orientation by more than one FGS pixel (about 0.06"), the ACS must exit the "Fine Guide" mode, execute the pointing change, and then reestablish fine guidance. Very small offsets <0.06" can be executed by the FSM, while the ACS remains in closed-loop fine guidance control.

Guiding for moving targets

For moving targets (in our Solar System), the process is similar, except that the FGS measures the guide star position in "Track" mode, which is less accurate compared to "Fine Guide" mode for a given guide star brightness. For moving targets, the ground system computes a trajectory for the guide star that keeps the solar system target stationary in the science instrument. The ACS then updates the control position of the guide star every 64 ms, and the FGS in "Track" mode adjusts the position of the guide star track box to follow the guide star.

Managing momentum

The planning and scheduling system provides predictive management of the expected momentum, but actual timelines may differ. Hence, the ACS participates in real-time management of the momentum on the observatory by monitoring the momentum as a function of time and taking autonomous action as needed to keep the observatory safe.

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JWST Communications Subsystem

The JWST communication subsystem provides 2-way communications with the observatory via the NASA Deep Space Network.

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JWST's communications subsystem is the part of the spacecraft bus that provides 2-way communications to and from the observatory during certain ground testing activities and throughout the operational phase. S-band frequencies are used for command uplink, low-rate telemetry downlink, and ranging. Ka-band frequencies are used for high rate downlink of science data and telemetry. All communications are routed through NASA's Deep Space Network, with 3 ground stations located in Canberra (Australia), Madrid (Spain), and Goldstone (USA). There are limits on the onboard data volume and data accumulation rates.

Onboard antennas

JWST has a 0.6 m Ka-band high-gain antenna (HGA) as well as a 0.2 m S-band medium-gain antenna (MGA). Both are mounted on a common articulated platform, generally referred to as the HGA platform. The HGA platform can be articulated to point at the earth for any orientation of the observatory. The broad beam pattern of the MGA ensures that 40 kbps real time S-band telemetry is available with any visible ground station. S- and Ka-band links can be operated simultaneously and support all communications for commissioning and normal operations.

The Ka-band downlink data rate has 3 selectable speeds: 0.875, 1.75, and 3.5 Mbytes/s. The highest speed is the default. The lower rates can be selected when needed to account for bad weather at the ground station.

High-gain antenna

Routine 2-way communications, including downlink of science data from the solid state recorder, can occur during science observations and during slews. As seen from Sun-Earth L2, the Ka-band downlink has a beam width about the same angular size as Earth. As such, the HGA pointing must be periodically adjusted to keep Earth centered. The HGA repointing maneuvers are expected to result in a small but measurable pointing disturbance, so they are planned not to occur during science integrations. The HGA must be moved every 10,000 s, which sets a limit on the maximum nominal duration of a science integration. There is an exception to this for certain observing modes requiring long uninterrupted integrations but where small gaps in the science data stream from a pointing disturbance is acceptable.

Some observatory engineering activities can only take place during a real time communications contact and require the suspension of science observations.

This article uses the S.I. definitions of gigabyte and megabyte: 1 Gbyte = 10^9 bytes, and 1 Mbyte = 10^6 bytes.

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JWST Propulsion

JWST's propulsion system provides maneuvering capability for orbital insertion, station keeping, and spacecraft momentum management.

The JWST propulsion subsystem is the part of the spacecraft bus that provides the means to correct JWST's orbit at the second Lagrange point (L2), to control attitude in certain ACS modes, and to unload stored momentum from the reaction wheels (when necessary). JWST nominally carries enough propellant for a 10.5-year mission, pending actual on-orbit performance.

Orbit correction maneuvers, also referred to as Delta-V maneuvers, are used to augment the launch vehicle injection velocity and to maintain a transfer trajectory into orbit about L2, and then to maintain the JWST orbit around L2 (station-keeping maneuvers) for the life of the mission. There are two types of thrusters for these functions. They are mounted on the spacecraft bus to avoid introducing contamination or heat sources near the OTE/ISIM side of the observatory. The Secondary Combustion Augmented Thrusters (SCAT) are used for orbit correction (Delta-V and station-keeping), and mono-propellant rocket engines (MRE-1) are used for attitude control and momentum unloading of the reaction wheels.

The SCATs are bi-propellant thrusters, using hydrazine (N_2H_4) and dinitrogen tetroxide (N_2O_4) as fuel and oxidizer, respectively. They operate in "blowdown mode" with one tank for each type of propellant and using gaseous helium as a pressurizing agent. There are 2 pairs of SCAT thrusters (paired for redundancy). One pair is located near the center of the bottom of the spacecraft bus where JWST attaches to the launch vehicle. These are used for the first Delta-V maneuvers to reach L2 with the correct velocity for the operational orbit. These maneuvers are executed before the sun shield is deployed.

The other pair of SCAT thrusters is mounted on a boom on the side of the spacecraft opposite the solar array, oriented such that their thrust direction passes through the deployed observatory's center of mass. These are used for the orbit insertion Delta-V maneuver and station-keeping maneuvers. This pair of SCAT thrusters are used after the observatory is fully is deployed.

The MRE-1 thrusters use hydrazine as a propellant. There are 8 MRE-1s located on the spacecraft and are oriented so that torque can be applied in roll, pitch, or yaw control axes. For momentum unloads, these thrusters are fired so that the applied torque provides the desired change in the angular momentum of the reaction wheels.

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JWST Target Viewing Constraints

JWST has time-variable viewing constraints, imposed by a combination of observatory safety concerns and target position in ecliptic coordinates.

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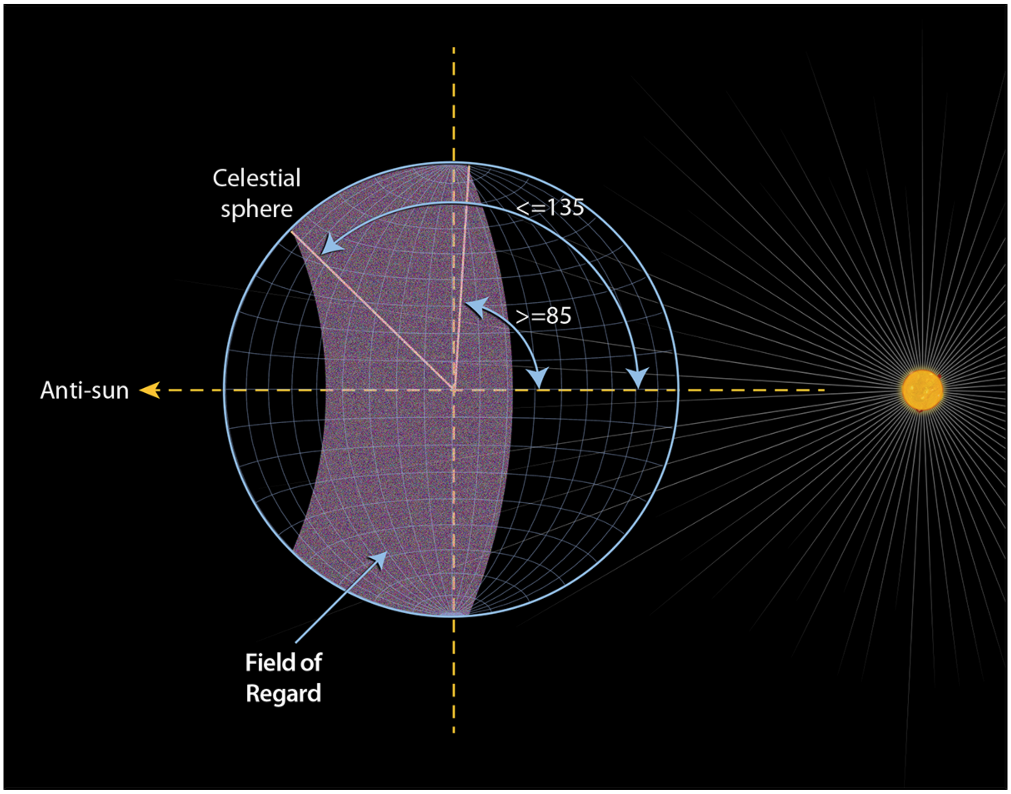
See also: JWST Observatory Coordinate System and Field of Regard
See also: JWST Position Angles, Ranges, and Offsets

At all times during the operational phase of the mission, the JWST telescope and science instruments must remain shielded from the sun. To not do so would endanger the entire functionality of the observatory. The geometry of the JWST sun shield limits where JWST can point at a given time and for how long. It also impacts the observatory's ability to observe the celestial sphere at certain position angles, especially for target positions at low ecliptic latitudes.

JWST field of regard (FOR)

The JWST field of regard (FOR) is the region of the sky where scientific observations can be conducted safely at a given time. The FOR is defined by the allowed range of boresight pointing angles for the observatory relative to the sun line, which must remain in the range 85° to 135° at all times to keep the telescope behind the sun shield. Thus, the FOR is a large torus on the sky that moves roughly 1° per day in ecliptic longitude, following the telescope in its path around the sun. Over time, this annulus sweeps over the entire celestial sphere. As a result of the FOR, JWST can observe about 39% of the full sky on any given day and can access 100% of the sky over 6 months. Figure 1 shows a schematic of the FOR.

Figure 1. The JWST field of regard



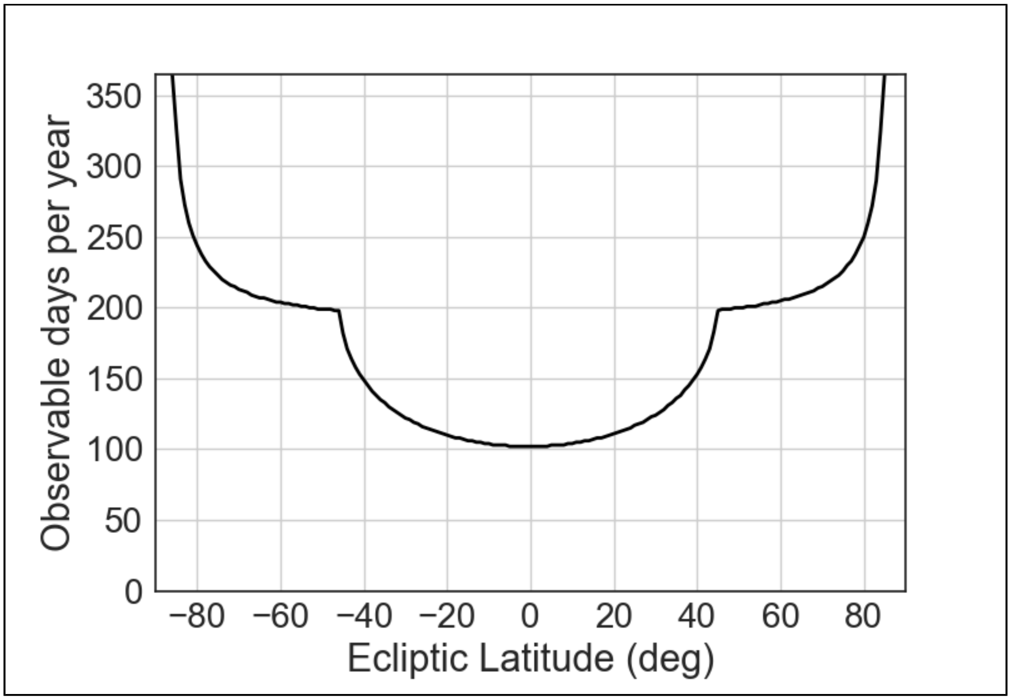
The JWST field of regard extends from a solar elongation of 85° to 135° and changes over time as the observatory orbits the sun. (Adapted from: JWST Mission Operations Concept Document, Figure 4.10.)

Target observability

Observability with JWST is very dependent on a given target's ecliptic latitude. Below 45° ecliptic latitude, JWST can observe targets in 2 visibility windows per year centered about 6 months apart, with each window lasting at least 50 days. Above 45° and below 85° ecliptic latitude, the visibility windows transition to one much longer visibility period. As Figure 2 shows, ecliptic latitude determines the number of days per year that targets are observable by JWST. Also, the allowed field of view position angles on the sky available for a given target are affected by the target's ecliptic latitude. These windows and allowed position angles can be calculated for a particular target using one of the JWST target visibility tools.

JWST has a relatively small continuous viewing zone (CVZ), located within 5° of the ecliptic poles. The CVZ is important for some science programs that involve monitoring throughout the year and will be useful for calibration observations. Although the roll flexibility is still about ±5°, the JWST field of view rotates around the V1 axis (boresight) through the entire available 360° over the course of the year.

Figure 2. Target observability as a function of ecliptic latitude



The number of days per year that targets are observable by JWST, as a function of ecliptic latitude. The graph shows the total number of days, but below 45° ecliptic latitude, this total visibility comes in the form of 2 smaller time periods separated by approximately 6 months. Above 45°, one longer viewing period is available for targets, lengthening until the continuous viewing zone is reached at approximately 85° ecliptic latitude. Available position angles are also limited by ecliptic latitude.

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