tinely made; see "Ultrasound in Medical Diagnosis," by Gilbert B. Devey and Peter N. T. Wells, *Scientific American*, May 1978, p. 98.)

39. Bats can examine the characteristics of objects—such as size, shape, distance, direction, and motion—by sensing the way the high-frequency sounds they emit are reflected off the objects back to the bat. Discuss qualitatively how each of these features affects the reflected sound waves. (See "Information Content of Bat Sonar Echoes," by J. A. Simmons, D. J. Howell, and N. Suga, *American Scientist*, March–April 1975, p. 204.)

40. Assume that you can detect an object by bouncing waves off it (such as in sonar or radar, for instance) as long as the object is larger than the wavelength of the waves. Then consider that bats and porpoises each can emit sound waves of frequency 100 kHz; however, bats can detect objects as small as insects but porpoises only small fish. Why the difference?

41. Is there a Doppler effect for sound when the observer or the source moves at right angles to the line joining them? How then can we determine the Doppler effect when the motion has a component at right angles to this line?

42. Two ships with steam whistles of the same pitch sound off in the harbor. Would you expect this to produce an interference pattern with regions of high and low intensity? If not, why not?

43. A satellite emits radio waves of constant frequency. These waves are picked up on the ground and made to beat against some standard frequency. The beat frequency is then sent through a loudspeaker and one "hears" the satellite signals. Describe how the sound changes as the satellite approaches, passes overhead, and recedes from the detector on the ground.

44. How and why do the Doppler effects for light and for sound differ? In what ways are they the same?

PROBLEMS

Where needed in the problems, use speed of sound in air = 343 m/s and density of air = 1.21 kg/m^3 unless otherwise specified.

Section 20-1 The Speed of Sound

1. Diagnostic ultrasound of frequency 4.50 MHz is used to examine tumors in soft tissue. (*a*) What is the wavelength in air of such a sound wave? (*b*) If the speed of sound in tissue is 1500 m/s, what is the wavelength of this wave in tissue?

2. If the wavelength of sound is large, by a factor of about 10, relative to the mean free path of the molecules, then sound waves can propagate through a gas. For air at room temperature the mean free path is about 0.1 μm. Calculate the frequency above which sound waves could not propagate.

3. Figure 15 shows a remarkably detailed image, of a transistor in a microelectronic circuit, formed by an acoustic microscope. The sound waves have a frequency of 4.2 GHz. The speed of such waves in the liquid helium in which the specimen is immersed is 240 m/s. (*a*) What is the wavelength of these ultrahigh-frequency acoustic waves? (*b*) The ribbon-like conductors in the figure are ~2 μm wide. To how many wavelengths does this correspond?

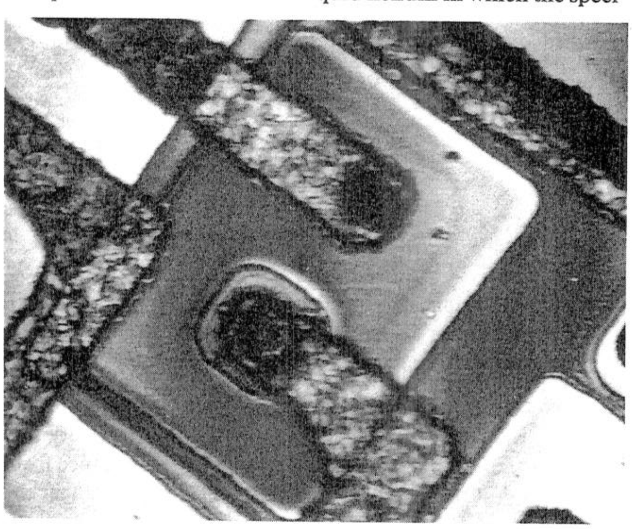

Figure 15 Problem 3.

4. (*a*) A rule for finding your distance from a lightning flash is to count seconds from the time you see the flash until you hear the thunder and then divide the count by 5. The result is supposed to give the distance in miles. Explain this rule and determine the percent error in it at 0°C and 1 atm pressure. (*b*) Devise a similar rule for obtaining the distance in kilometers.

5. A column of soldiers, marching at 120 paces per minute, keeps in step with the music of a band at the head of the column. It is observed that the men at the rear of the column are striding forward with the left foot when those in the band are advancing with the right. What is the length of the column approximately?

6. You are at a large outdoor concert, seated 300 m from the stage microphone. The concert is also being broadcast live, in stereo, around the world via satellite. Consider a listener 5000 km away. Who hears the music first and by what time difference?

7. The speed of sound in a certain metal is V. One end of a long pipe of that metal of length L is struck a hard blow. A listener at the other end hears two sounds, one from the wave that has traveled along the pipe and the other from the wave that has traveled through the air. (*a*) If v is the speed of sound in air, what time interval t elapses between the arrival of the two sounds? (*b*) A hammer strikes a long aluminum rod at one end. A listener, whose ear is close to the other end of the rod, hears the sound of the blow twice, with a 120-ms interval between. How long is the rod?

8. Earthquakes generate sound waves in the Earth. Unlike in a gas, there are both transverse (S) and longitudinal (P) sound waves in a solid. Typically, the speed of S waves is about 4.5 km/s and that of P waves 8.2 km/s. A seismograph records P and S waves from an earthquake. The first P waves

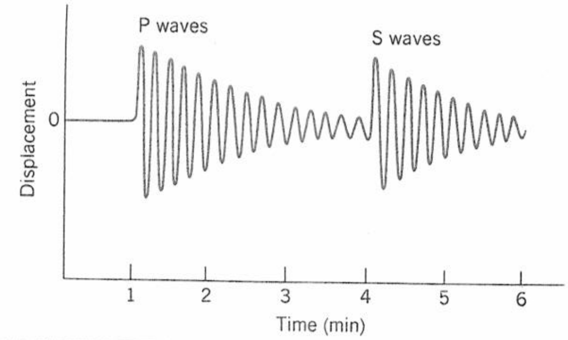

Figure 16 Problem 8.

arrive 3 min before the first S waves; see Fig. 16. How far away did the earthquake occur?

9. A stone is dropped into a well. The sound of the splash is heard 3.00 s later. What is the depth of the well?

Section 20-2 Traveling Longitudinal Waves

10. A continuous sinusoidal longitudinal wave is sent along a coiled spring from a vibrating source attached to it. The frequency of the source is 25 Hz, and the distance between successive rarefactions in the spring is 24 cm. (*a*) Find the wave speed. (*b*) If the maximum longitudinal displacement of a particle in the spring is 0.30 cm and the wave moves in the $-x$ direction, write the equation for the wave. Let the source be at $x = 0$ and the displacement $s = 0$ at the source when $t = 0$.

11. The pressure in a traveling sound wave is given by the equation

$$\Delta p = (1.48\text{ Pa})\sin(1.07\pi x - 334\pi t),$$

where x is in meters and t is in seconds. Find (*a*) the pressure amplitude, (*b*) the frequency, (*c*) the wavelength, and (*d*) the speed of the wave.

Section 20-3 Power and Intensity of Sound Waves

12. Show that the sound wave intensity I can be written in terms of the frequency ν and displacement amplitude s_m in the form

$$I = 2\pi^2 \rho v \nu^2 s_m^2.$$

13. A source emits spherical waves isotropically (that is, with equal intensity in all directions). The intensity of the wave 42.5 m from the source is 197 μW/m^2. Find the power output of the source.

14. A note of frequency 313 Hz has an intensity of 1.13 μW/m^2. What is the amplitude of the air vibrations caused by this sound?

15. A sound wave of intensity 1.60 μW/cm^2 passes through a surface of area 4.70 cm^2. How much energy passes through the surface in 1 h?

16. Find the intensity ratio of two sounds whose sound levels differ by 1.00 dB.

17. A certain sound level is increased by an additional 30 dB. Show that (*a*) its intensity increases by a factor of 1000 and (*b*) its pressure amplitude increases by a factor of 32.

18. A salesperson claimed that a stereo system would deliver 110 W of audio power. Testing the system with several speakers set up so as to simulate a point source, the consumer noted that she could get as close as 1.3 m with the volume full on before the sound hurt her ears. Should she report the firm to the Consumer Protection Agency?

19. A certain loudspeaker produces a sound with a frequency of 2.09 kHz and an intensity of 962 μW/m^2 at a distance of 6.11 m. Presume that there are no reflections and that the loudspeaker emits the same in all directions. (*a*) Find the intensity at 28.5 m. (*b*) Find the displacement amplitude at 6.11 m. (*c*) Calculate the pressure amplitude at 6.11 m.

20. (*a*) If two sound waves, one in air and one in water, are equal in intensity, what is the ratio of the pressure amplitude of the wave in water to that of the wave in air? (*b*) If the pressure amplitudes are equal instead, what is the ratio of the intensities of the waves? Assume the water is at 20°C.

21. Find the energy density in a sound wave 4.82 km from a 5.20-kW nuclear emergency siren (see Fig. 17), assuming the waves to be spherical and the propagation isotropic with no atmospheric absorption.

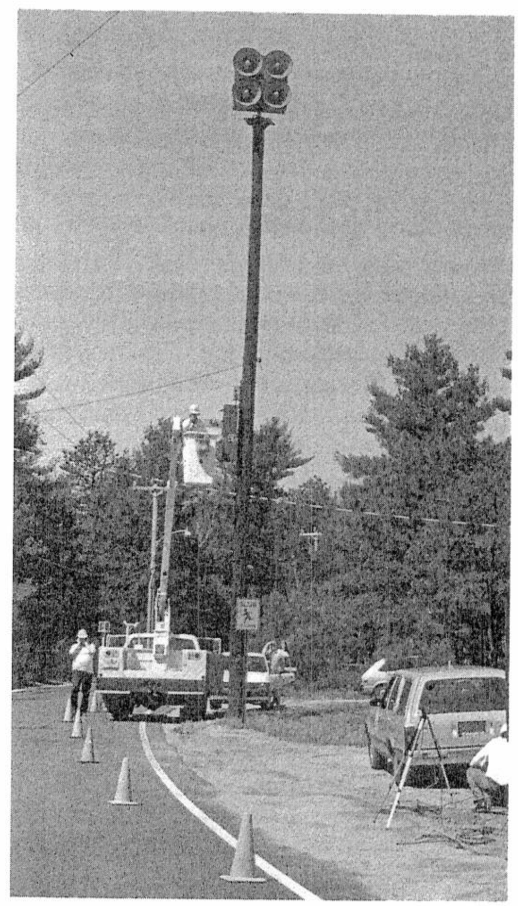

Figure 17 Problem 21.

22. A line source (for instance, a long freight train on a straight track) emits a cylindrical expanding wave. Assuming that the air absorbs no energy, find how (*a*) the intensity and (*b*) the amplitude of the wave depend on the distance from the source. Ignore reflections and consider points near the center of the train.

23. In Fig. 18 we show an acoustic interferometer, used to demonstrate the interference of sound waves. S is a source of sound (a loudspeaker, for instance), and D is a sound detector, such as the ear or a microphone. Path SBD can be varied in length, but path SAD is fixed. The interferometer contains air, and it is found that the sound intensity has a minimum value of $10\ \mu W/cm^2$ at one position of B and continuously climbs to a maximum value of $90\ \mu W/cm^2$ at a second position 1.65 cm from the first. Find (*a*) the frequency of the sound emitted from the source and (*b*) the relative amplitudes of the waves arriving at the detector for each of the two positions of B. (*c*) How can it happen that these waves have different amplitudes, considering that they originate at the same source?

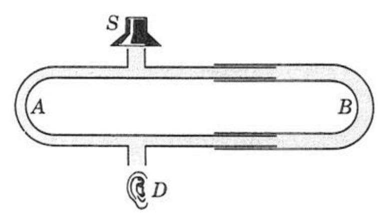

Figure 18 Problem 23.

24. You are standing at a distance D from an isotropic source of sound waves. You walk 51.4 m toward the source and observe that the intensity of these waves has doubled. Calculate the distance D.

25. Estimate the maximum possible sound level in decibels of sound waves in air. (*Hint:* Set the pressure amplitude equal to 1 atm.)

26. Suppose that the average sound level of human speech is 65 dB. How many persons in a room speaking at the same time each at 65 dB are needed to produce a sound level of 80 dB?

27. Suppose that a rustling leaf generates 8.4 dB of sound. Find the sound level from a tree with 2.71×10^5 rustling leaves.

28. In a test, a subsonic jet flies overhead at an altitude of 115 m. The sound level on the ground as the jet passes overhead is 150 dB. At what altitude should the plane fly so that the ground noise is no greater than 120 dB, the threshold of pain? Ignore the finite time required for the sound to reach the ground.

29. A certain loudspeaker (assumed to be a point source) emits 31.6 W of acoustic power. A small microphone of effective cross-sectional area 75.2 mm^2 is located 194 m from the loudspeaker. Calculate (*a*) the sound intensity at the microphone, (*b*) the power incident on the microphone, and (*c*) the amount of energy that impinges on the microphone in 25.0 min.

30. A sound wave of 42.0-cm wavelength enters the tube shown in Fig. 19. What must be the smallest radius r such that a minimum will be heard at the detector?

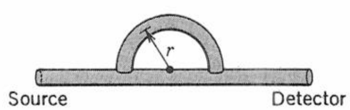

Figure 19 Problem 30.

31. Two stereo loudspeakers are separated by a distance of 2.12 m. Assume the amplitude of the sound from each speaker is approximately the same at the position of a listener, who is 3.75 m directly in front of one of the speakers; see Fig. 20. (*a*) For what frequencies in the audible range (20–20,000 Hz) will there be a minimum signal? (*b*) For what frequencies is the sound a maximum?

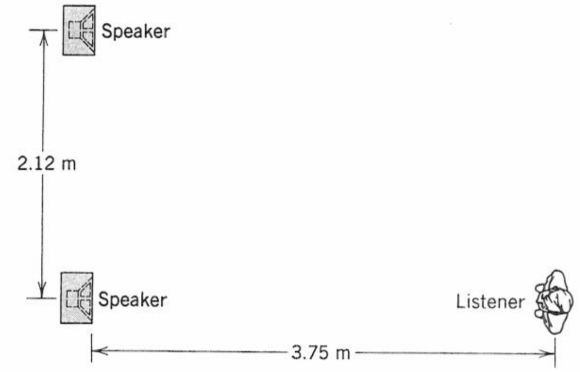

Figure 20 Problem 31.

32. A spherical sound source is placed at P_1 near a reflecting wall AB and a microphone is located at point P_2, as shown in Fig. 21. The frequency of the sound source is variable. Find the two lowest frequencies for which the sound intensity, as observed at P_2, will be a maximum. There is no phase change on reflection; the angle of incidence equals the angle of reflection.

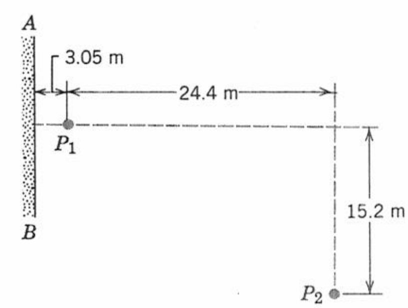

Figure 21 Problem 32.

33. Two sources of sound are separated by a distance of 5.00 m. They both emit sound at the same amplitude and frequency, 300 Hz, but they are 180° out of phase. At what points along the line connecting them will the sound intensity be the largest?

34. The *reverberation time* of an auditorium or concert hall is the time required for the sound intensity (in W/m^2) to decrease by a factor of 10^6. The reverberation time depends on the frequency of the sound. Suppose that in a particular concert hall, the reverberation time for a note of a certain frequency is 2.6 s. If the note is sounded at a sound level of 87 dB, how long will it take for the sound level to fall to 0 dB (the threshold of human hearing)?

35. A large parabolic reflector having a circular opening of radius 0.50 m is used to focus sound. If the energy is deliv-

ered from the focus to the ear of a listening detective through a tube of diameter 1.0 cm with 12% efficiency, how far away can a whispered conversation be understood? (Assume that the sound level of a whisper is 20 dB at 1.0 m from the source, considered to be a point, and that the threshold for hearing is 0 dB.)

Section 20-4 Standing Longitudinal Waves

36. The strings of a cello have a length L. (*a*) By what length ΔL must they be shortened by fingering to change the pitch by a frequency ratio r? (*b*) Find ΔL, if $L = 80.0$ cm and $r = \frac{6}{5}, \frac{5}{4}, \frac{4}{3}$, and $\frac{3}{2}$.

37. A sound wave in a fluid medium is reflected at a barrier so that a standing wave is formed. The distance between nodes is 3.84 cm and the speed of propagation is 1520 m/s. Find the frequency.

38. A well with vertical sides and water at the bottom resonates at 7.20 Hz and at no lower frequency. The air in the well has a density of 1.21 kg/m^3 and a bulk modulus of 1.41×10^5 Pa. How deep is the well?

39. S in Fig. 22 is a small loudspeaker driven by an audio oscillator and amplifier, adjustable in frequency from 1000 to 2000 Hz only. D is a piece of cylindrical sheetmetal pipe 45.7 cm long and open at both ends. (*a*) At what frequencies will resonance occur when the frequency emitted by the speaker is varied from 1000 to 2000 Hz? (*b*) Sketch the displacement nodes for each resonance. Neglect end effects.

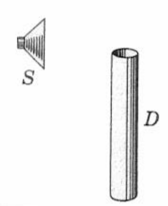

Figure 22 Problem 39.

40. The width of the terraces in an amphitheater in Los Angeles, Fig. 23, is 36 in. (=0.914 m). A single hand-clap occurring at the center of the stage will reflect back to the stage as a tone of what frequency?

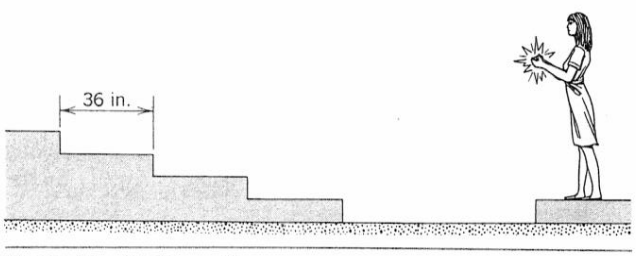

Figure 23 Problem 40.

41. A tunnel leading straight through a hill greatly amplifies tones at 135 and 138 Hz. Find the shortest length the tunnel could have.

42. The period of a pulsating variable star may be estimated by considering the star to be executing radial longitudinal pulsations in the fundamental standing wave mode; that is, the radius varies periodically with the time, with a displacement antinode at the surface. (*a*) Would you expect the center of the star to be a displacement node or antinode? (*b*) By analogy with the open organ pipe, show that the period of pulsation T is given by

$$T = \frac{4R}{v_S},$$

where R is the equilibrium radius of the star and v_S is the average sound speed. (*c*) Typical white dwarf stars are composed of material with a bulk modulus of 1.33×10^{22} Pa and a density of 1.0×10^{10} kg/m^3. They have radii equal to 0.009 solar radius. What is the approximate pulsation period of a white dwarf? (See "Pulsating Stars," by John R. Percy, *Scientific American,* June 1975, p. 66.)

43. In Fig. 24, a rod R is clamped at its center; a disk D at its end projects into a glass tube that has cork filings spread over its interior. A plunger P is provided at the other end of the tube. The rod is set into longitudinal vibration and the plunger is moved until the filings form a pattern of nodes and antinodes (the filings form well-defined ridges at the pressure antinodes). If we know the frequency ν of the longitudinal vibrations in the rod, a measurement of the average distance d between successive antinodes determines the speed of sound v in the gas in the tube. Show that

$$v = 2\nu d.$$

This is Kundt's method for determining the speed of sound in various gases.

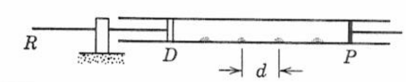

Figure 24 Problem 43.

Section 20-5 Vibrating Systems and Sources of Sound

44. (*a*) Find the speed of waves on an 820-mg violin string 22.0 cm long if the frequency of the fundamental is 920 Hz. (*b*) Calculate the tension in the string.

45. If a violin string is tuned to a certain note, by what factor must the tension in the string be increased if it is to emit a note of double the original frequency (that is, a note one octave higher in pitch)?

46. A certain violin string is 30 cm long between its fixed ends and has a mass of 2.0 g. The string sounds an A note (440 Hz) when played without fingering. Where must one put one's finger to play a C (528 Hz)?

47. An open organ pipe has a fundamental frequency of 291 Hz. The first overtone ($n = 3$) of a closed organ pipe has the same frequency as the second harmonic of the open pipe. How long is each pipe?

48. A tube 1.18 m long is closed at one end. A stretched wire is placed near the open end. The wire is 33.2 cm long and has a mass of 9.57 g. It is fixed at both ends and vibrates in its fundamental mode. It sets the air column in the tube into vibration at its fundamental frequency by resonance. Find (*a*) the frequency of oscillation of the air column and (*b*) the tension in the wire.

49. A 30.0-cm violin string with linear mass density 0.652 g/m is placed near a loudspeaker that is fed by an audio oscillator of variable frequency. It is found that the string is set into oscillation only at the frequencies 880 and 1320 Hz as the frequency of the oscillator is varied continuously over the range 500–1500 Hz. What is the tension in the string?

Section 20-6 Beats

50. A tuning fork of unknown frequency makes three beats per second with a standard fork of frequency 384 Hz. The beat frequency decreases when a small piece of wax is put on a prong of the first fork. What is the frequency of this fork?

51. The A string of a violin is a little too taut. Four beats per second are heard when it is sounded together with a tuning fork that is vibrating accurately at the pitch of concert A (440 Hz). What is the period of the violin string vibration?

52. You are given four tuning forks. The fork with the lowest frequency vibrates at 500 Hz. By using two tuning forks at a time, the following beat frequencies are heard: 1, 2, 3, 5, 7, and 8 Hz. What are the possible frequencies of the other three tuning forks?

53. You are given five tuning forks, each of which has a different frequency. By trying every pair of tuning forks, (*a*) what maximum number of *different* beat frequencies might be obtained? (*b*) What minimum number of *different* beat frequencies might be obtained?

Section 20-7 The Doppler Effect

54. A source S generates circular waves on the surface of a lake, the pattern of wave crests being shown in Fig. 25. The speed of the waves is 5.5 m/s and the crest-to-crest separation is 2.3 m. You are in a small boat heading directly toward S at a constant speed of 3.3 m/s with respect to the shore. What frequency of the waves do you observe?

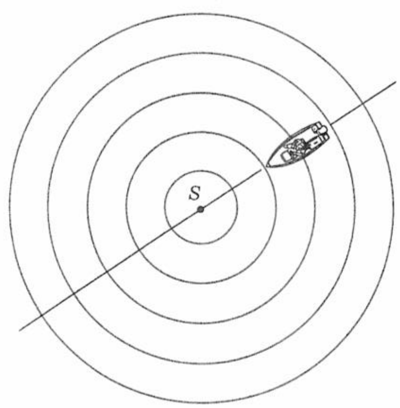

Figure 25 Problem 54.

55. The 15.8-kHz whine of the turbines in the jet engines of an aircraft moving with speed 193 m/s is heard at what frequency by the pilot of a second craft trying to overtake the first at a speed of 246 m/s?

56. An ambulance emitting a whine at 1602 Hz overtakes and passes a cyclist pedaling a bike at 2.63 m/s. After being passed, the cyclist hears a frequency of 1590 Hz. How fast is the ambulance moving?

57. A whistle of frequency 538 Hz moves in a circle of radius 71.2 cm at an angular speed of 14.7 rad/s. What are (*a*) the lowest and (*b*) the highest frequencies heard by a listener a long distance away at rest with respect to the center of the circle?

58. In 1845, Buys Ballot first tested the Doppler effect for sound. He put a trumpet player on a flatcar drawn by a locomotive and another player near the tracks. If each player blows a 440-Hz note, and if there are 4.0 beats/s as they approach each other, what is the speed of the flatcar?

59. A bullet is fired with a speed of 2200 ft/s. Find the angle made by the shock cone with the line of motion of the bullet.

60. Estimate the speed of the projectile illustrated in the photograph in Fig. 14. Assume the speed of sound in the medium through which the projectile is traveling to be 380 m/s.

61. The speed of light in water is 2.25×10^8 m/s (about three-fourths the speed in a vacuum). A beam of high-speed electrons from a betatron emits Cerenkov radiation in water, the wavefront being a cone of angle 58.0°. Find the speed of the electrons in the water.

62. Two identical tuning forks oscillate at 442 Hz. A person is located somewhere on the line between them. Calculate the beat frequency as measured by this individual if (*a*) she is standing still and the tuning forks both move to the right at 31.3 m/s, and (*b*) the tuning forks are stationary and the listener moves to the right at 31.3 m/s.

63. A plane flies at 396 m/s at constant altitude. The sonic boom reaches an observer on the ground 12.0 s after the plane flies overhead. Find the altitude of the plane. Assume the speed of sound to be 330 m/s.

64. A jet plane passes overhead at a height of 5140 m and a speed of Mach 1.52 (1.52 times the speed of sound). (*a*) Find the angle made by the shock wave with the line of motion of the jet. (*b*) How long after the jet has passed directly overhead will the shock wave reach the ground? Use 331 m/s for the speed of sound.

65. Figure 26 shows a transmitter and receiver of waves contained in a single instrument. It is used to measure the speed V of a target object (idealized as a flat plate) that is moving directly toward the unit, by analyzing the waves reflected from it. (*a*) Apply the Doppler equations twice, first with the target as observer and then with the target as a source, and show that the frequency ν_r of the reflected waves at the receiver is related to their source frequency ν_s by

$$\nu_r = \nu_s \left(\frac{v + V}{v - V} \right),$$

where v is the speed of the waves. (*b*) In a great many practical situations, $V \ll v$. In this case, show that the equation above becomes

$$\frac{\nu_r - \nu_s}{\nu_s} \approx \frac{2V}{v}.$$

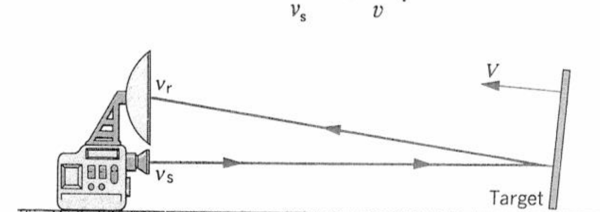

Figure 26 Problem 65.

66. A sonar device sends 148-kHz sound waves from a hiding police car toward a truck approaching at a speed of 44.7 m/s. Calculate the frequency of the reflected waves detected at the police car.

67. An acoustic burglar alarm consists of a source emitting waves of frequency 28.3 kHz. What will be the beat frequency of waves reflected from an intruder walking at 0.95 m/s directly away from the alarm?

68. A siren emitting a sound of frequency 1000 Hz moves away from you toward a cliff at a speed of 10.0 m/s. (*a*) What is the frequency of the sound you hear coming directly from the siren? (*b*) What is the frequency of the sound you hear reflected off the cliff? (*c*) Find the beat frequency. Could you hear the beats? Take the speed of sound in air as 330 m/s.

69. A person in a car blows a trumpet sounding at 438 Hz. The car is moving toward a wall at 19.3 m/s. Calculate (*a*) the frequency of the sound as received at the wall and (*b*) the frequency of the reflected sound arriving back at the source.

70. Two submarines are on a head-on collision course during maneuvers in the North Atlantic. The first sub is moving at 20.2 km/h and the second sub at 94.6 km/h. The first submarine sends out a sonar signal (sound wave in water) at 1030 Hz. Sonar waves travel at 5470 km/h. (*a*) The second sub picks up the signal. What frequency does the second sonar detector hear? (*b*) The first sub picks up the reflected signal. What frequency does the first sonar detector hear? See Fig. 27. The ocean is calm; assume no currents.

Figure 27 Problem 70.

71. A police car sounding its siren is moving at 27 m/s and approaching a stationary pedestrian. The police in the car hear the siren at 12.6 kHz but the pedestrian hears the siren at 13.7 kHz. Find the air temperature. (Assume that the speed of sound increases linearly with temperature between 0°C and 20°C; see Table 1.)

72. In a discussion of Doppler shifts of ultrasonic (high-frequency) waves used in medical diagnosis, the authors remark: "For every millimeter per second that a structure in the body moves, the frequency of the incident ultrasonic wave is shifted approximately 1.3 Hz/MHz." What speed of the ultrasonic waves in tissue do you deduce from this statement?

73. A bat is flittering about in a cave, navigating very effectively by the use of ultrasonic bleeps (short emissions of high-frequency sound lasting a millisecond or less and repeated several times a second). Assume that the sound emission frequency of the bat is 39.2 kHz. During one fast swoop directly toward a flat wall surface, the bat is moving at 8.58 m/s. Calculate the frequency of the sound the bat hears reflected off the wall.

74. A submarine moving north with a speed of 75.2 km/h with respect to the ocean floor emits a sonar signal (sound waves in water used in ways similar to radar; see Table 1) of frequency 989 Hz. If the ocean at that point has a current moving north at 30.5 km/h relative to the land, what frequency is observed by a ship drifting with the current north of the submarine? (*Hint:* All speeds in the Doppler equations must be taken with respect to the medium.)

75. A 2000-Hz siren and a civil defense official are both at rest with respect to the Earth. What frequency does the official hear if the wind is blowing at 12 m/s (*a*) from source to observer and (*b*) from observer to source?

76. Two trains on parallel tracks are traveling toward each other at 34.2 m/s relative to the ground. One train is blowing a whistle at 525 Hz. (*a*) What frequency will be heard on the other train in still air? (*b*) What frequency will be heard on the other train if the wind is blowing at 15.3 m/s parallel to the tracks and toward the whistle? (*c*) What frequency will be heard if the wind direction reverses?