CHAPTER 27

ANSWERS TO QUESTIONS

Q27.1 (a) Two waves interfere constructively if their path difference is zero, or an integral multiple of the wavelength. $\delta = m\lambda, \quad (m = 0, 1, 2, 3...)$.

(b) Two waves interfere destructively if their path difference is a half wavelength, or an odd multiple of $\lambda/2$. $\delta = \left(m + \frac{1}{2}\right)\lambda, \quad (m = 0, 1, 2...)$.

Q27.2 The light from the flashlights consists of many different wavelengths (that's why it's white) with random time differences between the light waves; therefore there is no *coherence* between the two sources; and no possibility of an interference pattern.

Q27.3 Underwater, the wavelength of the light would decrease, $\lambda_{UW} = \lambda_{air} / n_{water}$. Since the positions of light and dark bands are proportional to λ, (See Equations 27.5 and 27.6), the underwater fringe separation will decrease.

Q27.4 Every color produces its own pattern, with a spacing between the maxima that is characteristic of the wavelength. With several colors, the patterns are superimposed and it is difficult to pick out a single maximum. Using monochromatic light can eliminate this problem.

Q27.5 As the soap bubble becomes very thin, the thickness of the bubble approaches zero. Since light reflecting off the front of the soap surface is phase-shifted 180° and light reflecting off the back of the soap film is phase-shifted 0°, the reflected light meets the conditions for a minimum. Thus the soap film appears black.

Q27.6 If the oil film is brightest where it is thinnest, then $n_{air} < n_{oil} < n_{water}$. This is the condition for constructive reinforcement as the thickness of the oil film decreases toward zero.

Q27.7 Different colors with different wavelengths selectively reinforce for thicknesses of the soap film such that $2nt = \left(m + \frac{1}{2}\right)\lambda \quad (m = 0, 1, 2...)$. In the very thinnest regions, where t is near zero, destructive interference occurs and the film appears black.

Q27.8 Light passes between adjacent threads of the handkerchief. These regularly spaced meshes act like grooves in a diffraction grating.

Q27.9 If the film is more than a few wavelengths thick, the interference fringes are so close together that you cannot resolve them.

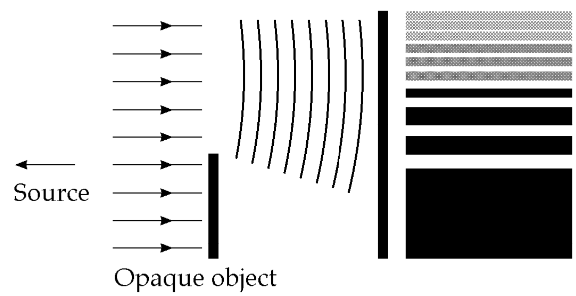
Q27.10 If R is large, light reflecting from the lower surface of the lens can interfere with light reflecting from the upper surface of the flat. The latter undergoes phase reversal on reflection while the former does not. Where there is negligible distance between the surfaces, at the center of the pattern you will see a dark spot because of the destructive interference associated with the 180° phase shift. Colored rings surround the dark spot. If the lens is a perfect sphere the rings are perfect circles. Distorted rings reveal bumps or hollows on the fine scale of the wavelength of visible light.

Q27.11 A camera lens will have more than one element, to correct (at least) for chromatic aberration. It will have several surfaces, each of which would reflect some fraction of the incident light. To maximize light throughput the surfaces need antireflective coatings.

Q27.12 One way to make an antireflective coating for perpendicularly incident radar waves is this: Measure the radar-reflectivity of the metal of your airplane. Suppose it is 90%. Then choose a light durable material that will reflect just about 45% of the radio wave energy incident on it. Measure its index of refraction. Onto the metal plaster a coating equal in thickness to one quarter of 3 cm divided by that index. Sell it quick and then you can sell to the supposed enemy new radars operating at 1.5 cm, which the coated metal will reflect with extra-high efficiency.

Q27.13 To do Young's double-slit interference experiment with light from an ordinary source, you must first pass the light through a prism or diffraction grating to disperse different colors into different directions. With a single narrow slit you select a single color and make that light diffract to cover both of the slits for the interference experiment. Thus you may have trouble lining things up and you will generally have low light power reaching the screen. The laser light is already monchromatic and coherent across the width of the beam.

Q27.14 If you are using an extended light source, the gray area at the edge of the shadow is the penumbra. A bug looking up from there would see the light source partly but not entirely blocked by the book. If you use a point source of light, hold it and the book motionless, and look at very small angles out from the geometrical edge of the shadow, you may see a series of bright and dark bands produced by diffraction of light at the straight edge, as shown in the diagram.

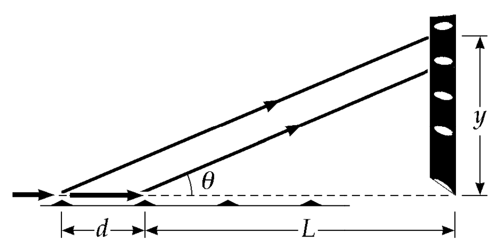


Q27.15 Audible sound has wavelengths on the order of meters or centimeters, while visible light has a wavelength on the order of half a micrometer. In this world of breadbox-sized objects, λ/a is large for sound, and sound diffracts around behind walls with doorways. But λ/a is a tiny fraction for visible light passing ordinary-size objects or apertures, so light changes its direction by only very small angles when it diffracts.

Another way of phrasing the answer: We can see by a small angle around a small obstacle or around the edge of a small opening. The side fringes in Figure 27.12 and the Arago spot in the center of Figure 27.13 show this diffraction. We cannot always hear around corners. Out-of-doors, away from reflecting surfaces, have someone a few meters distant face away from you and whisper. The high-frequency, short-wavelength, information-carrying components of the sound do not diffract around his head enough for you to understand his words.

Q27.16 We apply the equation $\theta_m = 1.22\,\lambda/D$ for the resolution of a circular aperture, the pupil of your eye. Suppose your dark-adapted eye has pupil diameter $D = 5$ mm. An average wavelength for visible light is $\lambda = 550$ nm. Suppose the headlights are 2 m apart and the car is a distance L away. Then $\theta_m = 2\text{ m}/L = 1.22 \times 1.1 \times 10^{-4}$ so $L \sim 10$ km. The actual distance is less than this because the variable-temperature air between you and the car makes the light refract unpredictably. The headlights twinkle like stars.

Q27.17 Consider incident light nearly parallel to the horizontal ruler. Suppose it scatters from bumps at distance d apart to produce a diffraction pattern on a vertical wall a distance L away. At a point of height y, where $\theta = y/L$ gives the scattering angle θ, the character of the interference is determined by the shift δ between beams scattered by adjacent bumps, where $\delta = d/\cos\theta - d$. Bright spots appear for $\delta = m\lambda$, where 0,1,2,3,.... For small θ, these equations combine and reduce to $m\lambda = y_m{}^2 d/2L^2$. Measurement of the heights y_m of bright spots allows calculation of the wavelength of the light.



Q27.18 The fine hair blocks off light that would otherwise go through a fine slit and produce a diffraction pattern on a distant screen. The width of the central maximum in the pattern is inversely proportional to the distance across the slit. When the hair is in place, it subtracts the same diffraction pattern from the projected disk of laser light. The hair produces a diffraction minimum that crosses the bright circle on the screen. The width of the minimum is inversely proportional to the diameter of the hair. The central minimum is flanked by narrower maxima and minima.

Q27.19 An AM radio wave has wavelength on the order of $(3\times10^8\text{ m/s})/(1\times10^6\text{ s}^{-1})\sim300\text{ m}$. This is large compared to the width of the mouth of a tunnel, so the AM radio waves can reflect from the surrounding ground as if the hole were not there. (In the same way, a metal screen forming the dish of a radio telescope can reflect radio waves as if it were solid, and a hole-riddled screen in the door of a microwave oven keeps the microwaves inside.) The wave does not "see" the hole. Very little of the radio wave energy enters the tunnel, and the AM radio signal fades. An FM radio wave has wavelength a hundred times smaller, on the order of a few meters. This is smaller than the size of the tunnel opening, so the wave can readily enter the opening. (On the other hand, the long wavelength of AM radio waves lets them diffract more around obstacles. Long-wavelength waves can change direction more in passing hills or large buildings, so in some experiments FM fades more than AM.)

Q27.20 The intensity of the light coming through the slit decreases as you would expect. The central maximum increases in width as the width of the slit decreases. In the condition $\sin\theta=\lambda/a$ for destructive interference on each side of the central maximum, θ increases as a decreases.

Q27.21 Suppose the coating is intermediate in index of refraction between vacuum and the glass. When the coating is very thin, light reflected from its top and bottom surfaces will interfere constructively, so you see the surface white and brighter. As the thickness reaches one quarter of the wavelength of violet light in the coating, destructive interference for violet will make the surface look red. Next to interfere destructively are blue, green, yellow, orange, and red, making the surface look red, purple, and then blue. As the coating gets still thicker, we can get constructive interference for violet and then for other colors in spectral order. Still thicker coating will give constructive and destructive interference for several visible wavelengths, so the reflected light will start to look white again.

Q27.22 Light scattered by closely spaced melanin fibers interferes constructively only in certain directions that depend on the wavelength and on the direction of the incident light. One section of a feather serves as a diffraction grating for short wavelength light, sending different colors in different directions. The color you see when viewing one section of a feather changes as the light source, the feather, or you move to change the angles of incidence or diffraction.

Q27.23 It is shown in the correct orientation. If the horizontal width of the opening is equal to or less than the wavelength of the sound, then the equation $a\sin\theta=(1)\lambda$ has the solution $\theta=90°$, or has no solution. The central diffraction maximum covers the whole seaward side. If the vertical height of the opening is large compared to the wavelength, then the angle in $a\sin\theta=(1)\lambda$ will be small, and the central diffraction maximum will form a thin horizontal sheet.

PROBLEM SOLUTIONS

27.1 $y_{\text{bright}} = \dfrac{\lambda L}{d} m$

For $m = 1$, $\lambda = \dfrac{yd}{L} = \dfrac{(3.40 \times 10^{-3}\ \text{m})(5.00 \times 10^{-4}\ \text{m})}{3.30\ \text{m}} = \boxed{515\ \text{nm}}$

27.2 $\lambda = \dfrac{v}{f} = \dfrac{354\ \text{m/s}}{2000\ \text{s}^{-1}} = 0.177\ \text{m}$

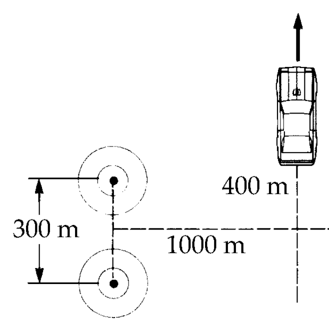
(a) $d\sin\theta = m\lambda$ so $(0.300\ \text{m})\sin\theta = 1(0.177\ \text{m})$ and $\theta = \boxed{36.2°}$

(b) $d\sin\theta = m\lambda$ so $d\sin 36.2° = 1(0.0300\ \text{m})$ and $d = \boxed{5.08\ \text{cm}}$

(c) $(1.00 \times 10^{-6}\ \text{m})\sin 36.2° = (1)\lambda$ so $\lambda = 590\ \text{nm}$

$f = \dfrac{c}{\lambda} = \dfrac{3.00 \times 10^{8}\ \text{m/s}}{5.90 \times 10^{-7}\ \text{m}} = \boxed{508\ \text{THz}}$

27.3 Note, with the conditions given, the small angle approximation **does not work well**. That is, $\sin\theta$, $\tan\theta$, and θ are significantly different. The approach to be used is outlined below.



(a) At the $m = 2$ maximum, $\tan\theta = \dfrac{400\ \text{m}}{1000\ \text{m}} = 0.400$

$\theta = 21.8°$

so $\lambda = \dfrac{d\sin\theta}{m} = \dfrac{(300\ \text{m})\sin 21.8°}{2} = \boxed{55.7\ \text{m}}$

(b) The next minimum encountered is the $m = 2$ minimum;

and at that point, $d\sin\theta = \left(m + \frac{1}{2}\right)\lambda$

which becomes $d\sin\theta = \frac{5}{2}\lambda$

or $\sin\theta = \frac{5}{2}\dfrac{\lambda}{d} = \frac{5}{2}\left(\dfrac{55.7\ \text{m}}{300\ \text{m}}\right) = 0.464$

and $\theta = 27.7°$

so $y = (1000\ \text{m})\tan 27.7° = 524\ \text{m}$

Therefore, the car must travel an additional $\boxed{124\ \text{m}}$.

27.4 $\lambda = \frac{340 \text{ m/s}}{2000 \text{ Hz}} = 0.170 \text{ m}$

Maxima are at $d \sin\theta = m\lambda$:

$m = 0$ gives $\theta = 0°$

$m = 1$ gives $\sin\theta = \frac{\lambda}{d} = \frac{0.170 \text{ m}}{0.350 \text{ m}}$ $\theta = 29.1°$

$m = 2$ gives $\sin\theta = \frac{2\lambda}{d} = 0.971$ $\theta = 76.3°$

$m = 3$ gives $\sin\theta = 1.46$ No solution.

Minima are at $d \sin\theta = \left(m + \frac{1}{2}\right)\lambda$:

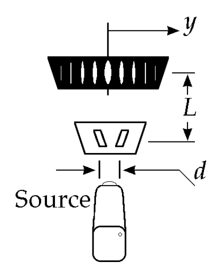
$m = 0$ gives $\sin\theta = \frac{\lambda}{2d} = 0.243$ $\theta = 14.1°$

$m = 1$ gives $\sin\theta = \frac{3\lambda}{2d} = 0.729$ $\theta = 46.8°$

$m = 2$ gives $\sin\theta = 1.21$ No solution.

So we have maxima at 0°, 29.1°, and 76.3°; minima at 14.1° and 46.8°

27.5 In the equation $d \sin\theta = \left(m + \frac{1}{2}\right)\lambda$



The first minimum is described by $m = 0$

and the tenth by $m = 9$: $\sin\theta = \frac{\lambda}{d}\left(9 + \frac{1}{2}\right)$

Also, $\tan\theta = y / L$

but for small θ, $\sin\theta \approx \tan\theta$

Thus, $d = \frac{9.5\lambda}{\sin\theta} = \frac{9.5\lambda L}{y}$

$$d = \frac{9.5\left(5890 \times 10^{-10} \text{ m}\right)(2.00 \text{ m})}{7.26 \times 10^{-3} \text{ m}} = 1.54 \times 10^{-3} \text{ m} = \boxed{1.54 \text{ mm}}$$

***27.6** At 30.0°, $d \sin\theta = m\lambda$

$(3.20\times 10^{-4}\text{ m})\sin 30.0° = m(500\times 10^{-9}\text{ m})$ so $m = 320$

There are 320 maxima to the right, 320 to the left, and one for $m = 0$ straight ahead.

There are $\boxed{641\text{ maxima}}$.

***27.7** Observe that the pilot must not only home in on the airport, but must be headed in the right direction when she arrives at the end of the runway.

(a) $\lambda = \dfrac{c}{f} = \dfrac{3\times 10^{8}\text{ m/s}}{30\times 10^{6}\text{ s}^{-1}} = \boxed{10.0\text{ m}}$

(b) The first side maximum is at an angle given by $d\sin\theta = (1)\lambda$.

$(40\text{ m})\sin\theta = 10\text{ m}$ $\theta = 14.5°$ $\tan\theta = y/L$

$y = L\tan\theta = (2000\text{ m})\tan 14.5° = \boxed{516\text{ m}}$

(c) The signal of 10-m wavelength in parts (a) and (b) would show maxima at 0°, 14.5°, 30.0°, 48.6°, and 90°. A signal of wavelength 11.23-m would show maxima at 0°, 16.3°, 34.2°, and 57.3°. The only value in common is 0°. If λ_1 and λ_2 were related by a ratio of small integers (a just musical consonance!) in $\lambda_1/\lambda_2 = n_1/n_2$, then the equations $d\sin\theta = n_2\lambda_1$ and $d\sin\theta = n_1\lambda_2$ would both be satisfied for the same nonzero angle. The pilot could come flying in with that inappropriate bearing, and run off the runway immediately after touchdown.

***27.8** $\phi = \dfrac{2\pi}{\lambda} d\sin\theta \approx \dfrac{2\pi}{\lambda} d\left(\dfrac{y}{L}\right)$

(a) $\phi = \dfrac{2\pi}{(5.00\times 10^{-7}\text{ m})}(1.20\times 10^{-4}\text{ m})\sin(0.500°) = \boxed{13.2\text{ rad}}$

(b) $\phi = \dfrac{2\pi}{(5.00\times 10^{-7}\text{ m})}(1.20\times 10^{-4}\text{ m})\left(\dfrac{5.00\times 10^{-3}\text{ m}}{1.20\text{ m}}\right) = \boxed{6.28\text{ rad}}$

(c) If $\phi = 0.333\text{ rad} = \dfrac{2\pi d\sin\theta}{\lambda}$ $\theta = \sin^{-1}\left(\dfrac{\lambda\phi}{2\pi d}\right) = \sin^{-1}\left[\dfrac{(5.00\times 10^{-7}\text{ m})(0.333\text{ rad})}{2\pi(1.20\times 10^{-4}\text{ m})}\right]$

$\theta = \boxed{1.27\times 10^{-2}\text{ deg}}$

(d) If $d\sin\theta = \dfrac{\lambda}{4}$ $\theta = \sin^{-1}\left(\dfrac{\lambda}{4d}\right) = \sin^{-1}\left[\dfrac{5\times 10^{-7}\text{ m}}{4(1.20\times 10^{-4}\text{ m})}\right]$

$\theta = \boxed{5.97\times 10^{-2}\text{ deg}}$

27.9 $$I_{av} = I_{\max} \cos^2\left(\frac{\pi d \sin\theta}{\lambda}\right)$$

For small θ, $$\sin\theta = \frac{y}{L}$$

and $$I_{av} = 0.750 I_{\max}$$

$$y = \frac{\lambda L}{\pi d} \cos^{-1}\sqrt{\frac{I_{av}}{I_{\max}}}$$

$$y = \frac{\left(6.00\times10^{-7}\right)(1.20 \text{ m})}{\pi\left(2.50\times10^{-3} \text{ m}\right)} \cos^{-1}\sqrt{\frac{0.750 I_{\max}}{I_{\max}}} = \boxed{48.0\ \mu\text{m}}$$

27.10 (a) $$\frac{I}{I_{\max}} = \cos^2\left(\frac{\phi}{2}\right)$$ (Equation 27.8)

Therefore, $$\phi = 2\cos^{-1}\sqrt{\frac{I}{I_{\max}}} = 2\cos^{-1}\sqrt{0.640} = \boxed{1.29 \text{ rad}}$$

(b) $$\delta = \frac{\lambda\phi}{2\pi} = \frac{(486 \text{ nm})(1.29 \text{ rad})}{2\pi} = \boxed{99.8 \text{ nm}}$$

***27.11** $$I = I_{\max} \cos^2\left(\frac{\pi y d}{\lambda L}\right)$$

$$\frac{I}{I_{\max}} = \cos^2\left[\frac{\pi\left(6.00\times10^{-3} \text{ m}\right)\left(1.80\times10^{-4} \text{ m}\right)}{\left(656.3\times10^{-9} \text{ m}\right)(0.800 \text{ m})}\right] = \boxed{0.987}$$

27.12 Light reflecting from the first surface suffers phase reversal. Light reflecting from the second surface does not, but passes twice through the thickness t of the film. So, for constructive interference, we require

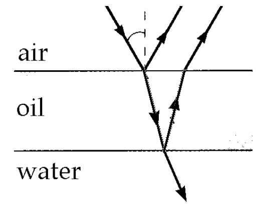
$$\frac{\lambda_n}{2} + 2t = \lambda_n$$

where $\lambda_n = \dfrac{\lambda}{n}$ is the wavelength in the material.

Then $$2t = \frac{\lambda_n}{2} = \frac{\lambda}{2n}$$

$$\lambda = 4nt = 4(1.33)(115 \text{ nm}) = \boxed{612 \text{ nm}}$$

27.13 (a) The light reflected from the top of the oil film undergoes phase reversal. Since 1.45 > 1.33, the light reflected from the bottom undergoes no reversal. For constructive interference of reflected light, we then have



$$2nt = \left(m + \tfrac{1}{2}\right)\lambda$$

or $$\lambda_m = \frac{2nt}{m+\frac{1}{2}} = \frac{2(1.45)(280\text{ nm})}{m+\frac{1}{2}}$$

Substituting for m gives: $m = 0$, $\lambda_0 = 1620$ nm (infrared)

$m = 1$, $\lambda_1 = 541$ nm (green)

$m = 2$, $\lambda_2 = 325$ nm (ultraviolet)

Both infrared and ultraviolet light are invisible to the human eye, so the dominant color in reflected light is green.

(b) The dominant wavelengths in the transmitted light are those that produce destructive interference in the reflected light. The condition for destructive interference upon reflection is

$$2nt = m\lambda$$

or $$\lambda_m = \frac{2nt}{m} = \frac{812\text{ nm}}{m}$$

Substituting for m gives: $m = 1$, $\lambda_1 = 812$ nm (near infrared)

$m = 2$, $\lambda_2 = 406$ nm (violet)

$m = 3$, $\lambda_3 = 271$ nm (ultraviolet)

Of these, the only wavelength visible to the human eye (and hence the dominate wavelength observed in the transmitted light) is 406 nm. Thus, the dominant color in the transmitted light is violet.

27.14 Treating the anti-reflectance coating like a camera-lens coating,

$$2t = \left(m + \tfrac{1}{2}\right)\frac{\lambda}{n}$$

Let $m = 0$: $$t = \frac{\lambda}{4n} = \frac{3.00\text{ cm}}{4(1.50)} = \boxed{0.500\text{ cm}}$$

This anti-reflectance coating could be easily countered by changing the wavelength of the radar — to 1.50 cm — now creating maximum reflection!

27.15 For destructive interference in the air,

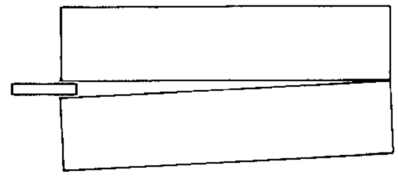
$$2t = m\lambda$$

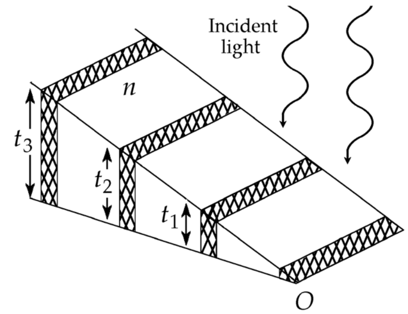
For 30 dark fringes, including the one where the plates meet,

$$t = \frac{29(600 \text{ nm})}{2} = 8.70 \times 10^{-6} \text{ m}$$

Therefore, the *radius* of the wire is

$$r = \frac{t}{2} = \frac{8.70\ \mu\text{m}}{2} = \boxed{4.35\ \mu\text{m}}$$





***27.16** $2nt = \left(m + \frac{1}{2}\right)\lambda$ so $t = \left(m + \frac{1}{2}\right)\frac{\lambda}{2n}$

Minimum $t = \left(\frac{1}{2}\right)\frac{(500 \text{ nm})}{2(1.30)} = \boxed{96.2 \text{ nm}}$

27.17 $\sin\theta = \frac{\lambda}{a} = \frac{6.328 \times 10^{-7}}{3.00 \times 10^{-4}} = 2.11 \times 10^{-3}$

$$\frac{y}{1.00 \text{ m}} = \tan\theta \approx \sin\theta = \theta \text{ (for small } \theta)$$

$$2y = \boxed{4.22 \text{ mm}}$$

27.18 The positions of the first-order minima are $y/L \approx \sin\theta = \pm\lambda/a$. Thus, the spacing between these two minima is $\Delta y = 2(\lambda/a)L$ and the wavelength is

$$\lambda = \left(\frac{\Delta y}{2}\right)\left(\frac{a}{L}\right) = \left(\frac{4.10 \times 10^{-3} \text{ m}}{2}\right)\left(\frac{0.550 \times 10^{-3} \text{ m}}{2.06 \text{ m}}\right) = \boxed{547 \text{ nm}}$$

27.19 $\frac{y}{L} = \sin\theta = \frac{m\lambda}{a}$ $\Delta y = 3.00 \times 10^{-3}$ nm

$\Delta m = 3 - 1 = 2$ and $a = \frac{\Delta m \lambda L}{\Delta y}$

$$a = \frac{2(690 \times 10^{-9} \text{ m})(0.500 \text{ m})}{(3.00 \times 10^{-3} \text{ m})} = \boxed{2.30 \times 10^{-4} \text{ m}}$$

27.20 For destructive interference,

$$\sin\theta = m\frac{\lambda}{a} = \frac{\lambda}{a} = \frac{5.00\text{ cm}}{36.0\text{ cm}} = 0.139$$

and $\theta = 7.98°$

$$\frac{d}{L} = \tan\theta$$

gives $d = L\tan\theta = (6.50\text{ m})\tan 7.98° = 0.912\text{ m}$

$$d = \boxed{91.2\text{ cm}}$$

27.21 If the speed of sound is 340 m/s, $\lambda = \frac{v}{f} = \frac{340\text{ m/s}}{650\text{ s}^{-1}} = 0.523\text{ m}$

Diffraction minima occur at angles described by $a\sin\theta = m\lambda$

$(1.10\text{ m})\sin\theta_1 = 1(0.523\text{ m})$ $\theta_1 = 28.4°$

$(1.10\text{ m})\sin\theta_2 = 2(0.523\text{ m})$ $\theta_2 = 72.0°$

$(1.10\text{ m})\sin\theta_3 = 3(0.523\text{ m})$ θ_3 nonexistent

Maxima appear straight ahead at $\boxed{0°}$ and left and right at an angle given approximately by

$(1.10\text{ m})\sin\theta_x = 1.5(0.523\text{ m})$ $\theta_x\ \boxed{\approx 46°}$

There is no solution to $a\sin\theta = 2.5\lambda$, so our answer is already complete, with $\boxed{\text{three}}$ sound maxima.

27.22 $$\sin\theta = \frac{\lambda}{a} = \frac{5.00\times10^{-7}\text{ m}}{5.00\times10^{-4}} = \boxed{1.00\times10^{-3}\text{ rad}}$$

27.23 Following Equation 27.16 for diffraction from a circular opening, the beam spreads into a cone of half-angle

$$\theta_{\min} = 1.22\frac{\lambda}{D} = 1.22\left(\frac{632.8\times10^{-9}\text{ m}}{0.00500\text{ m}}\right) = 1.54\times10^{-4}\text{ rad}$$

The radius of the beam ten kilometers away is, from the definition of radian measure,

$$r_{\text{beam}} = \theta_{\min}(1.00\times10^{4}\text{ m}) = 1.544\text{ m}$$

and its diameter is $d_{\text{beam}} = 2r_{\text{beam}} = \boxed{3.09\text{ m}}$

***27.24**

$$\theta_{\min} = 1.22\left(\frac{\text{wavelength}}{\text{pupil diameter}}\right) = \frac{\text{(distance between sources)}}{L}$$

so $$\frac{1.22\lambda}{d} = \frac{w}{vt}$$

$$w = \boxed{\frac{1.22\lambda(vt)}{d}}$$

where $\lambda \approx 650\text{ nm}$ is the average wavelength radiated by the red taillights.

27.25 By Rayleigh's criterion, two dots separated center-to-center by 2.00 mm would overlap

when $$\theta_{\min} = \frac{d}{L} = 1.22\frac{\lambda}{D}$$

Thus, $$L = \frac{dD}{1.22\lambda} = \frac{\left(2.00\times10^{-3}\text{ m}\right)\left(4.00\times10^{-3}\text{ m}\right)}{1.22\left(500\times10^{-9}\text{ m}\right)} = \boxed{13.1\text{ m}}$$

27.26 $$1.22\frac{\lambda}{D} = \frac{d}{L} \qquad \lambda = \frac{c}{f} = 0.0200\text{ m}$$

$$D = 2.10\text{ m} \qquad L = 9000\text{ m}$$

$$d = 1.22\frac{(0.0200\text{ m})(9000\text{ m})}{2.10\text{ m}} = \boxed{105\text{ m}}$$

***27.27** Apply Rayleigh's criterion, $$\theta_{\min} = \frac{x}{D} = 1.22\frac{\lambda}{d}$$

where $\theta_{\min}$ = half-angle of light cone,

x = radius of spot,

λ = wavelength of light,

d = diameter of telescope,

D = distance to Moon.

Then, the diameter of the spot on the Moon is

$$2x = 2\left(1.22\frac{\lambda D}{d}\right) = \frac{2(1.22)\left(694.3\times10^{-9}\text{ m}\right)\left(3.84\times10^{8}\text{ m}\right)}{2.70\text{ m}} = \boxed{241\text{ m}}$$

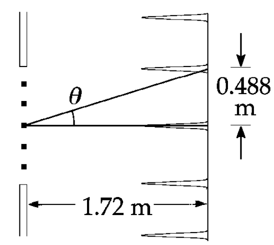
***27.28** The concave mirror of the spy satellite is probably about 2 m in diameter, and is surely not more than 5 m in diameter. That is the size of the largest piece of glass successfully cast to a precise shape, for the mirror of the Hale telescope on Mount Palomar. If the spy satellite had a larger mirror, its manufacture could not be kept secret, and it would be visible from the ground. Outer space is probably closer than your state capitol, but the satellite is surely above 200-km altitude, for reasonably low air friction. We find the distance between barely resolvable objects at a distance of 200 km, seen in yellow light through a 5-m aperture:

$$\frac{y}{L} = 1.22\frac{\lambda}{D}$$

$$y = (200\,000 \text{ m})(1.22)\left(\frac{6\times10^{-7} \text{ m}}{5 \text{ m}}\right) = 3 \text{ cm}$$

(Considering atmospheric seeing caused by variations in air density and temperature, the distance between barely resolvable objects is more like $(200\,000 \text{ m})(1 \text{ s})\left(\frac{1°}{3600 \text{ s}}\right)\left(\frac{\pi \text{ rad}}{180°}\right) = 97 \text{ cm}$.)
Thus the snooping spy satellite cannot see the difference between III and II or IV on a license plate. It cannot count coins spilled on a sidewalk, much less read the date on them.

27.29 The principal maxima are defined by



$d\sin\theta = m\lambda$ $\qquad m = 0, 1, 2, \ldots$

For $m = 1$, $\qquad \lambda = d\sin\theta$

where θ is the angle between the central ($m = 0$) and the first order ($m = 1$) maxima. The value of θ can be determined from the information given about the distance between maxima and the grating-to-screen distance. From the figure,

$$\tan\theta = \frac{0.488 \text{ m}}{1.72 \text{ m}} = 0.284$$

so $\qquad \theta = 15.8°$

and $\qquad \sin\theta = 0.273$

The distance between grating "slits" equals the reciprocal of the number of grating lines per centimeter

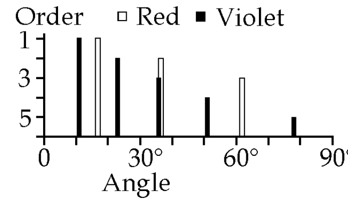
$$d = \frac{1}{5310 \text{ cm}^{-1}} = 1.88\times10^{-4} \text{ cm} = 1.88\times10^{3} \text{ nm}$$

The wavelength is $\qquad \lambda = d\sin\theta = (1.88\times10^{3} \text{ nm})(0.273) = \boxed{514 \text{ nm}}$

27.30 $\sin\theta = 0.350$: $\qquad d = \frac{\lambda}{\sin\theta} = \frac{632.8 \text{ nm}}{0.350} = 1.81\times10^{3} \text{ nm}$

Line spacing = $\boxed{1.81\ \mu\text{m}}$

27.31 The grating spacing is $d = \frac{1.00 \times 10^{-2} \text{ m}}{4500} = 2.22 \times 10^{-6} \text{ m}$



In the 1st-order spectrum, diffraction angles are given by

$\sin\theta = \frac{\lambda}{d}$: $\quad \sin\theta_1 = \frac{656 \times 10^{-9} \text{ m}}{2.22 \times 10^{-6} \text{ m}} = 0.295$

so that for red $\quad \theta_1 = 17.17°$

and for violet $\quad \sin\theta_2 = \frac{434 \times 10^{-9} \text{ m}}{2.22 \times 10^{-6} \text{ m}} = 0.195$

so that $\quad \theta_2 = 11.26°$

The angular separation is in first-order, $\quad \Delta\theta = 17.17° - 11.26° = \boxed{5.91°}$

In the second-order spectrum, $\quad \Delta\theta = \sin^{-1}\left(\frac{2\lambda_1}{d}\right) - \sin^{-1}\left(\frac{2\lambda_2}{d}\right) = \boxed{13.2°}$

Again, in the third order, $\quad \Delta\theta = \sin^{-1}\left(\frac{3\lambda_1}{d}\right) - \sin^{-1}\left(\frac{3\lambda_2}{d}\right) = \boxed{26.5°}$

Since the red does not appear in the fourth-order spectrum, the answer is complete.

***27.32** (a) $\quad d\sin\theta = m\lambda$

or $\quad d = \frac{m\lambda}{\sin\theta} = \frac{3(500 \times 10^{-9} \text{ m})}{\sin 32.0°} = 2.83 \ \mu\text{m}$

Therefore, lines per unit length $= \frac{1}{d} = \frac{1}{2.83 \times 10^{-6} \text{ m}}$

or lines per unit length $= 3.53 \times 10^5 \text{ m}^{-1} = \boxed{3.53 \times 10^3 \text{ cm}^{-1}}$.

(b) $\sin\theta = \frac{m\lambda}{d} = \frac{m(500 \times 10^{-9} \text{ m})}{2.83 \times 10^{-6} \text{ m}} = m(0.177)$

For $\sin\theta \le 1.00$, we must have $\quad m(0.177) \le 1.00$

or $\quad m \le 5.65$

Therefore, the highest order observed is $\quad m = 5$

Total number primary maxima observed is $\quad 2m + 1 = \boxed{11}$

27.33 $d = \dfrac{1}{800\ \text{mm}^{-1}} = 1.25 \times 10^{-6}\ \text{m}$

The blue light goes off at angles $\sin\theta_m = \dfrac{m\lambda}{d}$: $\theta_1 = \sin^{-1}\left(\dfrac{1 \times 5.00 \times 10^{-7}\ \text{m}}{1.25 \times 10^{-6}\ \text{m}}\right) = 23.6°$

$$\theta_2 = \sin^{-1}(2 \times 0.400) = 53.1°$$

$$\theta_3 = \sin^{-1}(3 \times 0.400) = \text{nonexistent}$$

The red end of the spectrum is at $\theta_1 = \sin^{-1}\left(\dfrac{1 \times 7.00 \times 10^{-7}\ \text{m}}{1.25 \times 10^{-6}\ \text{m}}\right) = 34.1°$

$$\theta_2 = \sin^{-1}(2 \times 0.560) = \text{nonexistent}$$

So only the first-order spectrum is complete, and **it does not overlap** the second-order spectrum.

***27.34** $d\sin\theta = m\lambda$

and, differentiating, $d(\cos\theta)d\theta = m\,d\lambda$

or $d\sqrt{1-\sin^2\theta}\,\Delta\theta \approx m\Delta\lambda$

$$d\sqrt{1-m^2\lambda^2/d^2}\,\Delta\theta \approx m\Delta\lambda$$

so $$\boxed{\Delta\theta \approx \dfrac{\Delta\lambda}{\sqrt{d^2/m^2-\lambda^2}}}$$

***27.35** $d = \dfrac{1.00 \times 10^{-3}\ \text{m/mm}}{250\ \text{lines/mm}} = 4.00 \times 10^{-6}\ \text{m} = 4000\ \text{nm}$ $d\sin\theta = m\lambda \Rightarrow m = \dfrac{d\sin\theta}{\lambda}$

(a) The number of times a complete order is seen is the same as the number of orders in which the long wavelength limit is visible.

$$m_{\text{max}} = \frac{d\sin\theta_{\text{max}}}{\lambda} = \frac{(4000\ \text{nm})\sin 90.0°}{700\ \text{nm}} = 5.71$$

or **5 orders is the maximum**

(b) The highest order in which the violet end of the spectrum can be seen is:

$$m_{\text{max}} = \frac{d\sin\theta_{\text{max}}}{\lambda} = \frac{(4000\ \text{nm})\sin 90.0°}{400\ \text{nm}} = 10.0$$

or **10 orders in the short-wavelength region**

27.36 $2d\sin\theta = m\lambda$: $\lambda = \frac{2d\sin\theta}{m} = \frac{2\left(0.353\times10^{-9}\text{ m}\right)\sin 7.60°}{1} = 9.34\times10^{-11}\text{ m} = \boxed{0.0934\text{ nm}}$

27.37 $2d\sin\theta = m\lambda$: $\sin\theta = \frac{m\lambda}{2d} = \frac{1\left(0.140\times10^{-9}\text{ m}\right)}{2\left(0.281\times10^{-9}\text{ m}\right)} = 0.249$

and $\boxed{\theta = 14.4°}$

***27.38** Figure 27.25 of the text shows the situation.

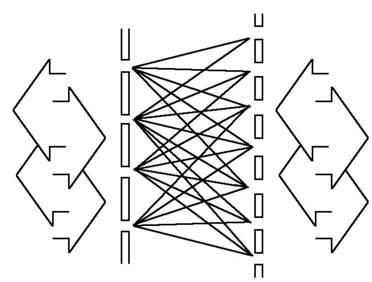
$2d\sin\theta = m\lambda$ or $\lambda = \frac{2d\sin\theta}{m}$

$m = 1$: $\lambda_1 = \frac{2(2.80\text{ m})\sin 80.0°}{1} = \boxed{5.51\text{ m}}$

$m = 2$: $\lambda_2 = \frac{2(2.80\text{ m})\sin 80.0°}{2} = \boxed{2.76\text{ m}}$

$m = 3$: $\lambda_3 = \frac{2(2.80\text{ m})\sin 80.0°}{3} = \boxed{1.84\text{ m}}$

***27.39** (a) The several narrow parallel slits make a diffraction grating. The zeroth- and first- order maxima are separated according to



$d\sin\theta = (1)\lambda$ $\sin\theta = \frac{\lambda}{d} = \frac{632.8\times10^{-9}\text{ m}}{1.2\times10^{-3}\text{ m}}$

$\theta = \sin^{-1}(0.000527) = 0.000527\text{ rad}$

$y = L\tan\theta = (1.40\text{ m})(0.000527) = \boxed{0.738\text{ mm}}$

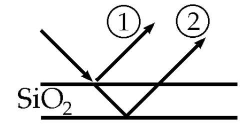
Many equally spaced transparent lines appear on the film. It is itself a diffraction grating. When the same light is sent through the film, it produces interference maxima separated according to

$d\sin\theta = (1)\lambda$ $\sin\theta = \frac{\lambda}{d} = \frac{632.8\times10^{-9}\text{ m}}{0.738\times10^{-3}\text{ m}} = 0.000857$

$y = L\tan\theta = (1.40\text{ m})(0.000857) = 1.20\text{ mm}$.

An image of the original set of slits appears on the screen. If the screen is removed, light diverges from the real images with the same wave fronts reconstructed as the original slits produced. Reasoning from the mathematics of Fourier transforms, Gabor showed that light diverging from any object, not just a set of slits, could be used. In the picture, the slits or maxima on the right are separated by 1.20 mm. The slits or maxima on the left are separated by 0.738 mm. The length difference between any pair of lines is an integer number of wavelengths. Light can be sent through equally well toward the right or toward the left.

***27.40** (a) The light in the cavity is incident perpendicularly on the mirrors, although the diagram shows a large angle of incidence for clarity. We ignore the variation of the index of refraction with wavelength. To minimize reflection at a vacuum wavelength of 632.8 nm, the net phase difference between rays (1) and (2) should be 180°. There is automatically a 180° shift in one of the two rays upon reflection, so the extra distance traveled by ray (2) should be one whole wavelength:



$$2t = \lambda / n$$

$$t = \frac{\lambda}{2n} = \frac{632.8 \text{ nm}}{2(1.458)} = \boxed{217 \text{ nm}}$$

(b) The total phase difference should be 360°, including contributions of 180° by reflection and 180° by extra distance traveled:

$$2t = \lambda / 2n$$

$$t = \frac{\lambda}{4n} = \frac{543 \text{ nm}}{4(1.458)} = \boxed{93.1 \text{ nm}}$$

27.41 My middle finger has width $d = 2$ cm.

(a) Two adjacent directions of constructive interference for 600-nm light are described by

$$d \sin\theta = m\lambda$$

$$\theta_0 = 0$$

$$\left(2\times10^{-2} \text{ m}\right)\sin\theta_1 = 1\left(6\times10^{-7} \text{ m}\right)$$

Thus, $\theta_1 = 2\times10^{-3}$ degree

and $\theta_1 - \theta_0 \boxed{\sim 10^{-3} \text{ degree}}$

(b) Choose $\theta_1 = 20°$

$$\left(2\times10^{-2} \text{ m}\right)\sin 20° = (1)\lambda$$

$$\lambda = 7 \text{ mm}$$

Millimeter waves are $\boxed{\text{microwaves}}$.

$f = \frac{c}{\lambda}$: $f = \frac{3\times10^{8} \text{ m/s}}{7\times10^{-3} \text{ m}} \boxed{\sim 10^{11} \text{ Hz}}$

***27.42** No phase shift upon reflection from the upper surface (glass to air) of the film, but there will be a shift of $\lambda/2$ due to the reflection at the lower surface of the film (air to metal). The total phase difference in the two reflected beams is

then $\delta = 2nt + \lambda/2$

For constructive interference, $\delta = m\lambda$

or $2(1.00)t + \lambda/2 = m\lambda$

Thus, the film thickness for the m^{th} order bright fringe is:

$$t_m = \left(m - \tfrac{1}{2}\right)\frac{\lambda}{2} = m\left(\frac{\lambda}{2}\right) - \frac{\lambda}{4}$$

and the thickness for the $m-1$ bright fringe is:

$$t_{m-1} = (m-1)\left(\frac{\lambda}{2}\right) - \frac{\lambda}{4}$$

Therefore, the change in thickness required to go from one bright fringe to the next is

$$\Delta t = t_m - t_{m-1} = \lambda/2$$

To go through 200 bright fringes, the change in thickness of the air film must be:

$$200(\lambda/2) = 100\lambda$$

Thus, the increase in the length of the rod is

$$\Delta L = 100\lambda = 100\left(5.00\times10^{-7}\text{ m}\right) = 5.00\times10^{-5}\text{ m}$$

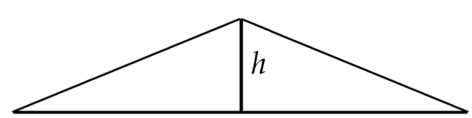
From $\Delta L = L_i \alpha \Delta T$

we have: $$\alpha = \frac{\Delta L}{L_i \Delta T} = \frac{5.00\times10^{-5}\text{ m}}{(0.100\text{ m})(25.0°\text{C})} = \boxed{20.0\times10^{-6}\text{ °C}^{-1}}$$

27.43 For destructive interference, the path length must differ by $m\lambda$. We may treat this problem as a double slit experiment if we remember the light undergoes a $\pi/2$-phase shift at the mirror. The second slit is the mirror image of the source, 1.00 cm below the mirror plane. Using Equation 27.5,

$$y_{\text{dark}} = \frac{m\lambda L}{d} = \frac{1\left(5.00\times10^{-7}\text{ m}\right)(100\text{ m})}{\left(2.00\times10^{-2}\text{ m}\right)} = \boxed{2.50\text{ mm}}$$

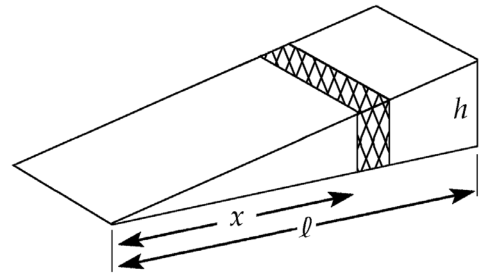
27.44 $2\sqrt{(15.0\text{ km})^2 + h^2} = 30.175\text{ km}$



$(15.0\text{ km})^2 + h^2 = 227.63$

$h = \boxed{1.62\text{ km}}$

27.45 For dark fringes, $2nt = m\lambda$



and at the edge of the wedge, $t = \dfrac{84(500\text{ nm})}{2}$.

When submerged in water, $2nt = m\lambda$

$$m = \frac{2(1.33)(42)(500\text{ nm})}{500\text{ nm}}$$

so $m + 1 = \boxed{113\text{ dark fringes}}$

27.46 (a) Minimum: $2nt = m\lambda_2$ for $m = 0, 1, 2, \ldots$

Maximum: $2nt = \left(m' + \frac{1}{2}\right)\lambda_1$ for $m' = 0, 1, 2, \ldots$

for $\lambda_1 > \lambda_2$, $\left(m' + \frac{1}{2}\right) < m$

so $m' = m - 1$

Then $2nt = m\lambda_2 = \left(m - \frac{1}{2}\right)\lambda_1$

$$2m\lambda_2 = 2m\lambda_1 - \lambda_1$$

so $\boxed{m = \dfrac{\lambda_1}{2(\lambda_1 - \lambda_2)}}$

(b) $m = \dfrac{500}{2(500 - 370)} = 1.92 \to 2$ (wavelengths measured to ± 5 nm)

Minimum: $2nt = m\lambda_2$

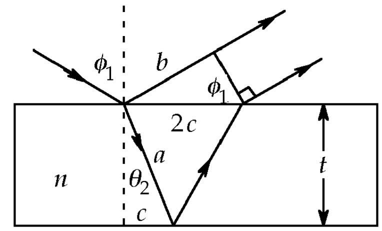
$2(1.40)t = 2(370\text{ nm})$ $t = 264\text{ nm}$

Maximum: $2nt = \left(m - 1 + \frac{1}{2}\right)\lambda = 1.5\lambda$

$2(1.40)t = 1.5(500\text{ nm})$ $t = 268\text{ nm}$

Film thickness $= \boxed{266\text{ nm}}$

***27.47** The shift between the two reflected waves is $\delta = 2na - b - \lambda/2$ where a and b are as shown in the ray diagram, n is the index of refraction, and the factor of $\lambda/2$ is due to phase reversal at the top surface. For constructive interference, $\delta = m\lambda$ where m has integer values. This condition becomes



$$2na - b = \left(m + \tfrac{1}{2}\right)\lambda \qquad (1)$$

From the figure's geometry, $$a = \frac{t}{\cos\theta_2}$$

$$c = a\sin\theta_2 = \frac{t\sin\theta_2}{\cos\theta_2}$$

$$b = 2c\sin\phi_1 = \frac{2t\sin\theta_2}{\cos\theta_2}\sin\phi_1$$

Also, from Snell's law, $$\sin\phi_1 = n\,\sin\theta_2$$

Thus, $$b = \frac{2nt\sin^2\theta_2}{\cos\theta_2}$$

With these results, the condition for constructive interference given in Equation (1) becomes:

$$2n\left(\frac{t}{\cos\theta_2}\right) - \frac{2nt\sin^2\theta_2}{\cos\theta_2} = \frac{2nt}{\cos\theta_2}\left(1 - \sin^2\theta_2\right) = \left(m + \tfrac{1}{2}\right)\lambda$$

or $$\boxed{2nt\cos\theta_2 = \left(m + \tfrac{1}{2}\right)\lambda}$$

***27.48** (a) Bright bands are observed when $$2nt = \left(m + \tfrac{1}{2}\right)\lambda$$

Hence, the first bright band ($m = 0$) corresponds to $nt = \lambda/4$

Since $$\frac{x_1}{x_2} = \frac{t_1}{t_2}$$

we have $$x_2 = x_1\left(\frac{t_2}{t_1}\right) = x_1\left(\frac{\lambda_2}{\lambda_1}\right) = (3.00\text{ cm})\left(\frac{680\text{ nm}}{420\text{ nm}}\right) = \boxed{4.86\text{ cm}}$$

(b) $$t_1 = \frac{\lambda_1}{4n} = \frac{420\text{ nm}}{4(1.33)} = \boxed{78.9\text{ nm}}$$

$$t_2 = \frac{\lambda_2}{4n} = \frac{680\text{ nm}}{4(1.33)} = \boxed{128\text{ nm}}$$

(c) $$\theta \approx \tan\theta = \frac{t_1}{x_1} = \frac{78.9\text{ nm}}{3.00\text{ cm}} = \boxed{2.63\times10^{-6}\text{ rad}}$$

27.49 The first minimum is at $a \sin\theta = (1)\lambda$

This has no solution if $\dfrac{\lambda}{a} > 1$

or if $a < \lambda = \boxed{632.8 \text{ nm}}$

***27.50** Consider vocal sound moving at 340 m/s and of frequency 3000 Hz. Its wavelength is

$$\lambda = \frac{v}{f} = \frac{340 \text{ m/s}}{3000 \text{ Hz}} = 0.113 \text{ m}$$

If your mouth, for horizontal dispersion, behaves similarly to a slit 6.00 cm wide, then $a \sin\theta = m\lambda$ predicts no diffraction minima. You are a nearly isotropic source of this sound. It spreads out from you nearly equally in all directions. On the other hand, if you use a megaphone with width 60.0 cm at its wide end, then $a \sin\theta = m\lambda$ predicts the first diffraction minimum at

$$\theta = \sin^{-1}\left(\frac{m\lambda}{a}\right) = \sin^{-1}\left(\frac{0.113 \text{ m}}{0.600 \text{ m}}\right) = 10.9°$$

This suggests that the sound is radiated mostly toward the front into a diverging beam of angular diameter only about 20°. With less sound energy wasted in other directions, more is available for your intended auditors. We could check that a distant observer to the side or behind you receives less sound when a megaphone is used.

27.51 $d = \dfrac{1}{400 \text{ mm}^{-1}} = 2.50 \times 10^{-6} \text{ m}$

(a) $d \sin\theta = m\lambda$: $\theta_a = \sin^{-1}\left(\dfrac{2 \times 541 \times 10^{-9} \text{ m}}{2.50 \times 10^{-6} \text{ m}}\right) = \boxed{25.6°}$

(b) $\lambda = \dfrac{541 \times 10^{-9} \text{ m}}{1.33} = 4.07 \times 10^{-7} \text{ m}$ $\theta_b = \sin^{-1}\left(\dfrac{2 \times 4.07 \times 10^{-7} \text{ m}}{2.50 \times 10^{-6} \text{ m}}\right) = \boxed{19.0°}$

(c) $d \sin\theta_a = 2\lambda$ $d \sin\theta_b = \dfrac{2\lambda}{n}$

$n \sin\theta_b = (1)\sin\theta_a$

***27.52** (a) $\lambda = \frac{v}{f}$: $\lambda = \frac{3.00 \times 10^8 \text{ m/s}}{1.40 \times 10^9 \text{ s}^{-1}} = 0.214 \text{ m}$

$\theta_{\min} = 1.22 \frac{\lambda}{D}$: $\theta_{\min} = 1.22 \left(\frac{0.214 \text{ m}}{3.60 \times 10^4 \text{ m}} \right) = \boxed{7.26 \ \mu\text{rad}}$

$\theta_{\min} = 7.26 \ \mu\text{rad} \left(\frac{180 \times 60 \times 60 \text{ s}}{\pi} \right) = \boxed{1.50 \text{ arc seconds}}$

(b) $\theta_{\min} = \frac{d}{L}$: $d = \theta_{\min} L = (7.26 \times 10^{-6} \text{ rad})(26\ 000 \text{ ly}) = \boxed{0.189 \text{ ly}}$

(c) $\theta_{\min} = 1.22 \frac{\lambda}{D}$ $\theta_{\min} = 1.22 \left(\frac{500 \times 10^{-9} \text{ m}}{12.0 \times 10^{-3} \text{ m}} \right) = \boxed{50.8 \ \mu\text{rad}}$ (10.5 seconds of arc)

(d) $d = \theta_{\min} L = (50.8 \times 10^{-6} \text{ rad})(30.0 \text{ m}) = 1.52 \times 10^{-3} \text{ m} = \boxed{1.52 \text{ mm}}$

***27.53** (a) We require $\theta_{\min} = 1.22 \frac{\lambda}{D} = \frac{\text{radius of diffraction disk}}{L} = \frac{D}{2L}$.

Then $\boxed{D^2 = 2.44 \lambda L}$

(b) $D = \sqrt{2.44 (500 \times 10^{-9} \text{ m})(0.150 \text{ m})} = \boxed{428 \ \mu\text{m}}$

ANSWERS TO EVEN NUMBERED PROBLEMS

2. (a) 36.2° (b) 5.08 cm (c) 508 THz

4. maxima at 0°, 29.1°, and 76.3°; minima at 14.1° and 46.8°

6. 641

8. (a) 13.2 rad (b) 6.28 rad
(c) 0.0127 degree (d) 0.0597 degree

10. (a) 1.29 rad (b) 99.8 nm

12. 612 nm

14. 0.500 cm

16. 96.2 nm

18. 547 nm

20. 91.2 cm

22. 1.00 mrad

24. $1.22\ \lambda vt/d$ where λ is about 650 nm

26. 105 m

28. Neither. It can resolve objects no closer than several centimeters apart.

30. 1.81 μm

32. (a) 3.53×10^3 lines/cm (b) Eleven maxima

34. See the solution

36. 93.4 pm

38. 5.51 m, 2.76 m, 1.84 m

40. (a) 217 nm (b) 93.1 nm

42. 20.0×10^{-6} °C^{-1}

44. 1.62 km

46. (a) See the solution (b) 266 nm

48. (a) 4.86 cm from the top (b) 78.9 nm and 128 nm (c) 2.63×10^{-6} rad

50. See the solution

52. (a) 7.26 μrad (1.50 seconds of arc) (b) 0.189 ly
(c) 50.8 μrad (10.5 seconds of arc) (d) 1.52 mm