TABLE OF CONTENTS

Chapter 18 —
CD-ROM Content

Supplemental Articles
- 144 MHz Duplexer Cavities

Chapter 18

Repeater Antenna Systems

Antenna systems for VHF and UHF repeater systems are discussed in this chapter. Most repeater antennas are fairly simple, being based on dipoles and vertical monopoles — no exotic theory is required. Because repeaters must simultaneously transmit and receive, however, special care and techniques are required for filtering and system construction. Obtaining the data necessary for repeater frequency coordination is also discussed. Material on duplexers and other topics was originally prepared by Domenic Mallozzi, N1DM. The chapter has been reviewed and updated for this edition by Ed Karl, KØKL, trustee for the KOØA and WBØHSI repeater systems.

18.1 BASIC REPEATER CONCEPTS

The antenna is a vital part of any repeater installation. Because the function of a repeater is to extend the range of communications between mobile and portable stations, the repeater antenna should be installed in the best possible location to provide the desired coverage. This usually means getting the antenna as high above the average local terrain as possible. In some instances, a repeater may need to have coverage only in a limited area or direction. When this is the case, antenna installation requirements will be completely different, with certain limits being set on height, gain and power.

18.1.1 HORIZONTAL AND VERTICAL POLARIZATION

Until the upsurge in FM repeater activity in the 1970s, most amateur VHF antennas were horizontally polarized. These days, very few repeater groups use horizontal polarization. The vast majority of VHF and UHF repeaters use vertically polarized antennas and all the antennas discussed in this chapter are of that type. (Horizontal polarization is sometimes used to allow separate repeaters to share the same input and/or output frequencies with closer-than-normal geographical spacing by using cross-polarization to provide additional rejection of the unwanted signals.)

18.1.2 TRANSMISSION LINES

Transmission lines used at VHF and above become very important antenna system components because feed line losses increase with frequency. The characteristics of feed lines commonly used at VHF and above are discussed in the chapter **Transmission Lines**. Although information is provided there for small-diameter RG-58 and RG-59 coaxes, these should not be used except for very short feed lines (25 feet or less) and interconnecting cables. These cable types are very lossy at VHF. In addition, the losses can be much higher if fittings and connections are not carefully installed.

The differences in loss between solid-polyethylene dielectric types (RG-8 and RG-11) and those using foamed polyethylene are significant at VHF and UHF. Hardline has the lowest loss and is often available as surplus. Buy the line with the lowest loss you can afford. Feed line losses should be included in designing your repeater antenna system and must be included when calculating *effective radiated power (ERP)* as shown later in this chapter.

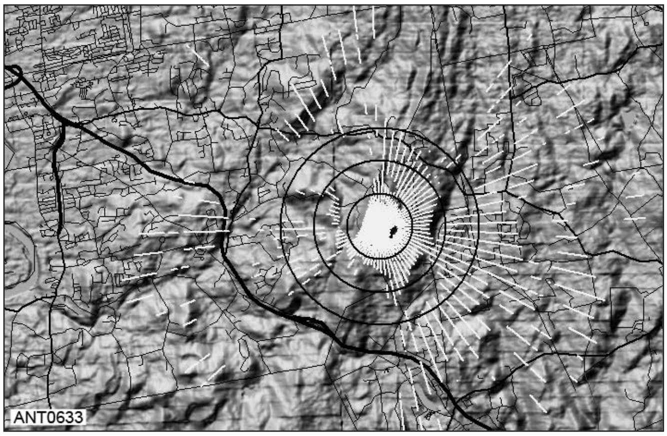

Figure 18.1 — *MicroDEM* topographic map, showing the coverage for a repeater placed on a 30-meter high tower in Glastonbury, CT. The white radial lines indicate the coverage in 5° increments of azimuth around the tower. The range circles are 1000 meters apart.

If you must bury coaxial cable, check with the cable manufacturer before doing so. Many popular varieties of coaxial cable should not be buried since the dielectric can become contaminated from moisture and soil chemicals. Some coaxial cables are labeled as "direct burial." Such a rating is the best way to be sure your cable can be buried without damage.

18.1.3 MATCHING

Losses are lowest in transmission lines that are matched to their characteristic impedances. If there is a mismatch at the end of the line, the losses increase. The *only way* to reduce the SWR on a transmission line is by matching the line *at the antenna*. Changing the length of a transmission line does not reduce the SWR except through loss, which is detrimental to system performance. The SWR is established by the impedance of the line and the impedance of the antenna, so matching must be done at the antenna end of the line.

The importance of matching, so far as feed line losses are concerned, is sometimes overstressed. But under some conditions, it is necessary to minimize feed line losses related to SWR if repeater performance is to be consistent. It is important to keep in mind that most VHF/UHF equipment is designed to operate into a 50-Ω load. The output circuitry will not be loaded properly if connected to a mismatched line. This leads to a reduction in output power, and in extreme cases, damage to the transmitter.

18.2 REPEATER ANTENNA SYSTEM DESIGN

Choosing a repeater or remote-base antenna system is as close as most amateurs come to designing a commercial-grade antenna system. The term *system* is used because most repeaters utilize not only an antenna and a transmission line, but also include duplexers, cavity filters, circulators or isolators in some configuration. Assembling the proper combination of these items in constructing a reliable system is both an art and a science. In this section, the functions of each component in a repeater antenna system and their successful integration are discussed. While every possible complication in constructing a repeater cannot be foreseen at the outset, this discussion should serve to steer you along the right lines in solving any problems encountered.

18.2.1 DETERMINING REPEATER COVERAGE AREA

Modern computer programs can show the coverage of a repeater using readily available topographic data from the Internet. In the chapter **HF Antenna System Design**, we described the *MicroDEM* program supplied on the CD-ROM accompanying this book. Dr Peter Guth, the author of *MicroDEM*, built into it the ability to generate terrain profiles that can be used with ARRL's *HFTA* (HF Terrain Assessment) program (also included on the CD-ROM).

MicroDEM has a wide range of capabilities beyond simply making terrain profiles. It can do *LOS* (line of sight) computations, based on visual or radio-horizon considerations. **Figure 18.1** shows a *MicroDEM* map for the area around Glastonbury, Connecticut. This is somewhat hilly terrain, and as a result the coverage for a repeater placed here on a 30-meter (100-foot) high tower would be somewhat spotty. Figure 18.1 shows a "Viewshed" on the map, in the form of the white terrain profile strokes in 5° increments around the tower.

Figure 18.2 shows the LOS for an azimuth of 80°, from a 30-meter high tower out to a distance of 8000 meters. The light-shaded areas on the profile are those that are illuminated directly by the antenna on the tower, while the dark portions of the profile are those that cannot be seen directly from the tower. This profile assumes that the mobile station is 2 meters high — the height of a 6-foot tall person with a handheld radio.

The terrain at an 80° azimuth allows direct radio view from the top of the tower out to about 1.8 km. From here, the downslope prevents direct view until about 2.5 km, where the terrain is briefly visible again from several hundred meters, disappearing from radio view until about 2.8 km, after which it becomes visible until about 3.6 km. Note that other than putting the repeater antenna on a higher tower, there is nothing that can be done to improve repeater coverage over this hilly terrain, although knife-edge diffraction off the hill tops will help fill in coverage gaps.

Repeater coverage can also be estimated by using the program *Radio Mobile for Windows* by Roger Coudé, VE2DBE (**www.cplus.org/rmw/english1.html**). The software is free

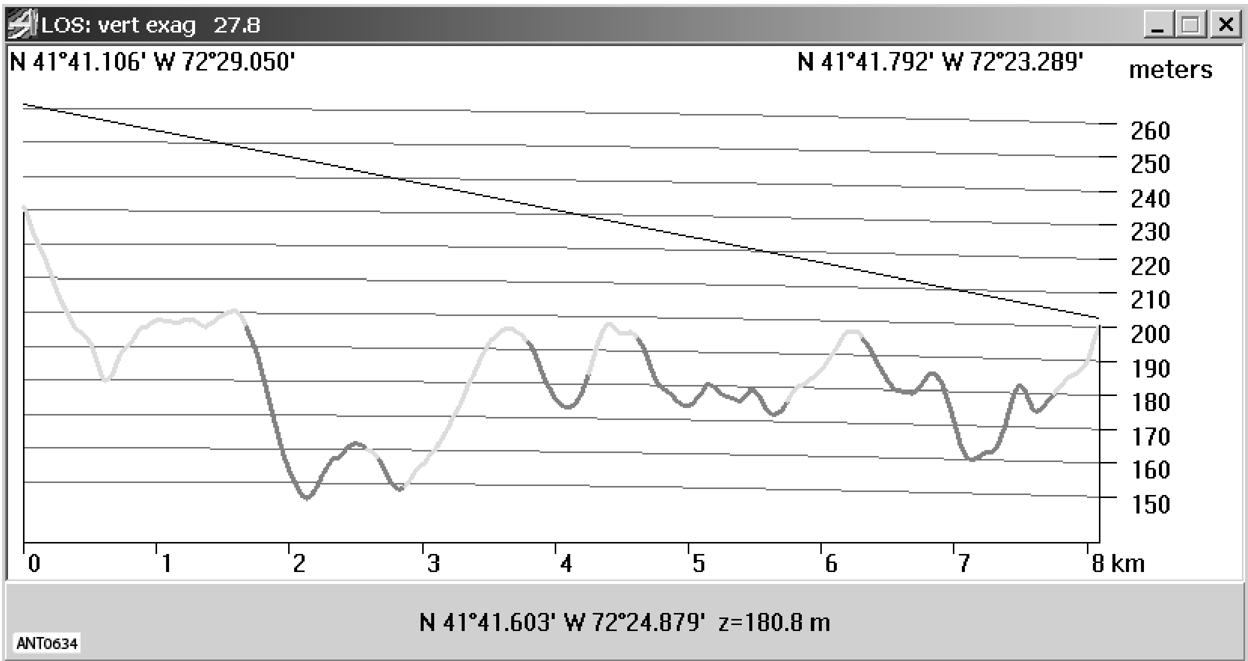

Figure 18.2 — An "LOS" (line of sight) profile at an azimuth of 80° from the tower in Figure 18.1. The light-gray portions of the terrain profile are visible from the top of the tower, while the dark portions are blocked by the terrain.

for amateur and other non-commercial uses. It produces coverage maps based on selectable environmental models and digitized terrain data. It does not produce output files that can be used by *HFTA* or other programs that automate the process of determining a repeater antenna's *height above average terrain (HAAT)*, a figure often required for frequency coordination applications.

18.2.2 THE REPEATER ANTENNA PATTERN

The most important part of the system is the antenna itself. As with any antenna, it must radiate and collect RF energy as efficiently as possible. Many repeaters use omnidirectional collinear antennas (see the Bibliography entries for Belrose and Collis at the end of this chapter) or groundplanes. These antennas are simple, mechanically robust, and are the most common type of antennas for both amateur and commercial repeaters.

An omnidirectional antenna is not always the best choice. For example, suppose a group wishes to set up a repeater to cover towns A and B and the interconnecting state highway shown in **Figure 18.3**. The available repeater site is marked on the map. No coverage is required to the west or south, or over the ocean. If an omnidirectional antenna is used in this case, a significant amount of the radiated signal goes in undesired directions. By using an antenna with a cardioid pattern, as shown in Figure 18.3, the coverage is concentrated in the desired directions. The repeater will be more effective in these locations, and signals from low-power portables and mobiles will be more reliable.

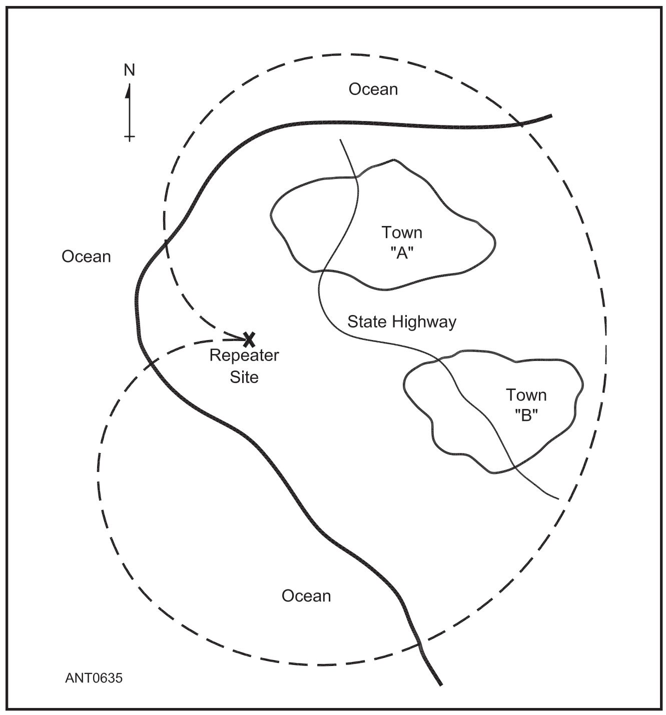

Figure 18.3 — There are many situations where equal repeater coverage is not desired in all directions from the "machine." One such situation is shown here, where the repeater is needed to cover only towns A and B and the interconnecting highway. An omnidirectional antenna would provide coverage in undesired directions, such as over the ocean. The broken line shows the radiation pattern of an antenna that is better suited to this circumstance.

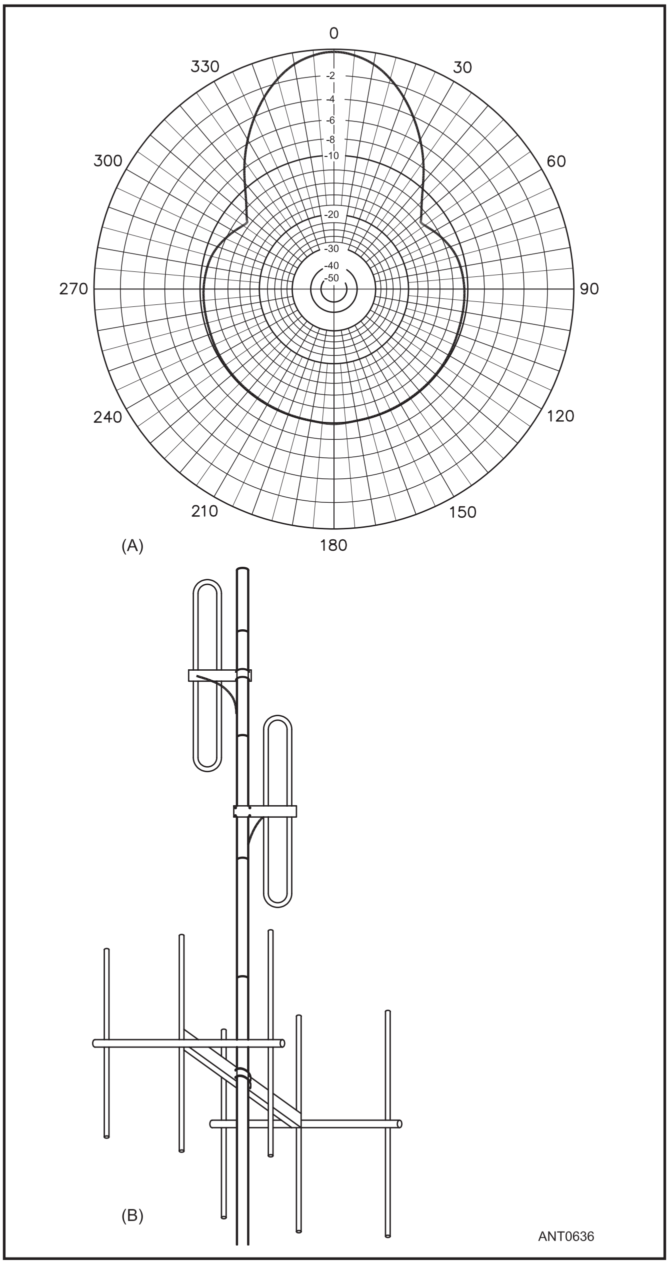

Figure 18.4 — The "keyhole" horizontal radiation pattern at A is generated by the combination of phased Yagis and vertical elements shown at B. Such a pattern is useful in overcoming coverage blockages resulting from local terrain features. (*Based on a design by Decibel Products*)

In many cases, antennas with special patterns are more expensive than omnidirectional models. This is an obvious consideration in designing a repeater antenna system. Over terrain where coverage may be difficult in some direction from the repeater site, it may be desirable to skew the antenna pattern in that direction. This can be accomplished by using a phased-vertical array or a combination of a Yagi and a phased vertical to produce a "keyhole" pattern. See **Figure 18.4**.

Repeaters are common on 440 MHz and above, and many groups invest in high-gain omnidirectional antennas.

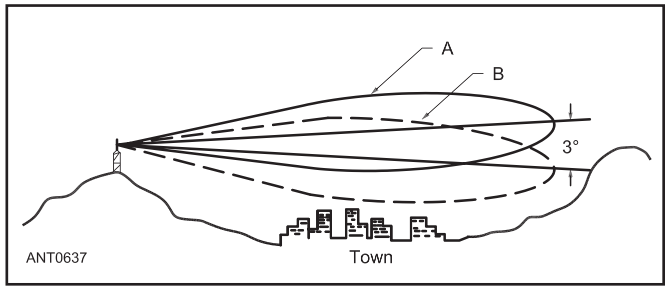

Figure 18.5 — Vertical-beam downtilt is another form of radiation-pattern distortion useful for improving repeater coverage. This technique can be employed in situations where the repeater station is at a greater elevation than the desired coverage area, when a high-gain omnidirectional antenna is used. Pattern A shows the normal vertical-plane radiation pattern of a high-gain omnidirectional antenna with respect to the desired coverage area (the town). Pattern B shows the pattern tilted down, and the coverage improvement is evident.

Obtaining high gain from an omnidirectional antenna requires vertical beamwidth reduction. In most cases, these antennas are designed to radiate their peak gain at the horizon, resulting in optimum coverage when the antenna is located at a moderate height over normal terrain. Unfortunately, in cases where the antenna is located at a very high site (overlooking the coverage area) this may not be the most desirable pattern. The vertical pattern of the antenna can be tilted downward, however, to facilitate coverage of the desired area. This is called *vertical-beam downtilt*.

An example of such a situation is shown in **Figure 18.5**. The repeater site overlooks a town in a valley. A 450-MHz repeater is needed to serve low-power portable and mobile stations. Constraints on the repeater dictate the use of an antenna with a gain of 11 dBi. (An omnidirectional antenna with this gain has a vertical beamwidth of approximately 6°.) If the repeater antenna has its peak gain at the horizon, a major portion of the transmitted signal is directed *above* the town, which becomes the best area from which to access the repeater. By tilting the pattern down 3°, the peak radiation will occur in the town.

Vertical-beam downtilt is generally produced by feeding the elements of a collinear vertical array slightly out of phase with each other. Lee Barrett, K7NM, showed such an array in *Ham Radio* magazine. (See the Bibliography at the end of this chapter.) Barrett gives the geometry and design of a four-pole array with progressive phase delay, and a computer program to model it. The technique is shown in **Figure 18.6**, with a free-space elevation plot showing downtilt in **Figure 18.7**.

Commercial antennas are sometimes available (at extra cost) with built-in downtilt characteristics. Before ordering such a commercial antenna, make sure that you really require it — they generally are special-order items and are not returnable.

There are disadvantages to improving coverage by means of vertical-beam downtilt. When compared to a standard collinear array, an antenna using vertical-beam downtilt will have somewhat greater minor lobes in the vertical pattern, resulting

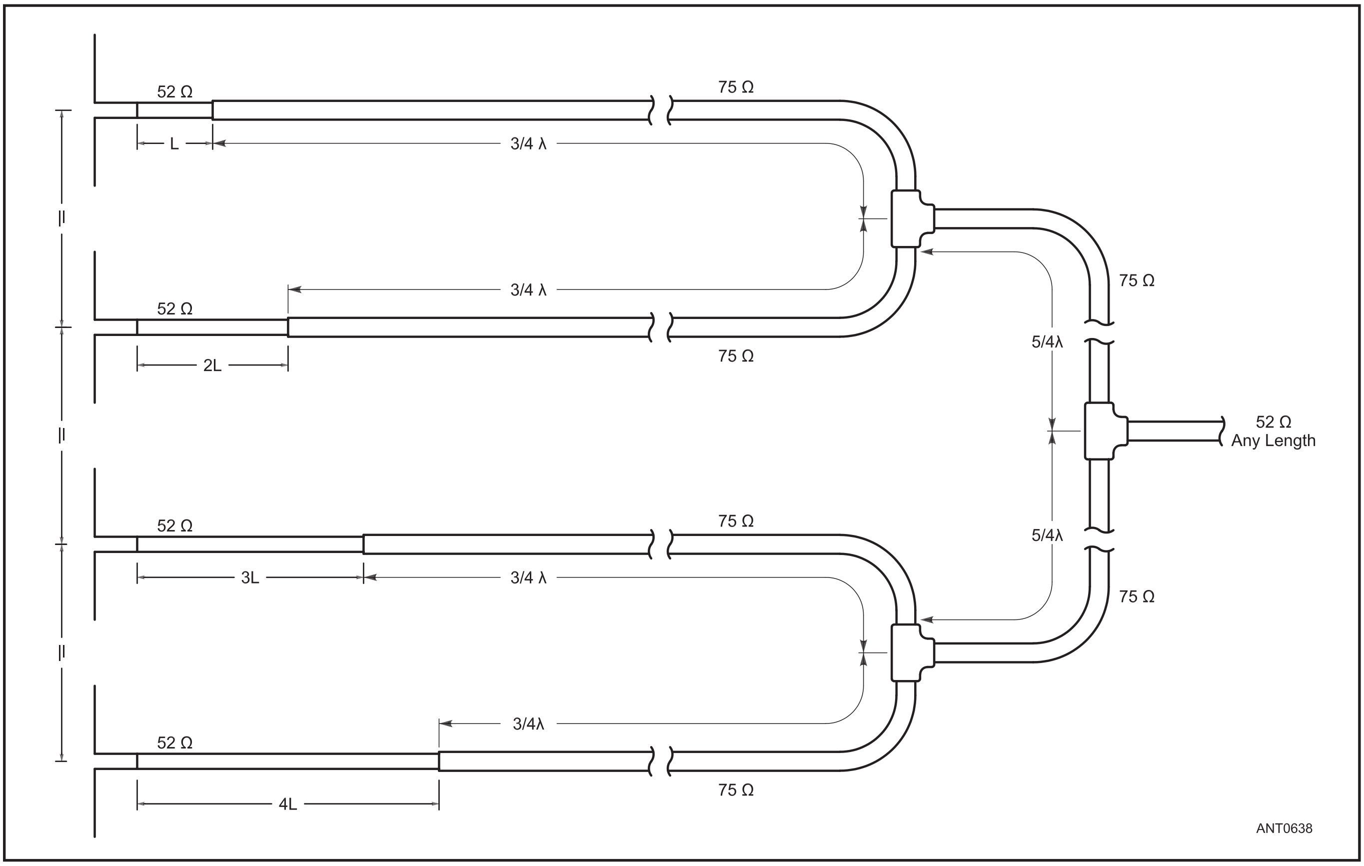

Figure 18.6 — Vertical-beam downtilt can be facilitated by inserting 52-Ω delay lines in series with the 75-Ω feed lines to the collinear elements of an omnidirectional antenna. The delay lines to each element are progressively longer so the phase shift between elements is uniform. Odd ¼-λ coaxial transformers are used in the main (75-Ω) feed system to match the dipole impedances to the driving point. Tilting the vertical beam in this way often produces minor lobes in the vertical pattern that do not exist when the elements are fed in phase.

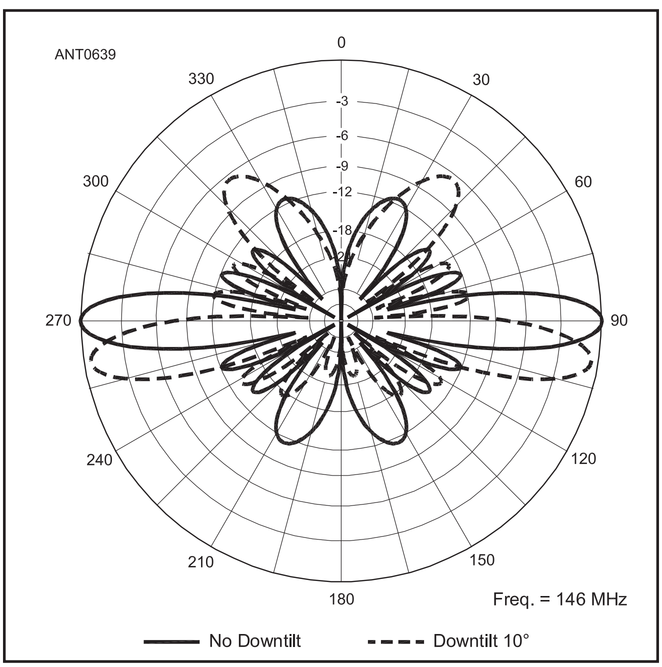

Figure 18.7 — Free-space elevation-plane patterns showing downtilting that results from progressive phase shifts for the feed currents for the dipole in Figure 18.6.

in reduced gain (usually less than 1 dB). Bandwidth is also slightly reduced. The reduction in gain, when combined with the downtilt characteristic, results in a reduction in total coverage area. These trade-offs, as well as the increased cost of a commercial antenna with downtilt, must be compared to the improvement in total performance in a situation where vertical-beam downtilt is contemplated.

If the antenna is located at the outer edge of desired coverage, *mechanical beamtilt* can also be used. The antenna is physically tilted several degrees to lower the main lobe in the favored direction. (It is raised in the unfavored direction.) For example, in the above cited installation a cardioid pattern gets the energy in the desired direction, tilting the antenna ensures the energy is directed into the desired geography.

An alternative to using special techniques to produce downtilt is to use an antenna with significant radiation at high elevation angles and invert it. Using such a low gain antenna mounted upside down results in all the energy being directed below the antenna. Consider the pattern of a ¼-wavelength ground-plane antenna. Most of the energy is radiated at angles between the horizon and the top of the radiator.

By inverting the ground plane antenna, you obtain solid coverage from the base of the antenna's mounting structure to the horizon. The tradeoff is losing some gain advantage in favor of good nearby coverage and elimination of the pattern nulls created when using electrical beamtilt.

Top Mounting and Side Mounting

Amateur repeaters often share towers with commercial and public service users. In many of these cases, other antennas are at the top of the tower, so the amateur antenna must be side mounted. A consequence of this arrangement is that the free-space pattern of the repeater antenna is distorted by the tower. This effect is especially noticeable when an omnidirectional antenna is side mounted on a structure.

The effects of supporting structures are most pronounced at close antenna spacings to the tower and with large support dimensions. The result is a measurable increase in gain in one direction and a partial null in the other direction (sometimes 15 dB deep). The shape of the supporting structure also influences pattern distortion. Many antenna manufacturers publish radiation patterns showing the effect of side mounting antennas in their catalogs.

Side mounting is not always a disadvantage. In cases where more (or less) coverage is desired in one direction, the supporting structure can be used to advantage. If pattern distortion is not acceptable, a solution is to mount antennas around the perimeter of the structure and feed them with the proper phasing to synthesize an omnidirectional pattern. Many manufacturers make antennas to accommodate such situations.

The effects of different mounting locations and arrangements can be illustrated with an array of exposed dipoles, **Figure 18.8**. Such an array is a very versatile antenna because, with simple rearrangement of the elements, it can develop either an omnidirectional pattern or an offset pattern. Figure 18.8A shows a basic collinear array of four vertical ½-λ elements. The vertical spacing between adjacent elements is 1 λ. All elements are fed in phase. If this array is placed in the clear and supported by a nonconducting mast, the calculated radiation resistance of each dipole element is on the order of 63 Ω. If the feed line is completely decoupled, the resulting azimuth pattern is omnidirectional. The vertical-plane pattern is shown in **Figure 18.9**.

Figure 18.8B shows the same array in a side-mounting arrangement, at a spacing of ¼ λ from a conducting mast. In this mounting arrangement, the mast takes on the role of a reflector, producing an F/B on the order of 5.7 dB. The azimuth pattern is shown in **Figure 18.10**. The vertical pattern is not significantly different from that of Figure 18.9, except the four small minor lobes (two on either side of the vertical axis) tend to become distorted. They are not as "clean," tending to merge into one minor lobe at some mast heights. This apparently is a function of currents in the supporting mast. The proximity of the mast also alters the feed-point impedance. For elements that are resonant in the configuration of Figure 18.8A, the calculated impedance in the arrangement of Figure 18.8B is in the order of $72 + j\,10\ \Omega$.

If side mounting is the only possibility and an omnidirectional pattern is required, the arrangement of Figure 18.8C may be used. The calculated azimuth pattern takes on a slight cloverleaf shape, but is within 1.5 dB of being circular. However, gain performance suffers, and the idealized vertical pattern of Figure 18.9 is not achieved. See **Figure 18.11**. Spacings other than ¼-λ from the mast were not investigated.

Effects of Other Conductors

Feed line proximity and tower-access ladders or cages

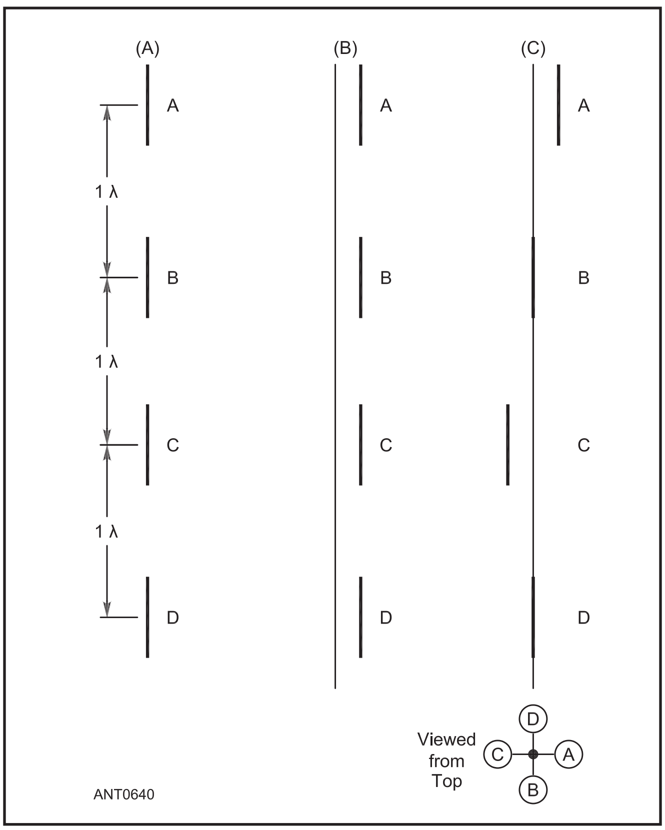

Figure 18.8 — Various arrangements of exposed dipole elements. At A is the basic collinear array of four elements. B shows the same elements mounted on the side of a mast, and C shows the elements in a side-mounted arrangement around the mast for omnidirectional coverage. See text and Figures 18.9 through 18.11 for radiation-pattern information.

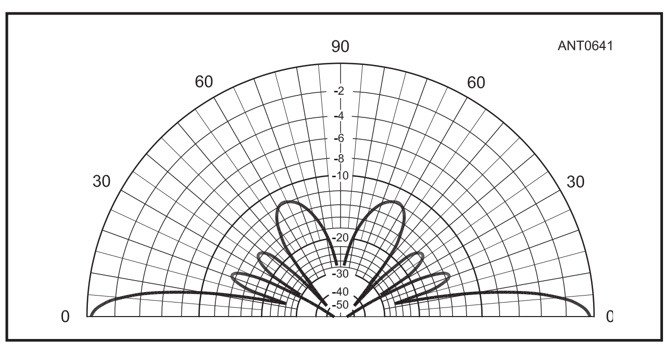

Figure 18.9 — Calculated vertical-plane pattern of the array of Figure 18.8A, assuming a nonconducting mast support and complete decoupling of the feeder. In azimuth the array is omnidirectional. The calculated gain of the array is 8.6 dBi at 0° elevation; the –3 dB point is at 6.5°.

also have an effect on the radiation patterns of side-mounted antennas. This subject was studied by Connolly and Blevins, and their findings are given in *IEEE Conference Proceedings* (see the Bibliography). Those considering mounting antennas on air-conditioning evaporators or maintenance penthouses on commercial buildings should consult this article. It gives considerable information on the effects of these structures on both unidirectional and omnidirectional antennas.

Metallic guy wires also affect antenna radiation patterns. Yang and Willis studied this and reported the results in *IRE Transactions on Vehicular Communications*. As expected, the closer the antenna is to the guy wires, the greater the effect on the radiation patterns. If the antennas are near the point where the guy wires meet the tower, the effect of the guy wires can be minimized by breaking them up with insulators every 0.75 λ for a distance of 2.25 λ to 3.0 λ from the antenna.

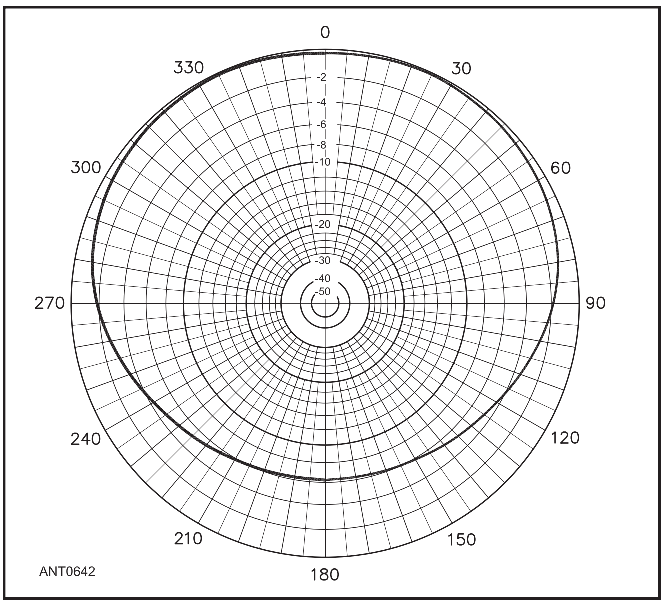

Figure 18.10 — Calculated azimuth pattern of the side-mounted array of Figure 18.8B, assuming ¼-λ spacing from a 4-inch mast. The calculated gain in the favored direction, away from the mast and through the elements, is 10.6 dBi.

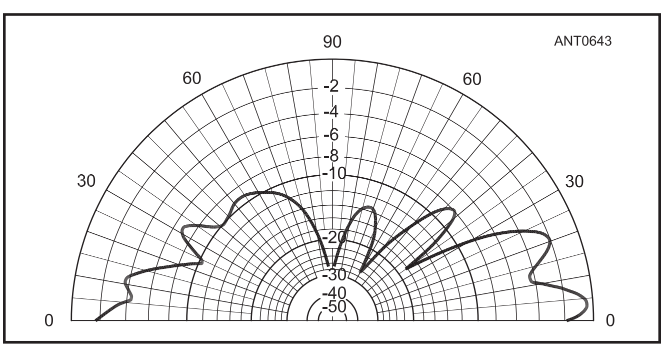

Figure 18.11 — Calculated vertical pattern of the array of Figure 18.8C, assuming ¼-λ element spacing from a 4-inch mast. The azimuth pattern is circular within 1.5 dB, and the calculated gain is 4.4 dBi.

Mechanical Construction Issues

Repeater antennas are usually installed in locations that are exposed to far more extreme weather conditions than ground-mounted antennas. Because they are installed on mountaintops, tall buildings, and tall towers, high winds, extreme temperatures, icing, and other hostile conditions are often encountered. For this reason, most garden variety amateur antennas are not suitable for repeater use even though they may meet electrical specifications for gain and frequency coverage. Unless you are skilled at the construction of mechanically-rugged antennas, it is recommended that a commercial antenna is used, particularly if the antenna is not easily accessed for repair and testing.

Mechanical integrity of the mount is also of great importance. An antenna hanging by the feed line and banging against the tower provides far from optimum performance and reliability. Use a mount that is appropriately secured to the tower and the antenna. Also use high-quality mounting hardware, preferably stainless steel (or bronze). If your local hardware store does not carry stainless steel hardware, try a marine supply store.

Be certain that the feed line connectors are properly waterproofed and that the feed line is properly supported along its length. Long lengths of cable are subject to contraction and expansion with temperature from season to season, so it is important that the cable not be so tight that contraction causes it to stress the connection at the antenna. This can cause the connection to become intermittent (and noisy) or, at worst, an open circuit. This is far from a pleasant situation if the antenna connection is 300 feet up a tower, and it happens to be the middle of the winter!

18.2.3 ISOLATION REQUIREMENTS

Because repeaters generally operate in full *duplex* (the transmitter and receiver operate simultaneously), the antenna system must act as a filter to keep the transmitter from blocking the receiver. The degree to which the transmitter and receiver must be isolated is a complex problem. It is quite dependent on the equipment used and the difference in transmitter and receiver frequencies (offset). Instead of going into great detail, a simplified example can be used for illustration.

Consider the design of a 144-MHz repeater with a 600-kHz offset. The transmitter has an RF output power of 10 W, and the receiver has a squelch sensitivity of 0.1 μV. This means there must be at least 1.9×10^{-16} W at the 52-Ω receiver-antenna terminals to detect a signal. If both the transmitter and receiver were on the same frequency, the isolation (attenuation) required between the transmitter and receiver antenna jacks to keep the transmitter from activating the receiver would be

$$\text{Isolation} = 10 \log \frac{10 \text{ W}}{1.9 \times 10^{-16} \text{ W}} = 167 \text{ dB}$$

Obviously there is no need for this much attenuation, because the repeater does not transmit and receive on the same frequency.

If the 10-W transmitter has noise 600 kHz away from the carrier frequency that is 45 dB below the carrier power, that 45 dB can be subtracted from the isolation requirement. Similarly, if the receiver can detect a 0.1 μV on-frequency signal in the presence of a signal 600 kHz away that is 40 dB greater than 0.1 μV, this 40 dB can also be subtracted from the isolation requirement. Therefore, the isolation requirement is

167 dB – 45 dB – 40 dB = 82 dB

Other factors enter into the isolation requirements as well. For example, if the transmitter power is increased by 10 dB (from 10 to 100 W), this 10 dB must be added to the isolation requirement. Typical requirements for 144- and 440-MHz repeaters are shown in **Figure 18.12**.

Obtaining the required isolation is the first problem to be considered in constructing a repeater antenna system. There are three common ways to obtain this isolation:

1) Physically separate the receiving and transmitting antennas so the combination of path loss for the spacing and the antenna radiation patterns results in the required isolation.

2) Use a combination of separate antennas and high-Q filters to develop the required isolation. (The high-Q filters serve to reduce the physical distance required between antennas.)

3) Use a combination filter and combiner system to allow the transmitter and receiver to share one antenna. Such a filter and combiner is called a *duplexer*.

Repeaters operating on 28 and 50 MHz generally use separate antennas to obtain the required isolation. This is largely because duplexers in this frequency range are both large and very expensive. It is generally less expensive to buy two antennas and link the sites by a committed phone line or an RF link than to purchase a duplexer. At 144 MHz and higher, duplexers are more commonly used. Duplexers are discussed in greater detail in a later section.

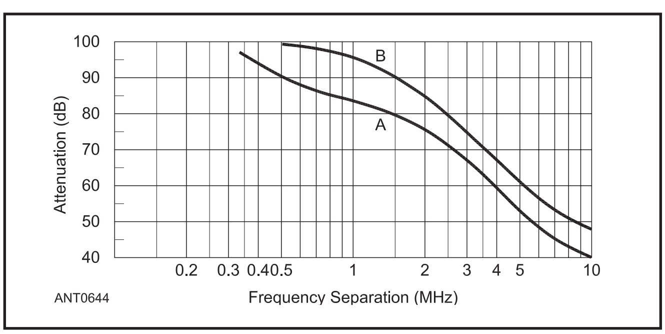

Figure 18.12 — Typical isolation requirements for repeater transmitters and receivers operating in the 132-174 MHz band (Curve A), and the 400-512 MHz band (Curve B). Required isolation in dB is plotted against frequency separation in MHz. These curves were developed for a 100-W transmitter. For other power levels, the isolation requirements will differ by the change in decibels relative to 100 W. Isolation requirements will vary with receiver sensitivity. (The values plotted were calculated for transmitter-carrier and receiver-noise suppression necessary to prevent more than 1 dB degradation in receiver 12-dB SINAD sensitivity.)

18.2.4 ISOLATION BY SEPARATE ANTENNAS

Receiver *desensing or de-sense* (gain reduction caused by the presence of a strong off-frequency signal) can be reduced and often eliminated by separation of the transmitting and receiving antennas. Obtaining the full 55 to 90 dB of isolation required for a repeater requires the separate antennas to be spaced a considerable distance apart (in wavelengths). (Separate antennas are not a solution for wide-band noise generated in the transmitter on the receive frequency. That noise must be removed with filters.)

Figure 18.13 shows the distances required to obtain specific values of isolation for vertical dipoles having horizontal separation (at A) and vertical separation (at B). The isolation gained by using separate antennas is subtracted from the total isolation requirement of the system. For example, if the transmitter and receiver antennas for a 450-MHz repeater are separated horizontally by 400 feet, the total isolation requirement in the system is reduced by about 64 dB.

Note from Figure 18.13B that a vertical separation of only about 25 feet also provides 64 dB of isolation. Vertical separation yields much more isolation than horizontal separation. Vertical separation is also more practical than horizontal, since only a single support is required.

An explanation of the significant difference between the two graphs is in order. The vertical spacing requirement for

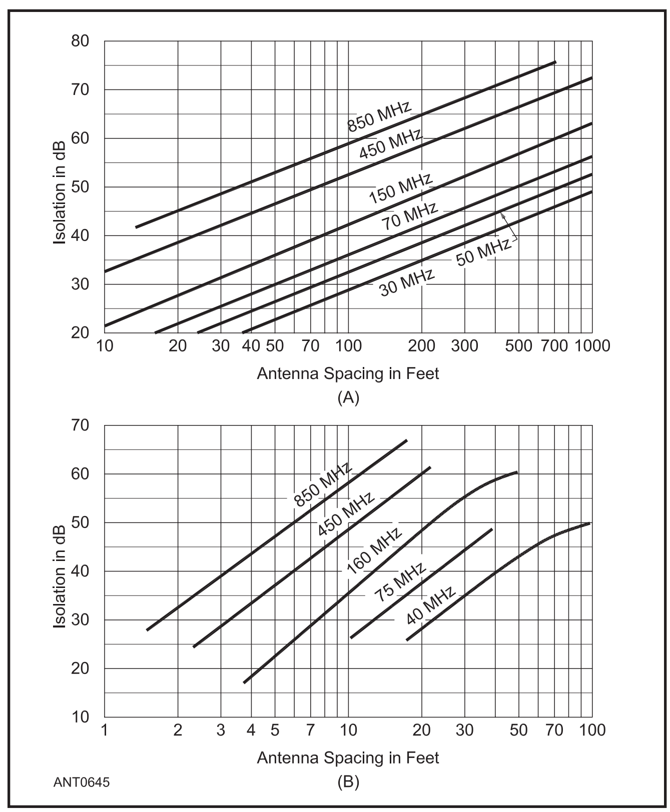

Figure 18.13 — At A, the amount of attenuation (isolation) provided by horizontal separation of vertical dipole antennas. At B, isolation afforded by vertical separation of vertical dipoles.

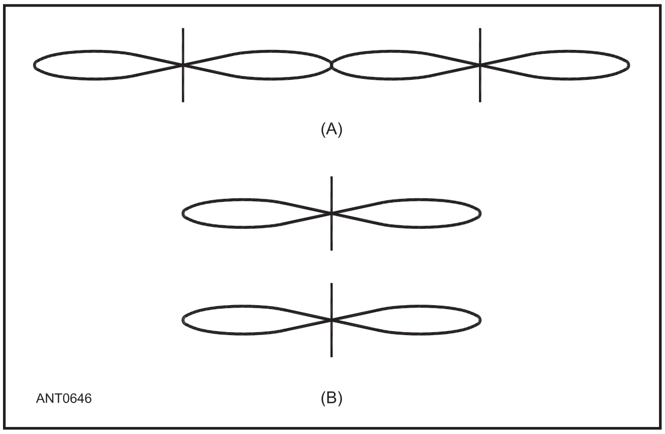

Figure 18.14 — A relative representation of the isolation advantage afforded by separating antennas horizontally (A) and vertically (B) is shown. A great deal of isolation is provided by vertical separation, but horizontal separation requires two supports and much greater distance to be as effective. Separate-site repeaters (those with transmitter and receiver at different locations) benefit much more from horizontal separation than do single-site installations.

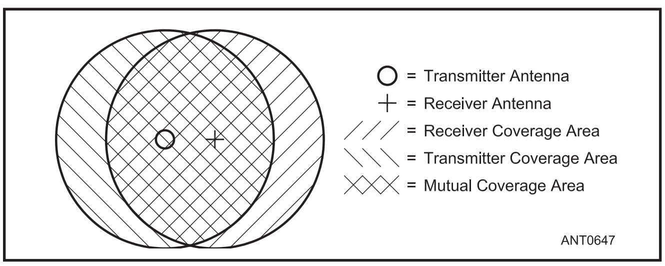

Figure 18.15 — Coverage disparity is a major problem for separate-site repeater antennas. The transmitter and receiver coverage areas overlap, but are not entirely mutually inclusive. Solving this problem requires a great deal of experimentation, as many factors are involved. Among these factors are terrain features and distortion of the antenna radiation patterns from supports.

60 dB attenuation (isolation) at 150 MHz is about 43 feet. The horizontal spacing for the same isolation level is on the order of 700 feet. **Figure 18.14** shows why this difference exists. The radiation patterns of the antennas at A overlap; each antenna has gain in the direction of the other. The path loss between the antennas is given by

$$\text{Path loss(dB)} = 20 \log \left(\frac{4 \pi d}{\lambda} \right)$$

where

d = distance between antennas

λ = wavelength, in the same units as d.

The isolation between the antennas in Figure 18.14A is the path loss less the antenna gains. Conversely, the antennas at B share pattern nulls, so the isolation is the path loss added to the depth of these nulls. This significantly reduces the spacing requirement for vertical separation. Because the depth of the pattern nulls is not infinite, some spacing is required. Combined horizontal and vertical spacing is much more difficult to quantify because the results are dependent on both radiation patterns and the positions of the antennas relative to each other.

Figure 18.16 — A coaxial cavity filter of the type used in many amateur and commercial repeater installations. Center-conductor length (and thus resonant frequency) is varied by adjustment of the knob (top).

Separate antennas have one major disadvantage: They create disparity in transmitter and receiver coverage. For example, say a 50-MHz repeater is installed over average terrain with the transmitter and repeater separated by 2 miles. If both antennas had perfect omnidirectional coverage, the situation depicted in **Figure 18.15** would exist. In this case, stations able to hear the repeater may not be able to access it, and vice versa. In practice, the situation can be considerably worse. This is especially true if the patterns of both antennas are not omnidirectional. If this disparity in coverage cannot be tolerated, the solution involves skewing the patterns of the antennas until their coverage areas are essentially the same.

18.2.5 ISOLATION BY CAVITY RESONATORS

As just discussed, receiver desensing can be reduced by separating the transmitter and receiver antennas. But the amount of transmitted energy that reaches the receiver input must often be decreased even farther. Other nearby transmitters can cause desensing as well. A *cavity resonator* (cavity filter) can be helpful in solving these problems. When properly designed and constructed, this type of resonator has very high Q. A commercially made cavity is shown in **Figure 18.16**.

A cavity resonator placed in series with a transmission line acts as a band-pass filter. For a resonator to operate in series, it must have input and output coupling loops (or probes). A cavity resonator can also be connected across (in parallel with) a transmission line. The cavity then acts as a band-reject (notch) filter, greatly attenuating energy at the frequency to which it is tuned. Only one coupling loop or probe is required for this method of filtering. This type of cavity could be used in the receiver line to "notch" the transmitter signal. Several cavities can be connected in series or parallel to increase the attenuation in a given configuration. The graphs of **Figure 18.17** show the attenuation of a single cavity (A) and a pair of cavities (B).

The only situation in which cavity filters would not help is the case where the off-frequency noise of the transmitter was right on the receiver frequency. With cavity resonators, an important point to remember is that addition of a cavity

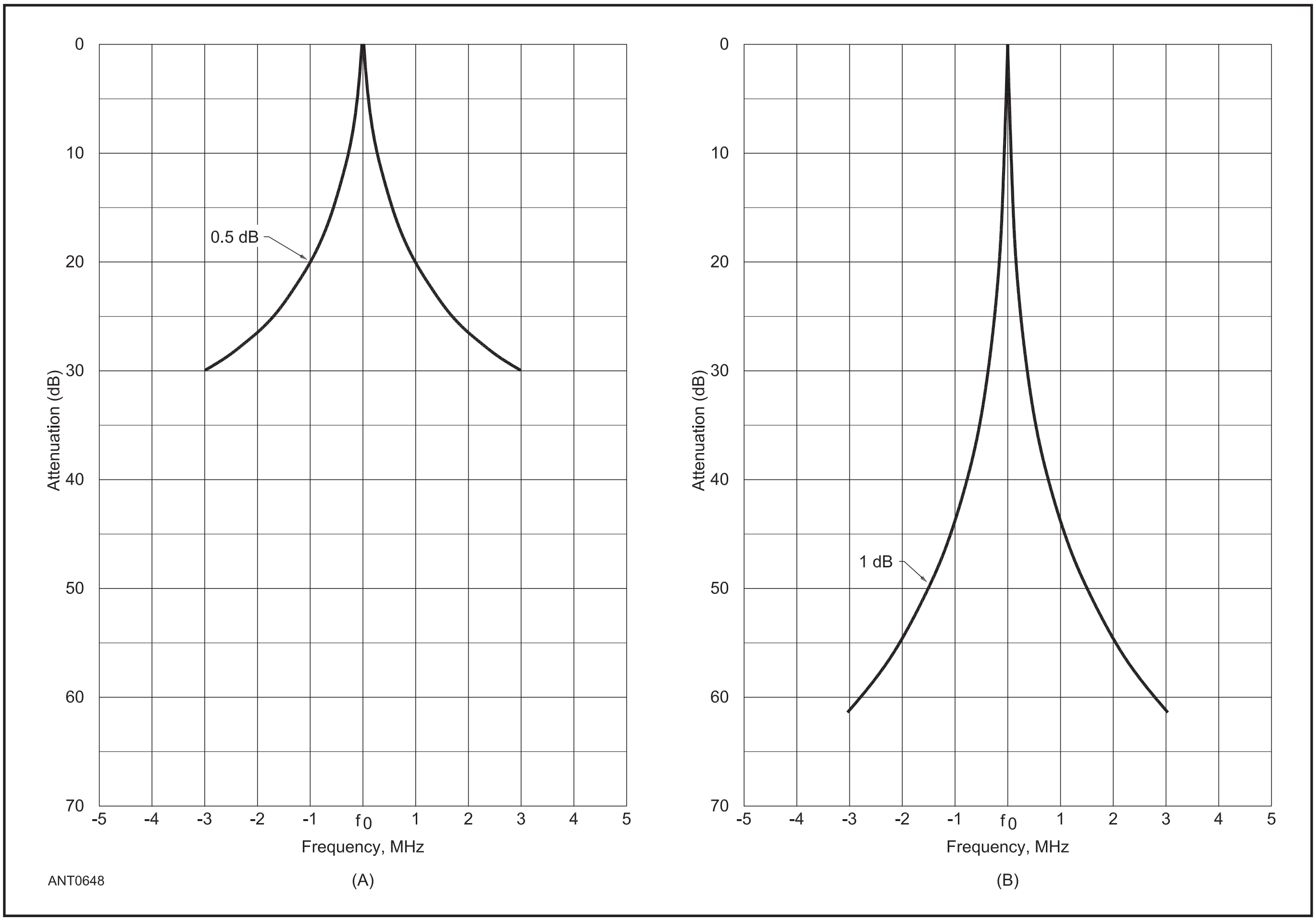

Figure 18.17 — Frequency response curves for a single cavity (A) and two cavities cascaded (B). These curves are for cavities with coupling loops, each having an insertion loss of 0.5 dB. (The total insertion loss is indicated in the body of each graph.) Selectivity will be greater if lighter coupling (greater insertion loss) can be tolerated.

across a transmission line may change the impedance of the system. This change can be compensated by adding tuning stubs along the transmission line.

18.2.6 ISOLATION BY DUPLEXERS

Most amateur repeaters in the 144-, 222- and 440-MHz bands use duplexers to obtain the necessary transmitter to receiver isolation. (Duplexers for 50 MHz systems are quite large and impractical at lower frequencies.) Duplexers have been commonly used in commercial repeaters for many years. The duplexer consists of two high-Q filters. One filter is used in the feed line from the transmitter to the antenna, and another between the antenna and the receiver. These filters must have low loss at the frequency to which they are tuned while having very high attenuation at the surrounding frequencies. To meet the high attenuation requirements at frequencies within as little as 0.4% of the frequency to which they are tuned, the filters usually take the form of cascaded transmission-line cavity filters. These are either band-pass filters, or band-pass filters with a rejection notch. (The rejection notch is tuned to the center frequency of the other filter.) The number of cascaded filter sections is determined by the frequency separation and the ultimate attenuation requirements.

Duplexers for the amateur bands represent a significant technical challenge, because in most cases amateur repeaters operate with significantly less frequency separation than their commercial counterparts. Many manufacturers market high-quality duplexers for the amateur frequencies.

Experience with modern receivers and transmitters used in commercial two-way service enables the successful use of four-cavity duplexers. Four-cavity duplexers should be

Duplexer or Diplexer?

Hams use these terms casually, often not realizing they refer to different functions. From the Amateur Radio perspective, a *duplexer* allows a transmitter and receiver operating on the same band to share a common antenna. Repeaters use duplexers. A *diplexer* allows multiple radios operating on different bands to share a common antenna. A diplexer would be used to allow a VHF and a UHF radio to share the same multiband antenna.

capable of isolation in the high 70 dB range. Today's commercial transceivers are very low in spurious products. Receiving sections are quite insensitive to off frequency signals. This results in repeater performance only dreamt of in the early days. Ease of alignment and low cost greatly ease the process of modern repeater installation.

Duplexers consist of very high-Q cavities whose resonant frequencies are determined by mechanical components, in particular the tuning rod. **Figure 18.18** shows the cutaway view of a typical duplexer cavity. A construction project for 144 MHz duplexer cavities is included on the CD-ROM included with this book.

The rod is usually made of a material that has a limited thermal expansion coefficient (such as Invar). Detuning of the cavity by environmental changes introduces unwanted losses in the antenna system. An article by Arnold in *Mobile Radio Technology* considered the causes of drift in the cavity (see the Bibliography). These can be divided into four major categories.

1) Ambient temperature variation (which leads to mechanical variations related to the thermal expansion coefficients of the materials used in the cavity).

2) Humidity (dielectric constant) variation.

3) Localized heating from the power dissipated in the cavity (resulting from its insertion loss).

4) Mechanical variations resulting from other factors (vibration, etc).

In addition, because of the high-Q nature of these cavities, the insertion loss of the duplexer increases when the signal is not at the peak of the filter response. This means, in practical terms, that less power is radiated for a given transmitter output power. Also, the drift in cavities in the receiver line results in increased system noise figure, reducing the sensitivity of the repeater.

As the frequency separation between the receiver and the transmitter decreases, the insertion loss of the duplexer reaches certain practical limits. At 144 MHz, the minimum insertion loss for 600 kHz spacing is 1.5 dB per filter.

Testing and using duplexers requires some special considerations (especially as frequency increases). Because duplexers are very high-Q devices, they are very sensitive to the termination impedances at their ports. A high SWR on any port is a serious problem because the apparent insertion loss of the duplexer will increase and the isolation may appear to decrease. Some have found that when duplexers are used at the limits of their isolation capabilities, a small change in antenna SWR is enough to cause receiver desensitization. This occurs most often under ice-loading conditions on antennas with open-wire phasing sections.

The choice of connectors in the duplexer system is important. BNC connectors are good for use below 300 MHz. Above 300 MHz their use is discouraged because even though many types of BNC connectors work well up to 1 GHz, older style standard BNC connectors are inadequate at UHF and above. Type N connectors should be used above 300 MHz. It is false economy to use marginal quality connectors. Some commercial users have reported deteriorated isolation in commercial UHF repeaters when using such connectors. Determining the location of a bad connector in a system is a complicated and frustrating process. Despite all these considerations, the duplexer is still the best method for obtaining isolation in the 144- to 925-MHz range.

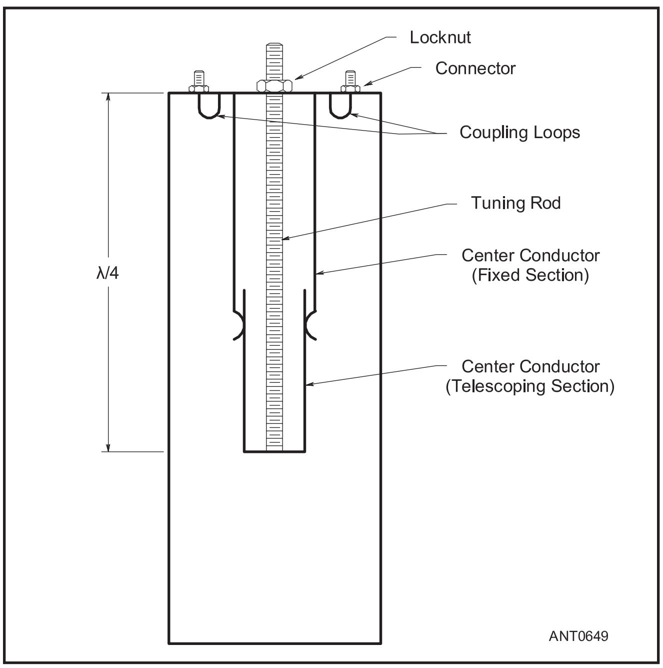

Figure 18.18 — Cutaway view of a typical cavity. Note the relative locations of the coupling loops to each other and to the center conductor of the cavity. A locknut is used to prevent movement of the tuning rod after adjustment.

18.3 ADVANCED TECHNIQUES

As the number of available antenna sites decreases and the cost of various peripheral items (such as coaxial cable) increases, amateur repeater groups are required to devise advanced techniques if repeaters are to remain effective. Some of the techniques discussed here have been applied in commercial services for many years, but until recently have not been economically justified for amateur use.

18.3.1 COUPLERS

One technique worth consideration is the use of *cross-band couplers*. To illustrate a situation where a cross-band coupler would be useful, consider the following example. A repeater group plans to install 144- and 902-MHz repeaters on the same tower. The group intends to erect both antennas on a horizontal cross arm at the 325-foot level. A 325-foot run of ⅞-inch Heliax costs several thousand dollars. If both antennas are to be mounted at the top of the tower, the logical approach would require two separate feed lines. A better solution involves the use of a single feed line for both repeaters, along with a cross-band coupler at each end of the line.

The use of the cross-band coupler is shown in **Figure 18.19.** As the term implies, the coupler allows two signals on different bands to share a common transmission line. Such couplers cost approximately $300 each. In our hypothetical example, this represents a significant saving over the cost of using separate feed lines. But, as with all compromises, there are disadvantages. Cross-band couplers have a loss of about 0.5 dB per unit. Therefore, the pair required represents a loss of 1.0 dB in *each* transmission path. If this loss can be tolerated, the cross-band coupler is a good solution.

Cross-band couplers do not allow two repeaters *on the same band* to share a single antenna and feed line. As repeater sites and tower space become scarcer, it may be desirable to have two repeaters on the same band share the same antenna. The solution to this problem is the use of a *transmitter multicoupler*. The multicoupler is related to the duplexers discussed earlier. It is a cavity filter and combiner that allows multiple transmitters and receivers to share the same antenna. This is a common commercial practice. A block diagram of a multicoupler system is shown in **Figure 18.20**.

The multicoupler, however, is a very expensive device, and has the disadvantage of even greater loss per transmission path than the standard duplexer. For example, a well-designed duplexer for 600 kHz spacing at 146 MHz has a loss per transmission path of approximately 1.5 dB. A four-channel multicoupler (the requirement for two repeaters) has an insertion loss per transmission path on the order of 2.5 dB or more. Another constraint of such a system is that the antenna must present a good match to the transmission line at all frequencies on which it will be used (both transmitting and receiving). This becomes difficult for the system with two repeaters operating at opposite ends of a band.

If you elect to purchase a commercial base-station

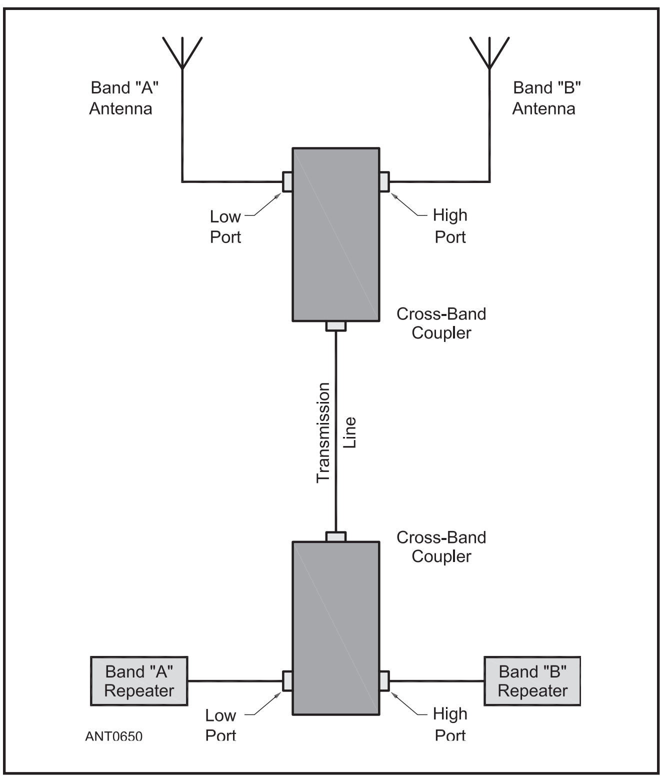

Figure 18.19 — Block diagram of a system using cross-band couplers to allow the use of a single feed line for two repeaters. If the feeder to the antenna location is long (more than 200 feet or so), cross-band couplers may provide a significant saving over separate feed lines, especially at the higher amateur repeater frequencies. Cross-band couplers cannot be used with two repeaters on the same band.

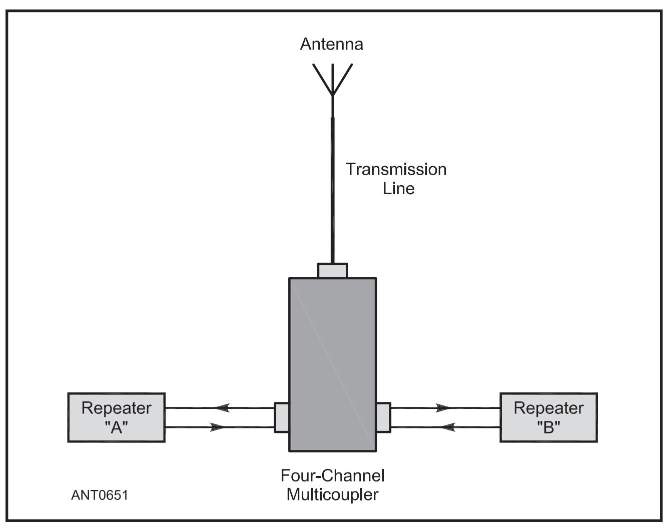

Figure 18.20 — Block diagram of a system using a transmitter multicoupler to allow a single feed line and antenna to be used by two repeaters on one band. The antenna must be designed to operate at all frequencies that the repeaters utilize. More than two repeaters can be operated this way by using a multicoupler with the appropriate number of input ports.

antenna that requires you to specify a frequency to which the antenna must be tuned, be sure to indicate to the manufacturer the intended use of the antenna and the frequency extremes. In some cases, the only way the manufacturer can accommodate your request is to provide an antenna with some vertical-beam uptilt at one end of the band and some downtilt at the other end of the band. In the case of antennas with very high gain, this in itself may become a serious problem. Careful analysis of the situation is necessary before assembling such a system.

18.3.2 DIVERSITY TECHNIQUES FOR REPEATERS

Mobile flutter, "dead spots" and similar problems are a real problem for the mobile operator. The popularity of handheld transceivers using low power and mediocre antennas causes similar problems. A solution to these difficulties is the use of some form of *diversity reception*. Diversity reception works because signals do not fade at the same rate when received by antennas at different locations (space diversity) or of different polarizations (polarization diversity).

Repeaters with large transmitter coverage areas often have difficulty "hearing" low power stations in peripheral areas or in dead spots. Space diversity is especially useful in such a situation. Space diversity utilizes separate receivers at different locations that are linked to the repeater. The repeater uses a circuit called a *voter* that determines which receiver has the best signal, and then selects the appropriate receiver from which to feed the repeater transmitter. This technique is helpful in urban areas where shadowing from large buildings and bridges causes problems. Space-diversity receiving, when properly executed, can give excellent results. But with the improvement come some disadvantages: added initial cost, maintenance costs, and the possibility of failure created by the extra equipment required. If installed and maintained carefully, problems are generally minimal.

A second improvement technique is the use of *circularly polarized* repeater antennas. This technique has been used in the FM broadcast field for many years, and has been considered for use in the mobile telephone service as well. Some experiments by amateurs have proved very promising, as discussed by Pasternak and Morris (see the Bibliography).

The improvement afforded by circular polarization is primarily a reduction in *mobile flutter*. The flutter on a mobile signal is caused by reflections from large buildings (in urban settings) or other terrain features. These reflections cause measurable polarization shifts, sometimes to the point where a vertically polarized signal at the transmitting site may appear to be primarily horizontally polarized after reflection.

A similar situation results from *multipath propagation*, where one or more reflected signals combine with the direct signal at the repeater to create varying effects on the signal. The multipath signal is subjected to large amplitude and phase variations at a relatively rapid rate.

In both of the situations described here, circular polarization can offer considerable improvement. This is because circularly polarized antennas respond equally to all linearly polarized signals, regardless of the plane of polarization. At this writing, there are no known sources of commercial circularly polarized omnidirectional antennas for the amateur bands. Pasternak and Morris describe a circularly polarized antenna made by modifying two commercial four-pole arrays.

18.4 DETERMINING EFFECTIVE ISOTROPIC RADIATED POWER (EIRP)

It is useful to know effective isotropic radiated power (EIRP) in calculating the coverage area of a repeater. The FCC formerly required EIRP to be entered in the log of every amateur repeater station. Although logging EIRP is no longer required, it is still useful to have this information on hand for repeater-coordination purposes and so system performance can be monitored periodically.

Calculation of EIRP is straightforward. The PEP output of the transmitter is simply multiplied by the gains and losses in the transmitting antenna system. (These gains and losses are best added or subtracted in decibels and then converted to a multiplying factor.) The following worksheet and example illustrate the calculations.

Transmitter power output (TPO)	__________W (PEP)
Feed line loss	__________ dB
Misc connecting cable loss	__________ dB
Duplexer loss	__________ dB
Isolator loss	__________ dB
Cross-band coupler loss	__________ dB
Cavity filter loss	__________ dB
Other loss	__________ dB
Total Losses (L)	__________ dB

G (dB) = antenna gain (dBi) – Total Losses (L)

where G = antenna system gain. (If antenna gain is specified in dBd, add 2.14 dB to obtain the gain in dBi.)

$M = 10^{G/10}$

where M = multiplying factor

EIRP (watts) = transmitter output (TPO) × M

Example

A repeater transmitter has a power output of 50 W PEP (50 W FM transmitter). The transmission line has a total loss of 1.8 dB. The duplexer used has a loss of 1.5 dB, and a circulator on the transmitter port has a loss of 0.3 dB. There are no cavity filters or cross-band couplers in the system. Antenna gain is 5.6 dBi.

Feed line loss	1.8 dB
Duplexer loss	1.5 dB
Isolator loss	0.3 dB
Cross-band coupler loss	0 dB
Cavity filter loss	0 dB
Total Losses (L)	3.6 dB

Antenna system gain in dB = G = antenna gain (dBi) – L

G = 5.6 dBi – 3.6 dB = 2 dB

Multiplying factor = $M = 10^{G/10}$

$M = 10^{2/10} = 1.585$

EIRP (watts) = transmitter output (TPO) × M

EIRP = 50 W × 1.585 = 79.25 W

If the antenna system is lossier than this example, G may be *negative*, resulting in a multiplying factor less than one. The result is an EIRP that is less than the transmitter output power. This situation can occur in practice, but for obvious reasons is not desirable.

18.5 ASSEMBLING A REPEATER ANTENNA SYSTEM

This section will aid you in planning and assembling your repeater antenna system. First, a repeater antenna selection checklist such as this will help you in evaluating the antenna system for your needs.

Gain needed	________	dBi
Pattern required	________	Omnidirectional
	________	Offset
	________	Cardioid
	________	Bidirectional
	________	Special pattern (specify)
Mounting	________	Top of tower
	________	Side of tower

(Determine effects of tower on pattern. Is the result consistent with the pattern required?)

Is downtilt required?	________	Yes
	________	No
Type of RF connector	________	UHF
	________	N
	________	BNC
	________	Other (specify)
Size (length)	________	
Weight	________	
Maximum cost	$________	

Commercial components are available for repeater and remote-base antenna systems from companies such as Celwave/RFS, Decibel Products (Andrew Corp), Sinclair Radio Laboratories Inc, TX/RX Systems Inc and Telewave Systems. Even though almost any antenna can be used for a repeater, heavy-duty antennas built to commercial standards are recommended for repeater service. Some companies offer their antennas with special features for repeater service (such as vertical-beam downtilt). It is best to review the print or online catalogs of current products from the manufacturers, both for general information and to determine which special options are available on their products. See the Resources for Repeater Builders section later in this chapter.

18.5.1 FREQUENCY COORDINATION

In order for a repeater system to be accepted by the regional frequency coordinator, the precise location of the repeater antenna system and its power output must be supplied. A typical list of data follows:

1) Latitude and longitude using the NAD27 continental US database

2) Antenna structure FAA registration number, if any

3) Antenna structure ground elevation

4) Antenna height above ground (the center of the radiating portion of the antenna)

5) Height Above Average Terrain (HAAT — see below)

6) Effective Isotropic Radiated Power (EIRP — see above)

7) Mounting and pattern of the antenna — omnidirectional, cardioid, elliptical, or bidirectional

8) Whether the antenna is top or side mounted and the favored and shadowed directions

9) Antenna beamwidth and front-to-back ratio, if applicable

10) Antenna polarization: vertical, horizontal, or circular/elliptical

Most of this information is easily obtained from the equipment specifications and antenna mounting plans.

Height Above Average Terrain or HAAT can be determined manually from topographic maps as explained on most frequency coordination websites. However, with online databases HAAT can be determined automatically. You will need the precise latitude and longitude of your antenna from a GPS receiver or from an online website such as **itouchmap.com/latlong.html**. The online FCC HAAT calculator is located at **www.fcc.gov/encyclopedia/antenna-height-above-average-terrain-haat-calculator.**

Enter your site data and the calculator will then report your HAAT. (RCAMSL is the sum of the antenna mounting structure's base elevation and the height to the radiating center of the antenna.) It can also produce a file that provides the required data from each of your specified radials. The following example is the calculator's output text for a repeater antenna located in St Charles, MO with a base at 180 meters of elevation and a supporting tower 50 meters high. HAAT was given as 85 meters and the following table reports average elevation along eight equally-spaced radials as required by most coordinators.

```
| 38 | 46 | 56.00 | N | 90 | 30 | 22.00 | W |
| FCC/NGDC Continental USA |
|  0.0 |  98.2 |
| 45.0 |  99.3 |
| 90.0 |  81.5 |
| 135.0 |  66.7 |
| 180.0 |  88.4 |
| 225.0 |  72.7 |
| 270.0 |  77.6 |
| 315.0 |  97.3 |
```

18.5.2 RESOURCES FOR REPEATER BUILDERS

Repeater building is a very popular activity and there are significant online resources for the repeater builder. For example, the Repeater Builder website (**www.repeater-builder.com**) has extensive archives of material on everything from the power supply to the antenna. An associated email reflector list is available at **groups.yahoo.com/group/Repeater-Builder.**

Most of the local and regional frequency coordinators also maintain their own websites that offer support to repeater operators. For example, the Area Repeater Coordination Council for Eastern Pennsylvania and Southern New Jersey (**www.arcc-inc.org**) supplies worksheets and other resources for determining repeater performance information.

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