Chapter 19

Antenna Systems for Space Communications

When we consider amateur space communications, we usually think about two basic modes: satellite and earth-moon-earth (EME—also referred to as *moonbounce*). At their essence, both modes communicate using one of the Earth's satellites—our natural satellite (the Moon) or one of a variety of manmade satellites.

There are two main differences between these satellites. The first is one of distance. The Moon is about 250,000 miles from Earth, while man-made satellites can be as far as 36,000 miles away. This 7:1 difference in distance makes a huge difference in the signals that arrive at the satellite, since transmission loss varies as the square of the distance. In other words, the signal arriving at the Moon is 20 dB weaker than that arriving at a geo-synchronous satellite 25,000 miles high, due to distance alone.

The second difference between the Moon and a man-made satellite is that the Moon is a *passive reflector*—and not a very good one at that, since it has a craggy and rather irregular surface, at least when compared to a flat mirror-like surface that would make an ideal reflector. Signals scattered by the Moon's irregular surface are thus weaker than for better reflecting surfaces. By comparison, a man-made satellite is an *active* system, where the satellite receives the signal coming from Earth, amplifies it and then retransmits the signal (usually at a different frequency) using a high-gain antenna. Think of a satellite as an ideal reflector, with gain.

The net result of these differences between a man-made satellite and the Earth's natural satellite is that moonbounce (EME) operation challenges the station builder considerably more than satellite operation, particularly in the area of antennas. Successful EME requires high transmitting power, superb receiver sensitivity and excellent operators capable of pulling weak signals out of the noise. This chapter will first explore antennas suitable for satellite operations and then describe techniques needed for EME work.

Common Ground

There are areas of commonality between satellite and EME antenna requirements, of course. Both require consideration of the effects of polarization and elevation angle, along with the azimuth directions of transmitted and received signals.

On the HF bands, signal polarization is generally of little concern, since the original polarization sense is lost after the signal passes through the ionosphere. At HF, vertical antennas receive sky-wave signals emanating from horizontal antennas, and vice versa. It is not beneficial to provide a means of varying the polarization at HF. With satellite communications, however, because of polarization changes, a signal that would disappear into the noise on one antenna may be S9 on one that is not sensitive to polarization direction. Elevation angle is also important from the standpoint of tracking and avoiding indiscriminate ground reflections that may cause nulls in signal strength.

Antennas for Satellite Work

We have amateur satellites providing links from 2 meters and up, and these provide opportunities to use antennas of many types—from the very simple to some pretty complex ones. This section was written by Dick Jansson, WD4FAB. It covers descriptions of a wide range of satellite antennas and points operators to source material for construction of many of them.

Antennas for LEO Satellites

Antenna design and construction requirements for use with Amateur satellites vary from low-gain antennas for low-earth-orbit (LEO) satellites to higher-gain antennas for the high-altitude elliptical-orbit satellites. You can operate the FM LEO satellites with a basic dual-band VHF/UHF FM transceiver or even a good FM H-T, as some amateurs have managed. Assuming that the transceiver is reasonably sensitive, you can even use a good "rubber duck" antenna. Some amateurs manage to work the FM birds with H-Ts and a multi-element directional antenna such as the popular Arrow Antenna, **Fig 1**. Of course, this means they must aim their antennas at the satellites, even as they cross overhead.

High-quality omnidirectional antennas for LEO service come in quite a number of forms and shapes. M^2 Enterprises has their EB-144 and EB-432 Eggbeater antennas, which have proven to be very useful and do not require any rotators for control. See **Fig 2**. The turnstile-over-reflector antenna has been around for a long time, as shown in **Fig 3**. Other operators have done well using low-gain Yagi antennas, such as those shown in **Fig 4**.

For even better performance, at the modest cost of a single, simple TV antenna rotator, check out the fixed-elevation *Texas Potato Masher* antenna by K5OE, **Fig 5.** This antenna provides a dual-band solution for medium-gain directional antennas for LEO satellites. This is a considerable improvement over omnidirectional antennas and does not require an elevation rotator for good performance.

There are still two LEO satellites that work on the 10-meter band, RS-15 and the newly resurrected AO-7. Both have 10-meter downlinks in the range of 29.3 to 29.5 MHz. Low-gain 10-meter antennas, such as dipoles or long-wire antennas, are used to receive these satellites.

Antennas for High-Altitude Satellites

The high-altitude, Phase-3 satellites, such as AO-10 (and the late AO-13), have been around for quite a number of years. The greater distances to the Phase-3 satellites mean that more transmitted power is needed to access them and weaker signals are received on the ground. Successful stations usually require ground-station antennas with significant gain (12 dBi or more), such as a set of high-gain Yagi antennas. See **Fig 6**. Note the use of two Yagi antennas mounted on each boom to provide *circular polarization*, usually referred to as CP.

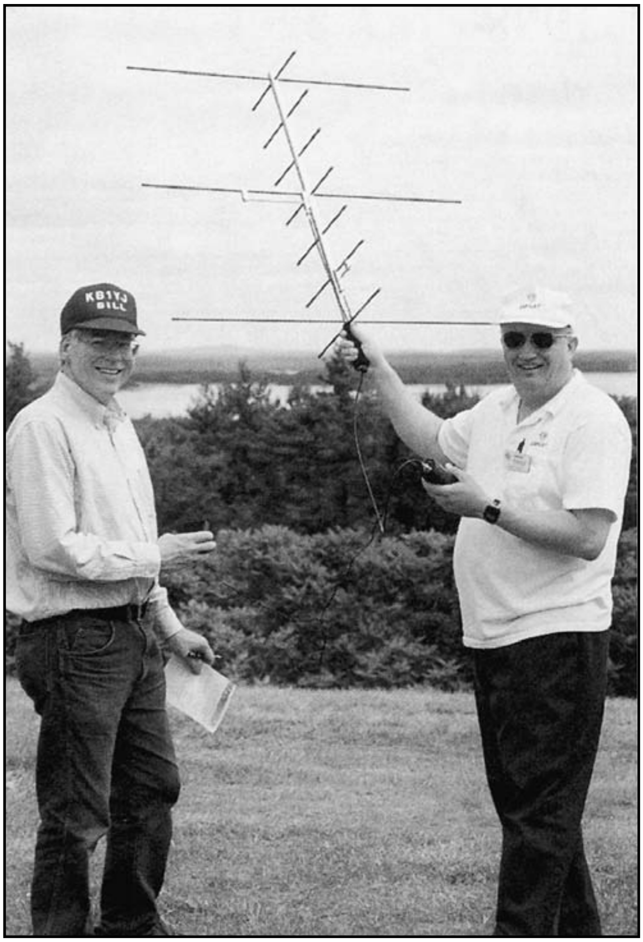


Fig 1—The hand-held "Arrow" gain antenna is popular for LEO FM operations. (*Photo courtesy* The AMSAT Journal, *Sept/Oct 1998.*)

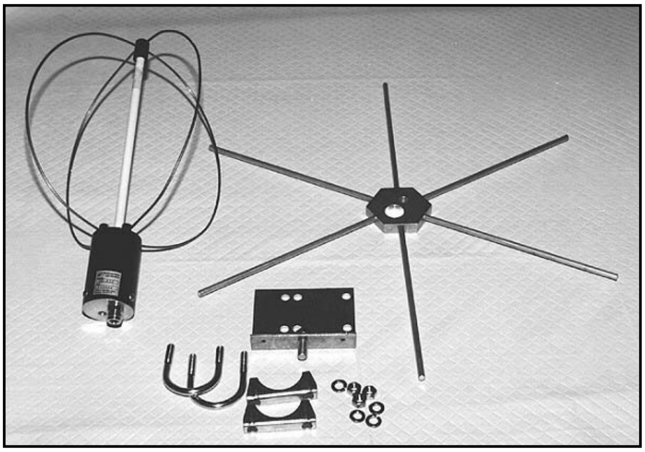


Fig 2—Eggbeater antennas are popular for base station LEO satellite operations. This EB-432 eggbeater antenna for 70 cm is small enough to put in an attic. Antenna gain pattern is helped with the radials placed below the antenna.

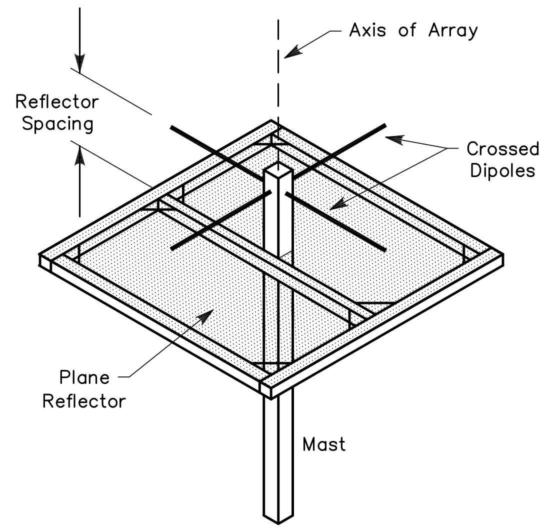


Fig 3—The Turnstile Over Reflector antenna has served well for LEO satellite service for a number of years.

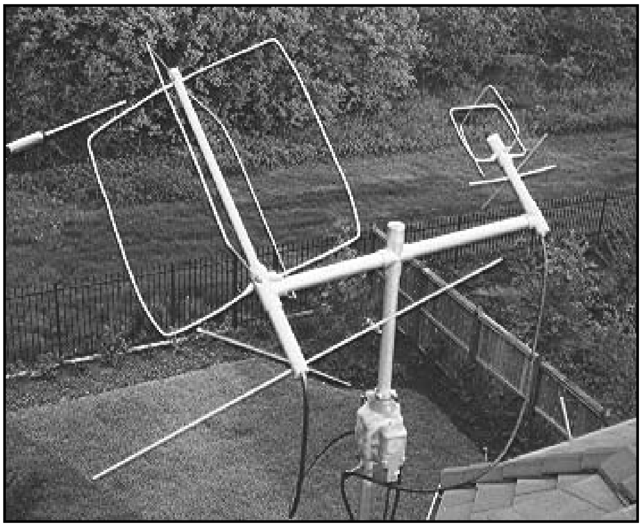


Fig 5—Jerry Brown, K5OE, uses his Texas Potato Masher antennas to work LEO satellites.

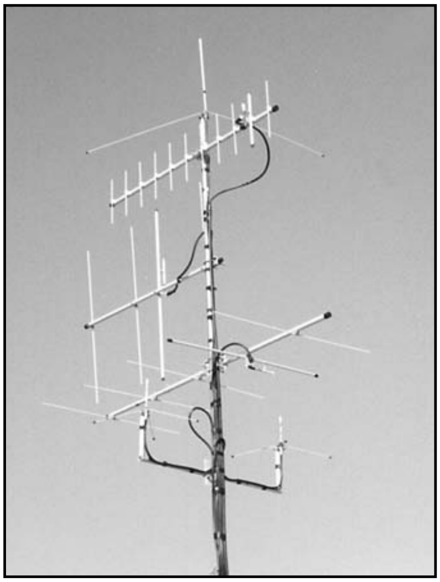


Fig 4—Simple ground plane and Yagi antennas can be used for LEO satellite contacts.

Fig 6—Dick Jansson, WD4FAB, used these 2-meter and 70-cm crossed Yagi's in RHCP for AO-10 and AO-13 operations. The satellite antennas are shown mounted above a 6-meter long-boom Yagi.

CIRCULAR POLARIZATION

Linearly polarized antennas are horizontal or vertical in terms of the antenna's position relative to the surface of the Earth, a reference that loses its meaning in space. The need to use circularly polarized (CP) antennas for space communications is well established. If spacecraft antennas used linear polarization, ground stations would not be able to maintain polarization alignment with the spacecraft because of changing orientations. The ideal antenna for random satellite polarizations is one with a circularly polarized radiation pattern.

There are two commonly used methods for obtaining circular polarization. One is with crossed linear elements such as dipoles or Yagis, as Fig 6 shows. The second popular CP method uses a helical antenna, described below. Other methods also exist, such as with the omnidirectional quadrifilar helix, **Fig 7**.

Polarization *sense* is a critical factor, especially in EME and satellite work. The IEEE standard uses the term "clockwise circular polarization" for a *receding* wave. Amateur technology follows the IEEE standard, calling clockwise polarization for a receding wave as right-hand, or RHCP. Either clockwise or a counter-clockwise (LHCP) sense can be selected by reversing the phasing harness of a crossed-Yagi antenna, see **Fig 8**. The sense of a helical antenna is fixed, determined by its physical construction.

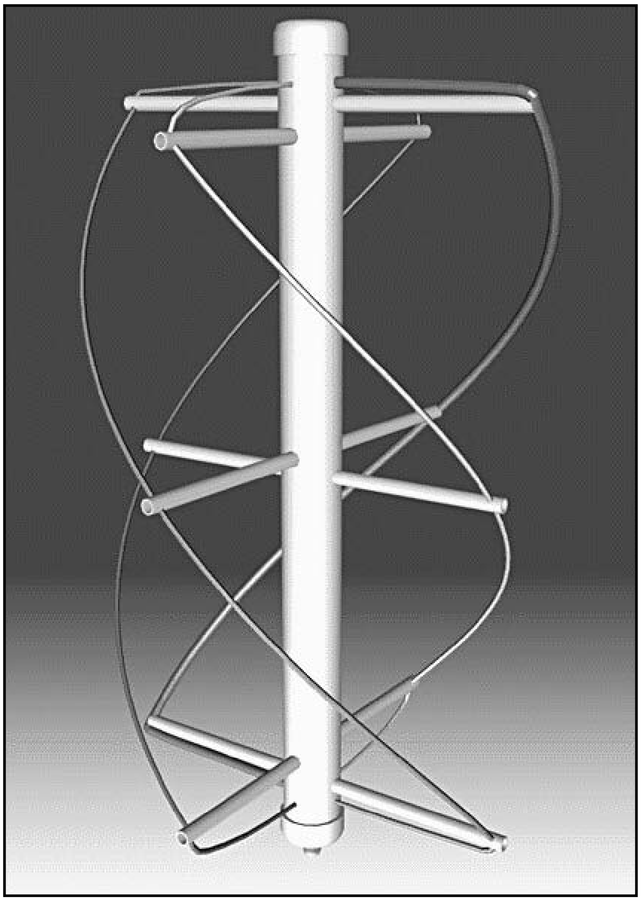


Fig 7—W3KH suggests that quadrifilar antennas can serve well for omnidirectional satellite-station antenna service.

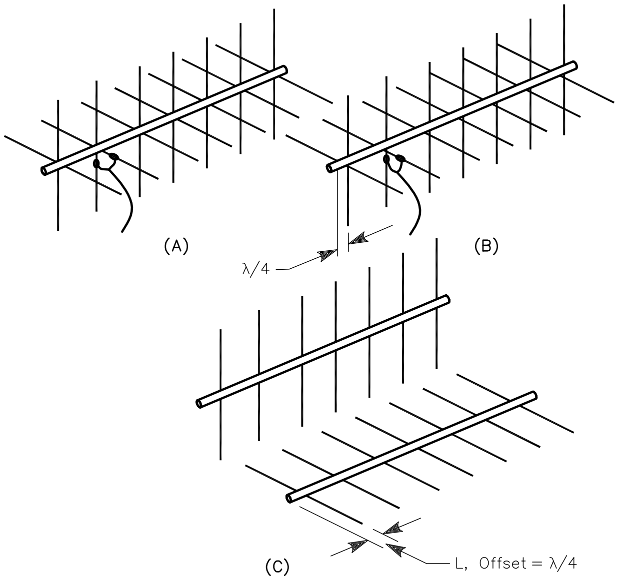


Fig 8—Evolution of the circularly polarized Yagi. The simplest form of crossed Yagi, A, is made to radiate circularly by feeding the two driven elements 90° out of phase. Antenna B has the driven elements fed in phase, but has the elements of one bay mounted $^{1}/_{4}$ λ forward from those of the other. Antenna C offers elliptical (circular) polarization using separate booms. The elements in one set are perpendicular to those of the other and are $^{1}/_{4}$ λ forward from those of the other.

See **Fig 9** for construction details.

In working through a satellite with a circularly polarized antenna, it is often convenient to have the capability of switching polarization sense. This is because the sense of the received signal of some of the LEO satellites reverses when the satellite passes its nearest point to you. If the received signal has right-hand circular polarization as the satellite approaches, it may have left-hand circularity as the satellite recedes. There is a sense reversal in EME work, as well, because of a phase reversal of the signal as it is reflected from the surface of the moon. A signal transmitted with right-hand circularity will be returned to the Earth with left-hand circularity. Similarly, the polarization is reversed as it is reflected from a dish antenna, so that for an overall RHCP performance, the feed antenna for the dish needs to be LHCP.

Crossed Linear Antennas

Dipoles radiate linearly polarized signals, and the polarization direction depends on the orientation of the antenna. It two dipoles are arranged for horizontal and vertical dipoles, and the two outputs are combined with the correct phase difference (90°), a circularly polarized wave results. Because the electric fields are identical in magnitude, the power from the transmitter will be equally divided between the two fields. Another way of looking at this is to consider the power as being divided between the two antennas; hence the gain of each is decreased by 3 dB when taken alone in the plane of its orientation.

A 90° phase shift must exist between the two antennas and the simplest way to obtain this shift is to use two feed lines to a coplanar pair of crossed-Yagi antennas. One feed-line section is $^{1}/_{4}$ λ longer than the other, as shown in Fig 8A. These separate feed lines are then paralleled to a common transmission line to the transmitter or receiver. Therein lies one of the headaches of this system. Assuming negligible coupling between the crossed antennas, the impedance presented to the common transmission line by the parallel combination is one half that of either section alone. (This is not true when there is mutual coupling between the antennas, as in phased arrays.) A practical construction method for implementing a RHCP/LHCP coplanar switched system is shown in **Fig 10**.

Another example of a coplanar crossed-Yagi antenna is shown in **Fig 11**. With this phasing-line method, any mismatch at one antenna will be magnified by the extra $^{1}/_{4}$ λ of transmission line. This upsets the current balance between the two antennas, resulting in a loss of polarization circularity. Another factor to consider is the attenuation of the cables used in the harness, along with the

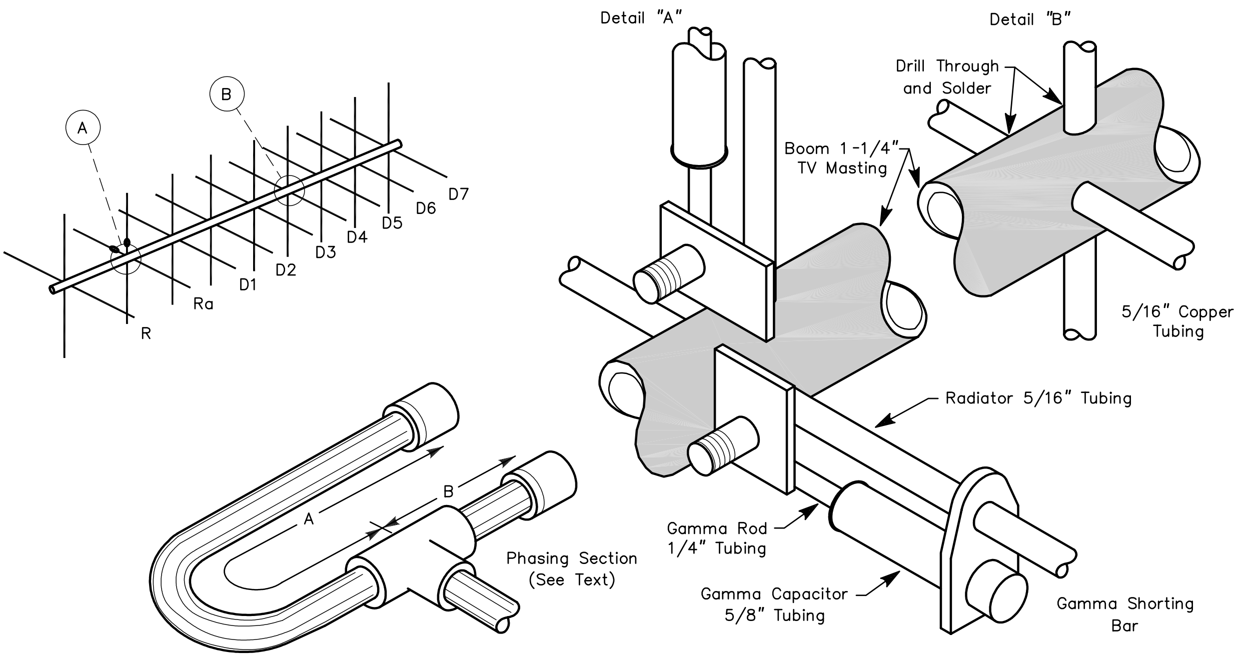


Fig 9—Construction details of a co-planar crossed-Yagi antenna.

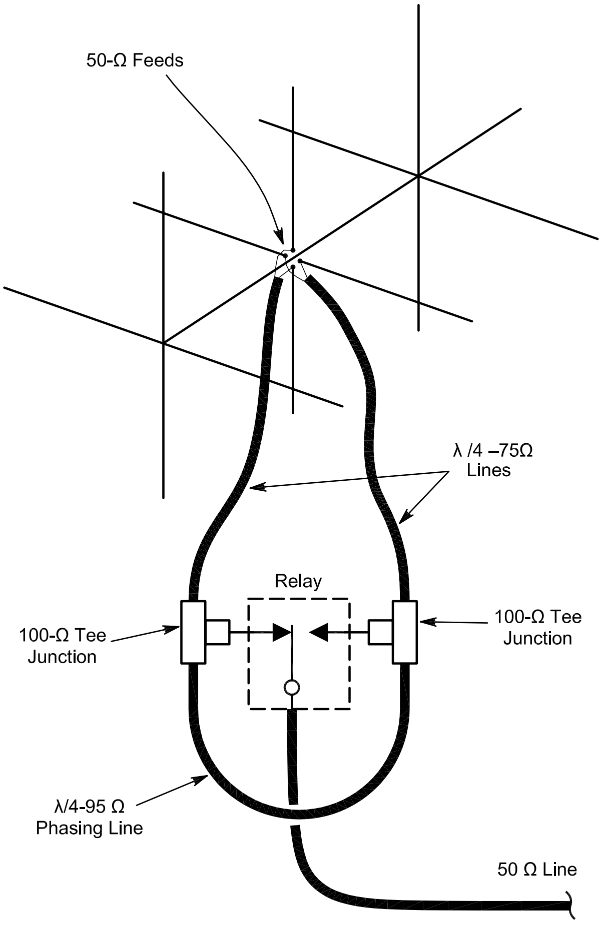


Fig 10—Co-planar crossed Yagi, circularly polarized antenna with switchable polarization phasing harness.

connectors. Good low-loss coaxial line should be used. Type-N or BNC connectors are preferable to the UHF variety.

Another method to obtain circular polarization is to use equal-length feed lines and place one antenna $^1/_4$ λ ahead of the other. This offset pair of Yagi-crossed antennas is shown in Fig 8B. The advantage of equal-length feed lines is that identical load impedances will be presented to the common feeder, as shown in **Fig 12**, which shows a fixed circularity sense feed. To obtain a switchable sense feed with the offset Yagi pair, you can use a connection like that of **Fig 13**, although you must compensate for the extra phase added by the relay and connectors.

Fig 8C diagrams a popular method of mounting two separate off-the-shelf Yagis at right angles to each other. The two Yagis may be physically offset by $^1/_4$ λ and fed in parallel, as shown in Fig 8C, or they may be mounted with no offset and fed 90° out of phase. Neither of these arrangements on two separate booms produces true circular polarization. Instead, *elliptical* polarization results from such a system. **Fig 14** is a photo of this type of mounting of Yagis on two booms for elliptical operation.

Helical Antennas

As mentioned, the second method to create a circularly polarized signal is by means of a helical antenna. The axial-mode helical antenna was introduced by Dr John Kraus, W8JK, in the 1940s. **Fig 15** shows examples of S-band (2400-MHz), V-band (145-MHz), and U-band (435-MHz) helical antennas, all constructed by WD4FAB for satellite service.

This antenna has two characteristics that make it

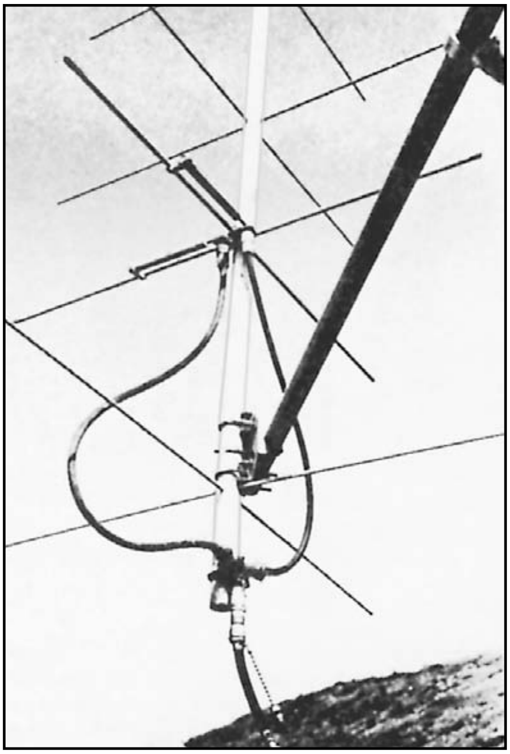


Fig 11—This VHF crossed Yagi design by KH6IJ (Jan 1973 *QST*) illustrates the co-planar, fixed-circularity Yagi.

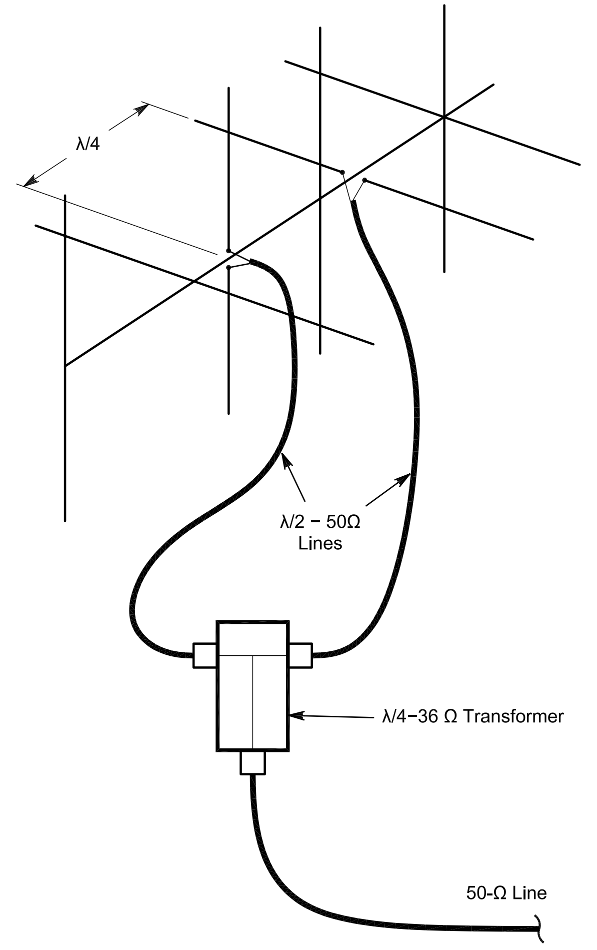


Fig 12—Offset crossed-Yagi circularly polarized antenna-phasing harness with fixed polarization.

especially interesting and useful in many applications. First, the helix is circularly polarized. As discussed earlier, circular polarization is simply linear polarization that continually rotates as it travels through space. In the case of a helical antenna, this rotation is about the axis of the antenna. This can be pictured as the second hand of a watch moving at the same rate as the applied frequency, where the position of the second hand can be thought of as the instantaneous polarization of the signal.

The second interesting property of the helical antenna is its predictable pattern, gain and impedance characteristics over a wide frequency range. This is one of the few antennas that has both broad bandwidth and high gain. The benefit of this property is that, when used for narrow-band applications, the helical antenna is very forgiving of mechanical inaccuracies.

Probably the most common amateur use of the helical antenna is in satellite communications, where the spinning of the satellite antenna system (relative to the earth) and the effects of Faraday rotation cause the polarization of the satellite signal to be unpredictable. Using a linearly polarized antenna in this situation results in deep fading, but with the helical antenna (which responds equally to linearly polarized signals), fading is essentially eliminated.

This same characteristic makes helical antennas useful in polarization-diversity systems. The advantages of circular polarization have been demonstrated on VHF voice schedules over non-optical paths, in cases where linearly polarized beams did not perform satisfactorily.

Another use for the helical antenna is the transmission of color ATV signals. Many beam antennas (when adjusted for maximum gain) have far less bandwidth than the required 6 MHz, or have non-uniform gain over this frequency range. The result is significant distortion of the transmitted and received signals, affecting color reproduction and other features. This problem becomes more aggravated over non-optical paths. The helix exhibits maximum gain (within 1 dB) more than 20 MHz anywhere above 420 MHz.

The helical antenna can be used to advantage with multimode rigs, especially above 420 MHz. Not only does the helix give high gain over an entire amateur band, but it also allows operation on FM, SSB and CW without the need for separate vertically and horizontally polarized antennas.

Helical Antenna Basics

The helical antenna is an unusual specimen in the antenna world, in that its physical configuration gives a

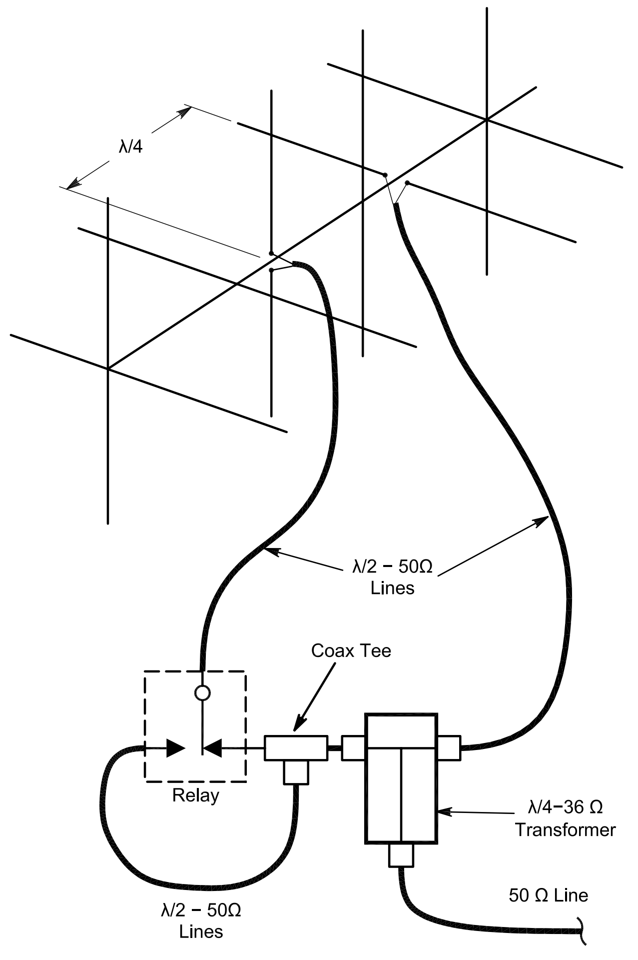


Fig 13—Offset crossed-Yagi circularly polarized antenna-phasing harness with switchable polarization.

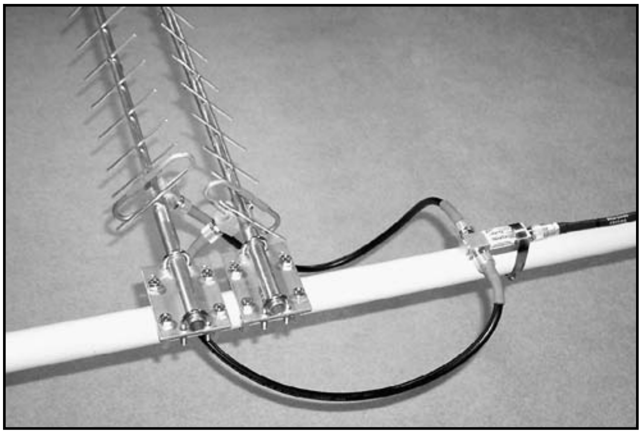


Fig 14—An example of offset crossed-Yagi circularly polarized antennas with fixed polarization. This example is a pair of M^2 23CM22EZA antennas, for L band (1269 MHz), mounted on an elevation boom. (*WD4FAB photo*.)

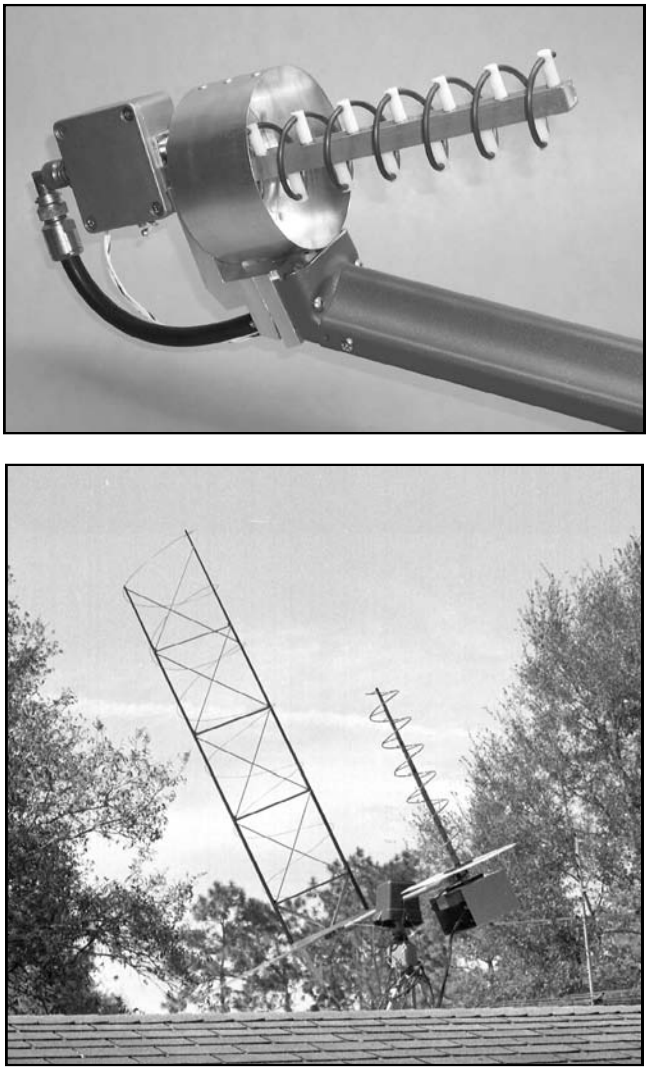


Fig 15—At top, a seven-turn LHCP helical antenna for S-band dish feed for AO-40 service. This helical antenna uses a cupped reflector and has a preamplifier mounted directly to the antenna feed point. At bottom, a pair of helical antennas for AO-10 service on 2 meters and 70 cm. The 2-meter helical antenna is not small! (*WD4FAB photos*.)

hint to its electrical performance. A helix looks like a large air-wound coil with one of its ends fed against a ground plane, as shown in **Fig 16**. The ground plane is a screen of 0.8 λ to 1.1 λ diameter (or on a side for a square ground plane). The circumference (C_λ) of the coil form must be between 0.75 λ and 1.33 λ for the antenna to radiate in the axial mode. The coil should have at least three turns to radiate in this mode. The ratio of the spacing between turns (in wavelengths), S_λ to C_λ, should be in the range of 0.2126 to 0.2867. This ratio range results from the requirement that the pitch angle, α, of the helix be between 12° and 16°, where:

$$\alpha = \arctan \frac{S_\lambda}{C_\lambda} \qquad \text{(Eq 1)}$$

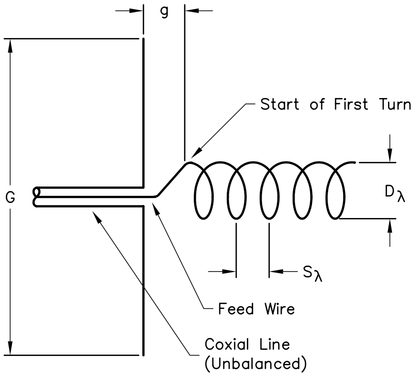


Fig 16—The basic helical antenna and design equations.

These constraints result in a single main lobe along the axis of the coil. This is easily visualized from Fig 15A. The winding of the helix comes away from the cupped reflector with a counterclockwise winding direction for a LHCP. (The winding can also be a clockwise—this results in a RHCP polarization sense.)

A helix with a C_λ of 1λ has a wave propagating from one end of the coil (at the ground plane), corresponding to an instantaneous dipole "across" the helix. The electrical rotation of this dipole produces circularly polarized radiation. Because the wave is moving along the helix conductor at nearly the speed of light, the rotation of the electrical dipole is at a very high rate, and true circular polarization results.

The IEEE definition, in simple terms, is that when viewing the antenna from the feed-point end, a clockwise wind results in right-hand circular polarization (RHCP), and a counterclockwise wind results in left-hand circular polarization (LHCP). This is important, because when two stations use helical antennas over a nonreflective path, both must use antennas with the same polarization sense. If antennas of opposite sense are used, a signal loss of at least 20 dB results from the cross polarization alone.

As mentioned previously, circularly polarized antennas can be used in communications with any linearly polarized antenna (horizontal or vertical), because circularly polarized antennas respond equally to all linearly polarized signals. The gain of a helix is 3 dB less than the theoretical gain in this case, because the linearly polarized antenna does not respond to linear signal components that are orthogonally polarized relative to it.

The response of a helix to all polarizations is indicated by a term called *axial ratio*, also known as *circularity*. Axial ratio is the ratio of amplitude of the polarization that gives maximum response to the amplitude of the polarization that gives minimum response. An ideal circularly polarized antenna has an axial ratio of 1.0. A well-designed practical helix exhibits an axial ratio of 1.0 to 1.1. The axial ratio of a helix is:

$$\mathrm{AR} = \frac{2n + 1}{2n} \qquad \text{(Eq 2)}$$

where:

AR = axial ratio
n = the number of turns in the helix

Axial ratio can be measured in two ways. The first is to excite the helix and use a linearly polarized antenna with an amplitude detector to measure the axial ratio directly. This is done by rotating the linearly polarized antenna in a plane perpendicular to the axis of the helix and comparing the maximum and minimum amplitude values. The ratio of maximum to minimum is the axial ratio.

The impedance of the helix is easily predicted. The terminal impedance of a helix is unbalanced, and is defined by:

$$Z = 140 \times C_\lambda \qquad \text{(Eq 3)}$$

where Z is the impedance of the helix in ohms.

The gain of a helical antenna is determined by its physical characteristics. Gain can be calculated from:

$$\mathrm{Gain}\,(\mathrm{dBi}) = 11.8 + 10 \log \left(C_\lambda^{\,2}\, n S_\lambda \right) \qquad \text{(Eq 4)}$$

In practice, helical antennas do not deliver the gain in Eq 4 for antennas with turns count greater than about twelve. There will be more discussions in this area when practical antennas are discussed.

The beamwidth of the helical antenna (in degrees) at the half-power points is:

$$\mathrm{BW} = \frac{52}{C_\lambda \sqrt{n S_\lambda}} \qquad \text{(Eq 5)}$$

The diameter of the helical antenna conductor should be between 0.006 λ and 0.05 λ, but smaller diameters have been used successfully at 144 MHz. The previously noted diameter of the ground plane (0.8 λ to 1.1 λ) should not be exceeded if you desire a clean radiation pattern. As the ground plane size is increased, the sidelobe levels also increase. Cupped ground planes have been used according to Kraus, as in Fig 15. (The ground plane need not be solid; it can be in the form of a spoked wheel or a frame covered with hardware cloth or screen.)

50-Ω Helix Feed

Joe Cadwallader, K6ZMW, presented this feed method in June 1981 *QST*. Terminate the helix in an N connector mounted on the ground screen at the periphery of the helix. See **Fig 17**. Connect the helix conductor to the N connector as close to the ground screen as possible (**Fig 18**). Then adjust the first quarter turn of the helix to a close spacing from the reflector.

This modification goes a long way toward curing a deficiency of the helix—the 140-Ω nominal feed-point

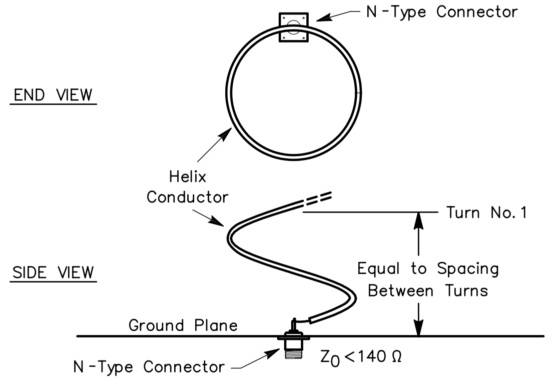


Fig 17—End view and side view of peripherally fed helix.

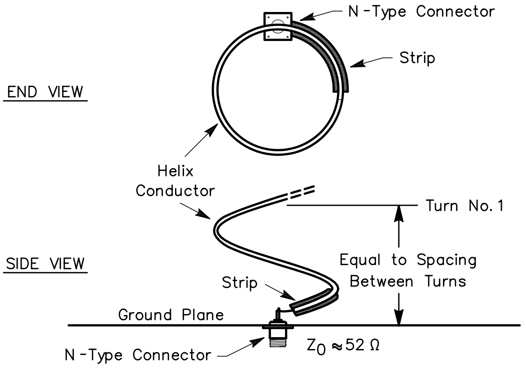


Fig 19—End view and side view of peripherally fed helix with metal strip added to improve transformer action.

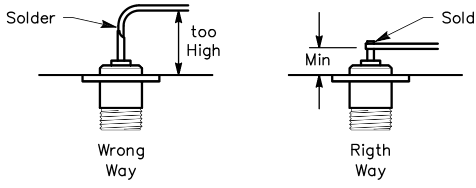


Fig 18—Wrong and right ways to attach helix to a type N connector for 50-Ω feed.

impedance. The traditional λ/4 matching section has proved difficult to fabricate and maintain. But if the helix is fed at the periphery, the first quarter turn of the helix conductor (leaving the N connector) acts much like a transmission line—a single conductor over a perfectly conducting ground plane. The impedance of such a transmission line is:

$$Z_0 = 138 \log \frac{4h}{d} \qquad \text{(Eq 6)}$$

where:

Z_0 = line impedance in ohms
h = height of the center of the conductor above the ground plane
d = conductor diameter (in the same units as h).

The impedance of the helix is 140 Ω a turn or two away from the feed point. But as the helix conductor swoops down toward the feed connector (and the ground plane), h gets smaller, so the impedance decreases. The 140-Ω nominal impedance of the helix is transformed to a lower value. For any particular conductor diameter, an optimum height can be found that will produce a feed-point impedance equal to 50 Ω. The height should be kept very small, and the diameter should be large. Apply power to the helix and measure the SWR at the operating frequency. Adjust the height for an optimum match.

Typically, the conductor diameter may not be large enough to yield a 50-Ω match at practical (small) values of h. In this case, a strip of thin brass shim stock or flashing copper can be soldered to the first quarter turn of the helix conductor (**Fig 19**). This effectively increases the conductor diameter, which causes the impedance to decrease further yet. The edges of this strip can be slit every $^1/_2$ inch or so, and the strip bent up or down (toward or away from the ground plane) to tune the line for an optimum match.

This approach yields a perfect match to nearly any coax. The usually wide bandwidth of the helix (70% for less than 2:1 SWR) will be reduced slightly (to about 40%) for the same conditions. This reduction is not enough to be of any consequence for most amateur work. The improvements in performance, ease of assembly and adjustment are well worth the effort in making the helix more practical to build and tune.

ANTENNAS FOR AO-40 OPERATIONS

Antennas for successful operations on AO-40 come in many shapes and sizes. AO-40 has provided amateurs the opportunity to broadly experiment with antennas.

Fig 20 shows the satellite antennas at WD4FAB. The Yagi antennas are used for the U- and L-band AO-40 uplinks and the V-band AO-10 downlink, while the S-band dish antenna is for the AO-40 downlink. These satellite antennas are tower mounted at 63 feet (19 meters) to avoid pointing into the many nearby trees and suffering from the resulting "green attenuation." Of course, satellite antennas do not always need to be mounted high on a tower if dense foliage is not a problem. If satellite antennas are mounted lower down, feed-line length and losses can reduced.

Another benefit, however, to tower mounting of satellite antennas is that they can be used for terrestrial ham communications and contests. The fact that the antennas are set up for CP does not really degrade these other operating activities.

Experience with AO-40 has clearly shown the advan-

Fig 20—Details of WD4FAB's tower cluster of satellite antennas including a home-brew elevation rotator. Top to bottom: M^2 436-CP30, a CP U-band antenna; two M^2 23CM22EZA antennas in a CP array for L band; "FABStar" dish antenna with helix feed for S band; M^2 2M-CP22, a CP V-band antenna (only partially shown.) To left of dish antenna is a NEMA4 equipment box with an internal 40-W L-band amplifier, and also hosts externally mounted preamplifiers. (*WD4FAB photo*)

Fig 21—Domenico, I8CVS, has this cluster of satellite antennas for AO-40. Left to right: array of 4 × 23-element Yagi horizontally polarized for L band; 1.2-meter dish with 3-turn helix feed for S band; 15-turn RHCP helical antenna for U band; 60-cm dish for X band. All microwave preamplifiers and power amplifiers are homebrew and are mounted on this antenna cluster. (*I8CVS photo.*)

tages of using RHCP antennas for both the uplink and downlink communications. The antennas shown in Fig 20 are a single-boom RHCP Yagi antenna for U band, a pair of closely spaced Yagi antennas phased for RHCP for L band (see Fig 14), and a helix-fed dish antenna for S band. The antenna gain requirements for U band can easily be met with the gain of a 30-element crossed Yagi. Antennas of this size have boom lengths of 4 to 4$^1/_2$ wavelengths. The enterprising constructor can build a Yagi antenna from one of several references, however most of us prefer to purchase well-tested antennas from commercial sources as M^2 or Hy-Gain. In the past, KLM (now out of business) had offered a 40-element CP Yagi for U-band satellite service, and many of these are still in satisfactory use today.

U-band uplink requirements for AO-40 have clearly demonstrated the need for gain less than 16 to 17 dBic RHCP, with an RF power of less than 50 W PEP at the antenna (≈ 2,500 W-PEP EIRP with a RHCP antenna) depending upon the *squint angle*. (The squint angle is the angle at which the main axis of the satellite is pointed away from your antenna on the ground. If the squint angle is less than half of the half-power beamwidth, the ground station will be within the spacecraft antenna's nominal beam width.)

A gain of 16 to 17 dBic RHCP can be obtained from a 30-element crossed Yagi, AO-13 type antenna, and is good news, considering that the satellite may be over 60,000 km (37,000 miles) from your station. Success on the U-band uplinks to AO-40 is easier than those for L band at wider squint angles more than 20°. At squint angles less than 10°, U-band uplink operation can even be done with 1-5 W power outputs to a RHCP antenna (≈ 200 W-PEP EIRP with RHCP). These lower levels mean that smaller antennas can be used. In practice, these uplinks will produce downlink signals that are 10 to 15 dB above the noise floor, or S7 signals over an S3 noise floor. The beacon will give a downlink S9 signal for these same conditions.

WD4FAB's experience with the AO-40 L-band uplink has demonstrated that 40 W-PEP delivered to an antenna with a gain of ≈ 19dBic (3,000 W-PEP EIRP with RHCP) is needed for operations at the highest altitudes of AO-40 and with squint angles ≤ 15°. This is the pretty compact L-band antenna arrangement with two 22-element antennas in a RHCP array shown in Fig 14 and 20. Other operators have experience that using a 1.2-meter L-band dish antenna and 40 W of RF power (6,100 W-PEP EIRP with RHCP) can also provide a superb uplink for squint angles even up to 25°. A dish antenna can have a practical gain of about 21 to 22 dBic. These uplinks will provide the user a downlink that is 10 to 18 dB above the transponder noise floor. In more practical terms, this is an S7 to 8 signal over a S3 transponder noise floor, a very comfortable armchair copy.

Fig 22—Wilfred Carey, ZS6JT, constructed this cluster of satellite and EME antennas. Left to right: 2 × 23-element offset feed Yagi for U band; 1.64-meter dish with 2¼-turn helix feed for S band; 2 × 11-element coplanar feed Yagi for V band. (*ZS6JT photo.*)

Using the L-band uplink for AO-40, instead of the U-band uplink, allows the use of Yagi antennas that more manageable, since their size for a given gain is only one third of those for U-band. With L band there is a narrower difference between using a dish antenna and a Yagi, since a 21- to 22-dBic dish antenna would be only about 1.2 meters (4 feet) in diameter. However, some of us may not have such "real estate" available on our towers and may seek a lower wind-loading solution offered by Yagis. Long-boom rod-element Yagi, or loop-Yagi antennas are commercially offered by M^2 and DEM, although this band is about the highest for practical Yagis. The example shown in Fig 20 is a pair of rod-element Yagi antennas from M^2 in a CP arrangement with a gain of 18 to 19 dBic.

Other amateurs have successful AO-40 operation with different arrangements. **Fig 21** shows I8CVS's 4 × 23-element linear array for a 1270 MHz, a 1.2-meter solid dish for 2400 MHz, a 15-turn helical antenna for 435 MHz, and a 60-cm dish for 10,451 MHz. This arrangement clearly shows the advantage and accessibility of having a roof-mounted antenna.

Fig 22 shows ZS6JT's setup, with a 1.64-meter home-built mesh dish for 2400 MHz and two home-built crossed Yagi antennas, one for 435 MHz and the other for 145 MHz. Note that in these examples, the antennas permit terrestrial communication as well as satellite service. Two of these stations have also maintained the capability to operate the LEO satellites with U- and V-band antennas.

A number of amateurs have taken advantage of the availability of surplus C-band TVRO dishes, since most users of satellite television have moved up to the more

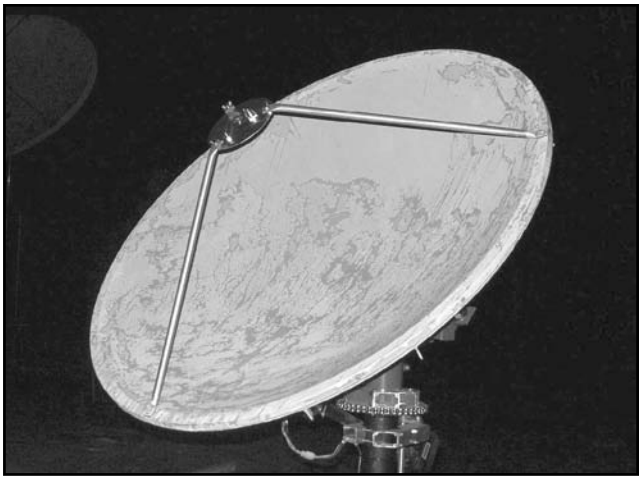


Fig 23—Robert Suding, W0LMD, modified this 4-foot dish antenna with a patch feed for S band and an Az-El mount. (*W0LMD photo.*)

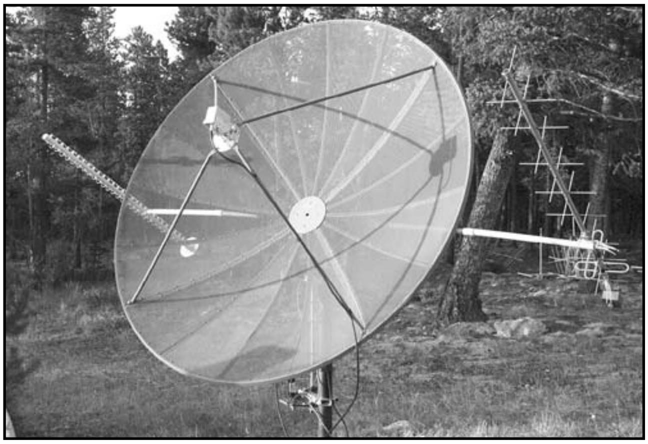


Fig 24—W0LMD graduated to this 8-foot dish with patch feed for S band for AO-40. On the left is a helical antenna for L band and on the right is a 2 × 9-element offset-feed Yagi for U band. A home-brew Az-El mount is provided. (*W0LMD photo.*)

convenient K band using 0.5-meter dishes. Some examples of these dish conversions for satellite communications are shown in **Fig 23**, a W0LMD 4-foot dish with patch feed and Az-El mount. **Fig 24** shows a W0LMD 8-foot dish with patch feed, Az-El mount, a U-band Yagi, and an L-band helical antenna.

Fig 25 is a W0LMD 10-foot dish with tri-band patch feed and Az-El mount; and **Fig 26** is also a W0LMD

Fig 25—W0LMD increased to this 10-foot dish for AO-40 operations, with a triband patch feed for U, L, and S bands on an Az-El mount. (*W0LMD photo.*)

Fig 26—W0LMD found the ultimate in this 14-foot dish for AO-40, with a triband patch feed and Az-El mount. (*W0LMD photo.*)

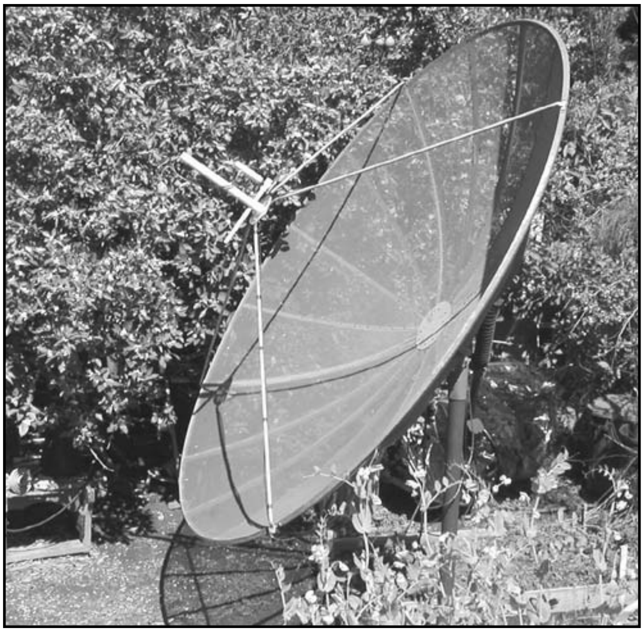


Fig 27—Clair E. Cessna, K6LG, has this 10-foot dish with S-band patch feed. This dish uses the original polar-mounting system and offsets the patch feed to compensate for AO-40's deviation from the Clarke belt. (*K6LG photo.*)

Fig 28—K5GNA's "circularized" mesh modification of an MMDS dish antenna with a helix-CP feed and DEP preamp. The dish modification reduces the spillover loss by making the antenna fully circular. (*K5OE photo.*)

14-foot dish with tri-band patch feed and Az-El mounting. Other operators, like K6LG, have been able to use TVRO dishes, **Fig 27**, with multiband patch feeds and still use, within limits, their polar-mounting system, as will be explained later.

Other hams have taken advantage of other surplus dish situations. **Fig 28** shows modified MMDS dishes, by K5GNA, and **Fig 29**, by K5OE, both using helix feeds. **Fig 30** shows a 75-cm high modified PrimeStar offset feed dish, by WD4FAB, using a longer helical feed antenna because of the higher f/D ratio of this dish configuration. This dish provides 5 dB of Sun noise, which is good performance. These efforts have rewarded their users with superb service on AO-40. Many have experimented with different feed and mounting systems. These experiments will be further illustrated.

One very popular spun-aluminum dish antenna seen in use on AO-40 has been the G3RUH-ON6UG 60-cm unit with its S-band patch feed, **Fig 31**. A kit, complete with a CP-patch feed is available from SSB-USA and has a gain of 21 dBic. It provides a 2.5-dB Sun noise signal. Surplus dishes have not been the only source for antennas for AO-40 operations, since some ingenious operators have even turned to the use of cardboard boxes. See **Figs 32** to **35**.

Fig 29—Mesh modification of an MMDS dish antenna by Jerry Brown, K5OE, with a helix-CP feed and DEM preamplifier mounted directly to the helix feed point. (*K5OE photo.*)

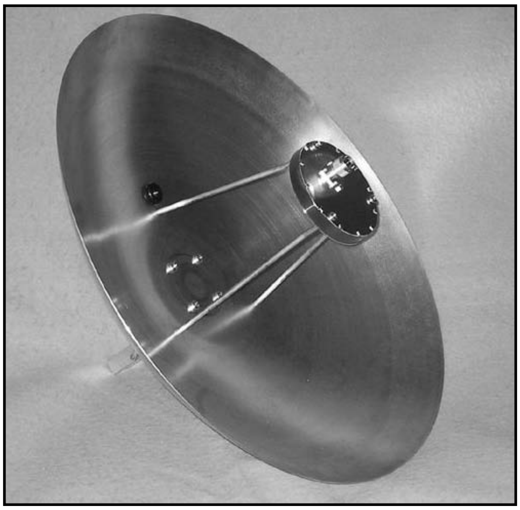


Fig 31—G3RUH's 60-cm spun-aluminum dish with CP-patch feed is available as a kit. This antenna has been popular with many AO-40 operators all over the world.

Fig 30—PrimeStar offset-fed dish with WD4FAB's helix-feed antenna. N0NSV was so pleased with the modification that he renamed the dish "FABStar," and made a new label! (*N0NSV photo.*)

Fig 32—A complete satellite station with the tracking laptop, FT-847 transceiver, and both downlink and uplink cardboard-box antennas.

Parabolic Reflector Antennas

The satellite S-band downlinks have become very popular for a variety of reasons:

- Good performance with physically small downlink antennas
- Availability of good-quality downconverters
- Availability of preamps at reasonable prices.

A number of people advocate S-band operation, including Bill McCaa, KØRZ, who led the team that designed and built the AO-13 S-band transponder and James Miller, G3RUH, who operates one of the AO-40 command stations. Ed Krome, K9EK, and James Miller have published a number of articles detailing construction of preamps, downconverters and antennas for S band.

Some access AO-40's S-band downlink using compact S-band helical antennas. See **Fig 36**. With the demise of AO-40's S1 transmitter and its high-gain downlink antenna, enthusiasts have had to employ high-gain parabolic-dish antennas to use AO-40's S2 downlink, with its lower-gain helical antenna.

WØLMD notes that like a bulb in a flashlight, the

Fig 33—The completed high-performance corner-reflector uplink antenna for U band. Note how the box corners hold the reflectors and dipole feed in place. The rear legs set the antenna elevation to 20°—this gives good coverage at the design latitude but will need modification for other stations.

Fig 35—Side view of the downlink pyramidal horn showing the elevation control supports and how the downconverter is attached to the horn. The downconverter is pulled forward by the tape to align the probe wire parallel to the rear surface of the horn.

Fig 34—Front view of the downlink pyramidal horn showing how it is mounted in the support carton. Notice the coax probe at the back of the horn.

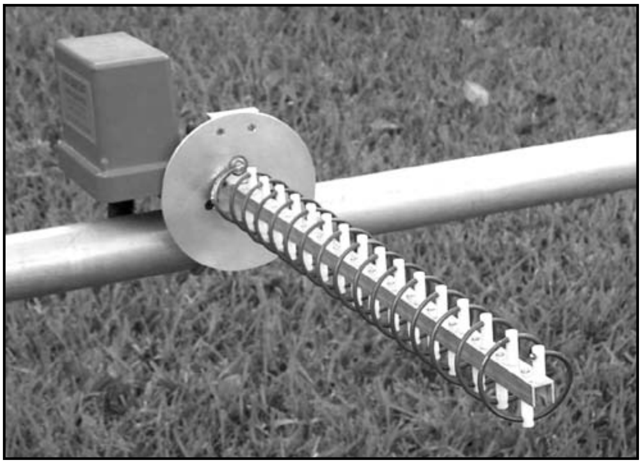


Fig 36—WD4FAB's example of a 16-turn S-band helical antenna for AO-40. This is about the maximum length of any practical helix. Note the SSB UEK2000 downconverter mounted behind the reflector of the antenna. (*WD4FAB photo.*)

parabolic reflector or dish antenna must have a feed source looking into the surface of the dish. Some dishes are designed so that the feed source is mounted directly in front of the dish. This is referred to as a *center-fed dish*. Other dishes are designed so that the feed source is off to one side, referred to as an *off-center-fed dish*, or just offset-fed dish, as shown in Fig 30. The offset-fed dish may be considered a side section of a center-fed dish. The center-fed dish experiences some signal degradation due to blockage of the feed system, but this is usually an insignificantly small amount. The offset-fed dish is initially more difficult to aim, since the direction of reception is not the center axis, as it is for center-fed dishes.

The basic design precepts of parabolic-dish antennas are covered in more detail in the EME Antenna section of this chapter. Dish antenna properties specific to satellite operations are covered here. The dish's parabola can be designed so the focus point is closer to the surface of the dish, referred to a *short-focal-length* dish, or further away from the dish's surface, referred to as a *long-focal-length* dish. To determine the exact focal length, measure the diameter of the dish and the depth of the dish.

$$f = \frac{D^2}{16d} \qquad \text{(Eq 7)}$$

The focal length divided by the diameter of the dish gives the *focal ratio*, commonly shown as f/D. Center-fed dishes usually have short-focal ratios in the range of f/D = 0.3 to 0.45. Offset-fed dishes usually have longer focal lengths, with f/D = 0.45 to 0.80. If you attach two small mirrors to the outer front surface of a dish and then point the dish at the Sun, you can easily find the focus point of the dish. Put the reflector of the patch or helix feed just beyond this point of focus.

An alternate method for finding a dish's focal length is suggested by W1GHZ (ex-N1BWT), who provides a computer program called *HDL_ANT*, available at: **www.w1ghz.org/10g/10g_home.htm**. The method literally measures a solid-surface dish by the dimensions of the bowl of water that it will form when properly positioned. (See: **www.qsl.net/n1bwt/chap5.pdf**.) WD4FAB used this method on the dish of Fig 30, carefully leveling the bowl, plugging bolt holes, and filling it with water to measure the data needed by the W1GHZ Web-site calculation.

While many of us enjoy building our own antennas, surplus-market availability of these small dish antennas makes their construction unproductive. Many AO-40 operators have followed the practices of AO-13 operators using a surplus MMDS linear-screen parabolic reflector antenna, Figs 28 and 29. These grid-dish antennas are often called *barbeque dishes*. K5OE and K5GNA have shown how to greatly improve these linearly polarized reflectors by adapting them for the CP service desired for AO-40. Simple methods can be used to *circularize* a linear dish and to further add to its gain using simple methods to increase the dish area and feed efficiency.

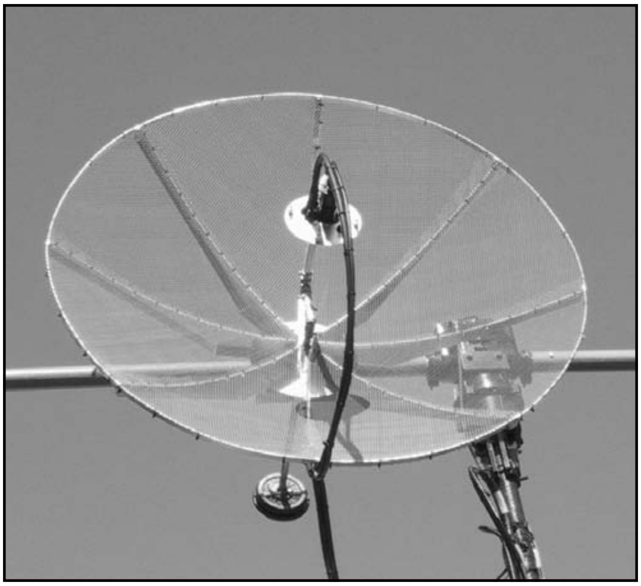


Fig 37—Prototype 1.2-meter dish by Rick Fletcher, KG6IAL, using a dual-band (L and S) patch-feed antenna for AO-40. See text. This kit dish is covered with 1/4-inch mesh. (*KG6IAL photo.*)

Another approach is the construction of a kit-type dish antenna, just becoming available in 1.2-meter and 1.8-meter diameters. This ingenious design by KG6IAL is available from his Web site **www.teksharp.com/**. **Fig 37** shows the prototype of the 1.2-meter dish with an f/D of 0.30. The 1.2-meter dish is fed with a dual-band patch feed for L and S bands. The 1.8-meter dish is designed for up to three bands using a tri-band patch feed for the U, L and S bands. This dish will permit U-band operation. A Central States VHF Society measurement on a similar sized dish (by W0LMD) with a patch feed showed a gain of about 17.1 dBic (actual measurement was 12.0 dBd linearly fed). This performance along with a small V-band (145 MHz) Yagi would permit a very modest satellite antenna assembly for all of the VHF/UHF LEO satellites, as well as AO-40.

The ingenuity of the design of the KG6IAL antenna is that it is constructed of robust, 1/8-inch-thick aluminum sheet that is numerically machined for the parabolic shape of the ribs. The backsides of the ribs are stiffened by a bent flange edge. The panel mesh is attached by using small tie-wraps or small aluminum wire through the mesh and holes provided along the parabolic edge. KG6IAL used 1/4-inch mesh in the prototype antenna to reduce wind loading. A single formed conduit post is provided in the kit for mounting the patch-feed assembly. The post extends rearward to permit the attachment of a counterweight, if needed.

AO-40 has also provided some additional challenges to the ham operator. Besides its well-known S-band downlink, AO-40 also has a K-band downlink in the range of

24.05 GHz. This quite low-powered transmitter has provided a substantial challenge to some operators, such as N1JEZ, K5OE, W5LUA, G3WDG and others. N1JEZ documented his work in *QST* while K5OE shows his K-band work on his Web site and in the *Proceedings of the AMSAT Space Symposium*. See **Fig 38**.

Parabolic Dish Antenna Construction

In the USA large numbers of dishes can be obtained either free or at low cost. But in some parts of the world dishes are not so plentiful, so hams make their own. **Fig 39** shows G3RUH's S-band dish antenna. There are three parts to the dish antenna—the parabolic reflector, the boom and the feed. There are as many ways to construct this as there are constructors. You need not slavishly replicate every nuance of the design. The only critical dimensions occur in the feed system. After construction, you will have a 60-cm diameter S-band RHCP dish antenna with a gain of about 20 dBi and a 3-dB beamwidth of 18°. Coupled with the proper downconverter, performance will be more than adequate for S-band downlink.

The parabolic reflector used for the original antenna was intended to be a lampshade. Several of these aluminum reflectors were located in department-store surplus. The dish is 585 mm in diameter and 110 mm deep, corresponding to an f/D ratio of 585/110/16 = 0.33 and a focal length of 0.33 × 585 = 194 mm. The f/D of 0.33 is a bit too concave for a simple feed to give optimal performance but the price was right, and the under-illumination keeps ground noise pickup to a minimum. The reflector already had a 40-mm hole in the center with three 4-mm holes around it in a 25-mm radius circle.

The boom passes through the center of the reflector and is made from 12.7-mm square aluminum tube. The boom must be long enough to mount to the rotator boom on the backside of the dish. The part of the boom extending through to the front of the dish must be long enough

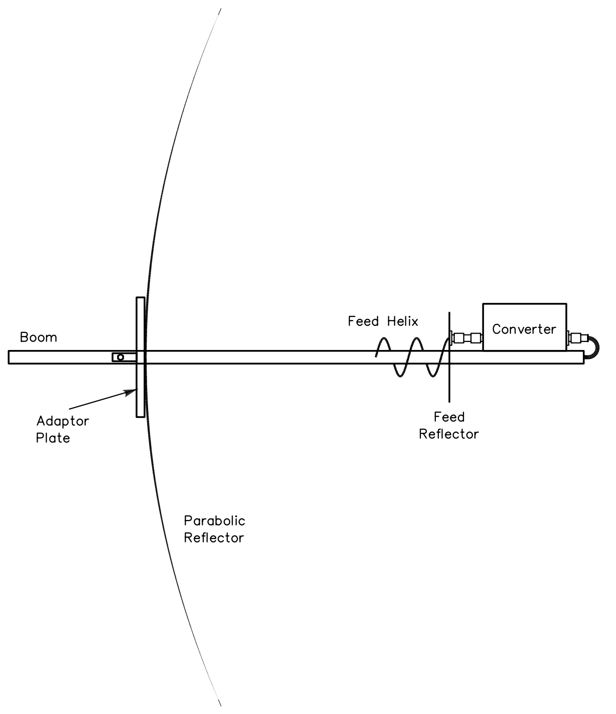


Fig 39—Detail of 60-cm S-band dish antenna with feed.

Fig 38—K5OE found this K-band dish on the Web and has set it up for the AO-40 K-band downlink. (*K5OE photo.*)

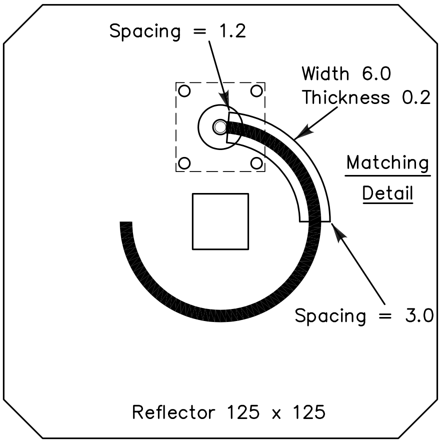
to mount the feed at the focus. If you choose to mount the downconverter or a preamp near the feed, some additional length will be necessary. Carefully check the requirements for your particular setup.

A 3-mm thick piece of aluminum, 65 mm in diameter, supports the boom at the center of the reflector. Once the center mounting plate is installed, the center boom is attached using four small angle brackets—two on each side of the reflector. See Fig 39 for details of reflector and boom assembly.

A small helix is used for the S-band antenna feed. The reflector for the helix is made from a 125-mm square piece of 1.6-mm thick aluminum. The center of the reflector has a 13-mm hole to accommodate the square center boom described above. The type-N connector is mounted to the reflector about 21.25 mm from the middle. This distance from the middle is, of course, the radius of a helical antenna for S-band. Mount the N connector with spacers so that the back of the connector is flush with the reflector surface. The helix feed assembly is shown in **Fig 40**.

Copper wire, or tubing, about 3.2 mm in diameter is used to form the helix. Wind four turns around a 40-mm diameter form. The turns are wound counterclockwise. This is because the polarization sense is reversed from RHCP when reflected from the dish surface. The wire helix will spring out slightly when winding is complete.

Once the helix is wound, carefully stretch it so that the turns are spaced 28 mm (±1 mm). Make sure the finished spacing of the turns is nice and even. Cut off the first half turn. Carefully bend the first quarter turn about 10° so it will be parallel to the reflector surface once the helix is attached to the N connector. This quarter turn will form part of the matching section.



All dimensions are in mm.

Fig 40—Details of helix feed for S-band dish antennas. The type-N connector is fixed with three screws and is mounted on a 1.6-mm spacer to bring the PTFE molding flush with the reflector. An easier mounting can be using a smaller TNC connector. Reflectors should be 95 to 100 mm in diameter.

Cut a strip of brass, 0.2 mm thick and 6 mm wide, and match the curvature of the first quarter turn of the helix, using a paper pattern. Be careful to get this pattern and subsequent brass cutting done exactly right. Using a large soldering iron and working on a heatproof surface, solder the brass strip to the first $^1/_4$ turn of the helix. Unless you are experienced at this type of soldering, getting the strip attached just right will require some practice. If it doesn't turn out right, just dismantle, wipe clean and try again.

After tack soldering the end of the helix to the type-N connector, the first $^1/_4$ turn, with its brass strip in place, should be 1.2 mm above the reflector at its start (at the N connector) and 3.0 mm at its end. Be sure to line up the helix so its axis is perpendicular to the reflector. Cut off any extra turns to make the finished helix have $2^1/_4$ turns total. Once you are satisfied, apply a generous amount of solder at the point the helix attaches to the N connector. Remember this is all that supports the helix.

Once the feed assembly is completed, pass the boom through the middle hole and complete the mounting by any suitable method. The middle of the helix should be at the geometric focus of the dish. In the figures shown here, the feed is connected directly to the downconverter and then the downconverter is attached to the boom. You may require a slightly different configuration depending on whether you are attaching a downconverter, preamp or just a cable with connector. Angle brackets may be used to secure the feed to the boom in a manner similar to the boom-to-reflector mounting. Be sure to use some method of waterproofing if needed for your preamp and/or downconverter.

Dish Feeds

W0LMD describes in **www.ultimatecharger.com/** that feeding a dish has two major factors that determine the efficiency. Like a flashlight bulb, the feed source should evenly illuminate the entire dish, and none of the feed energy should spillover outside the dish's reflecting surface. No feed system is perfect in illuminating a dish. Losses affect the gain from either under-illuminating or over-illuminating the dish (spillover losses). Typical dish efficiency is 50%. That's 3 dB of lost gain. A great feed system for one dish can be a real lemon on another. A patch feed system is very wide angle, but a helix feed system is narrow angle.

W0LMD has experimented with helical feeds for low f/D antennas ("deep" dishes) shown in **Fig 41**. A short-focal-ratio center-fed dish requires a wide-angle feed system to fully illuminate the dish, making the CP patch the preferred feed system. When used with an offset-fed dish, a patch-type feed system will result in a considerable spillover, or over-illumination loss, with an increased sensitivity to off-axis QRM, due to the higher f/D of this dish. Offset-fed

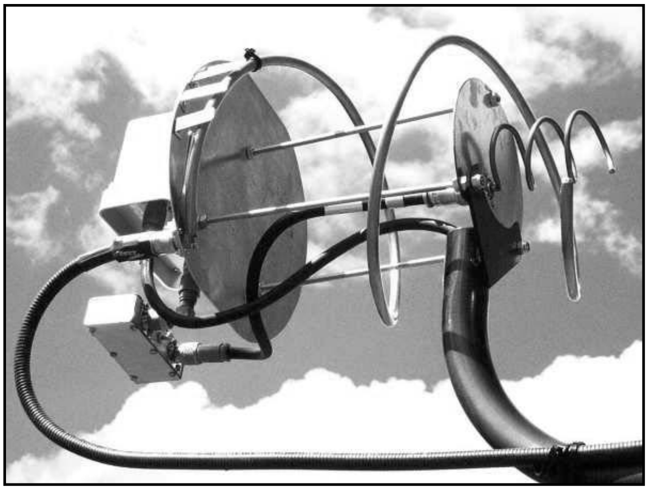


Fig 41—W0LMD's dual helix-dish feed for U and S bands. This early experimental feed was found to be wanting and he then turned to patch feeds for dishes. (*W0LMD photo.*)

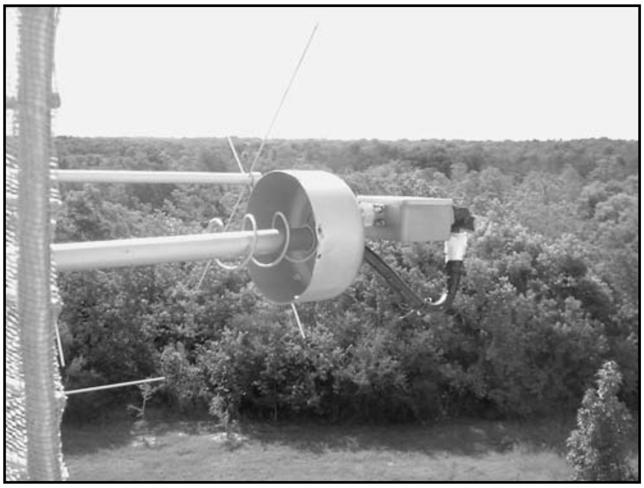


Fig 42—K5OE's helix feed for his MMDS S-band dish antenna. (*K5OE photo.*)

dishes do much better when fed with a helix antenna.

A helix feed is simplicity personified. Mount a type N connector on a flat reflector plate and solder a couple of turns wire to the inner terminal. Designs are anywhere from 2 to 6 turns. The two-turn helices are used for very short-focal-length dishes in the f/D = 0.3 region, and the 6-turn helices are used with longer-focal-length (f/D ~ 0.6) dishes, typically offset-fed dishes. Since AO-40 is right circular and the dish reflection will reverse the polarity, the helix should be wound left circular, looking forward from the connector. Helix feeds work poorly on the short-focal-length dishes but really perform well on the longer-focal-length offset-fed dishes. K5OE shows us the helix feed for his modified MMDS dish in **Fig 42**. This design employs the cupped reflector of W8JK.

A Helix Feed for an Offset-Dish Antenna

This section describes WD4FAB's surplus PrimeStar offset-fed dish antenna with a 7-turn helical feed antenna, shown in Fig 30. This S-band antenna can receive Sun noise 5 dB above sky noise. (Don't try to receive Sun noise with the antenna looking near the horizon, since terrestrial noise will be greater than 5 dB, at least in a big-city environment.) WD4FAB received the dish from N0NSV, who renamed the finished product the "FABStar."

The dish's reflector is a bit out of the ordinary, with the shape of a horizontal ellipse. It is still a single paraboloid, illuminated with an unusual feed horn. At 2401 MHz (S band) we can choose to under-illuminate the sides of the dish while properly feeding the central section, or over-illuminate the center while properly feeding the sides. WD4FAB chose to under-illuminate. The W1GHZ water-bowl measurements showed this to be a dish with a focal point of 500.6 mm and requiring a feed for an f/D = 0.79. The total illumination angle of the feed is 69.8° in the vertical direction and a feed horn with a 3-dB beamwidth of 40.3°. At 50% efficiency this antenna was calculated to provide a gain of 21.9 dBi. A 7-turn helical feed antenna was estimated to provide the needed characteristics for this dish and is shown in **Fig 43**.

The helix is basically constructed as described for the G3RUH parabolic dish above. A matching section for the first λ/4 turn of the helix is spaced from the reflector at 2 mm at the start and 8 mm at the end of that fractional turn. Modifications of the G3RUH design include the addition of a cup reflector, a design feature used by the originator of the helical antenna, John Kraus, W8JK. For the reflector, a 2-mm thick circular plate is cut for a 94 mm (0.75 λ) diameter with a thin aluminum sheet metal cup, formed with a depth of 47 mm. Employment of the cup enhances the performance of the reflector for a dish feed, as shown by K5OE. (See the K5OE material on the CD-ROM accompanying this book.)

The important information for this 7-turn helical antenna is:

- Boom: 12.7-mm square tube or "C" channel.
- Element: 1/8-inch diameter copper wire or tubing.

Close wind the element on a circular 1.50-inch tube or rod; the finished winding is 40 mm in diameter and spaced to a helical angle of 12.3°, or 28 mm spacing. These dimensions work out for an element circumference of 1.0 λ about the center of the wire.

When WD4FAB tackled this antenna, he felt that the small number of helical element supports used by G3RUH would be inadequate, in view of the real-life bird traffic on the antennas at his QTH. He chose to use PTFE (Teflon) support posts every 1/2 turn. This closer spacing of posts permitted a careful control of the helix-winding diameter and spacing and also made the antenna very

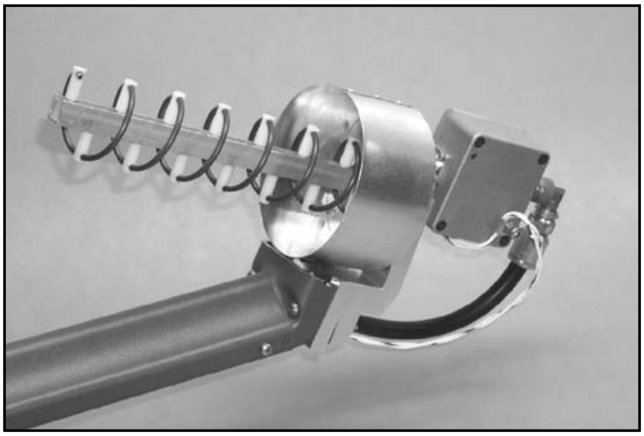


Fig 43—Seven-turn LHCP helix feed for an offset dish, long f/D, antenna, with DEM preamp. (*WD4FAB photo.*)

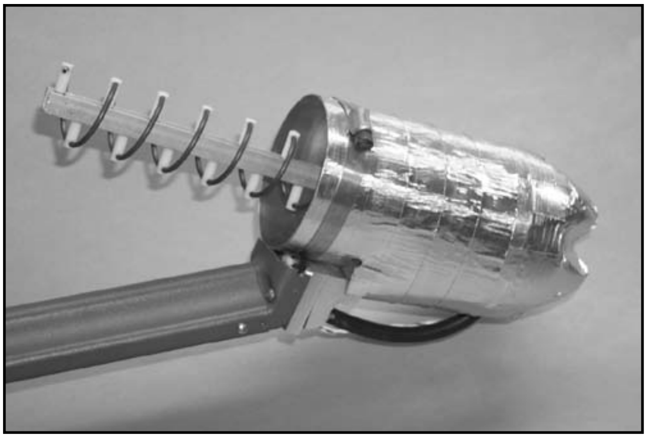


Fig 45—Rain cover for preamp using a two-liter soft-drink bottle with aluminum foil tape for protection from sun damage. (*WD4FAB photo.*)

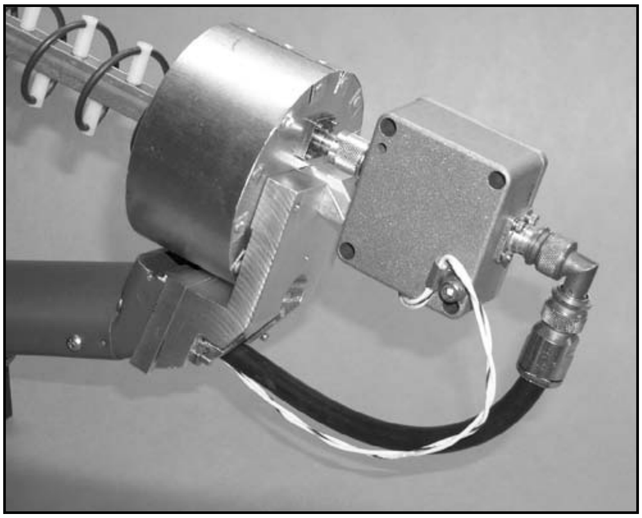


Fig 44—Mounting details of seven-turn helix and preamp. (*WD4FAB photo.*)

robust. He set up a fixture on the drill press to uniformly predrill the holes for the element spacers and boom. Attachment of the reflector is through three very small aluminum angle brackets on the element side of the boom.

Mounting of the helix to the dish requires modification of the dish's receiver-mounting boom. **Fig 44** shows these modifications using a machined mount. NM2A constructed one of these antennas and showed that a machine shop is not needed for this construction. He made a "Z" shaped mount from aluminum-angle plate and then used a spacer from a block of acrylic sheet. The key here is to get the dish focal point at the 1.5-turn point of the feed antenna, which is also at about the lip of the reflector cup.

The W1GHZ data for this focal point is 500.6 mm from the bottom edge of the dish and 744.4 mm from the top edge. A two-string measurement of this point can confirm the focal point, as shown by Wade in his writings. When mounting this feed antenna the constructor must be cautious to aim the feed at the beam-center of the dish, and not the geometric center, as the original microwave horn antenna was constructed. Taking the illumination angle information noted above, the helical feed antenna should be aimed 5.5° down from the geometric center of the dish.

As illustrated in Fig 44, a DEM preamp was directly mounted to the feed helix, using a TNC female connector on the helix, chosen for this case, since N connectors are quite large for this antenna. A male chassis connector should be mounted on the preamp so that the preamp can be directly connected to the antenna without any adaptors. This photo also illustrates how the reflector cup walls were riveted to the reflector plate.

Exposed connectors must be protected from rainwater. Commonly materials such as messy Vinyl Mastic Pads (3M 2200) or Hand Moldable Plastic (Coax Seal) are used. Since this is a tight location for such mastic applications, a rain cover was made instead from a 2-liter soft-drink bottle, **Fig 45**. Properly cutting off the top of the bottle allows it to be slid over the helix reflector cup and secured with a large hose clamp. You must provide UV protection for the plastic bottle and that was done with a wrapping of aluminum foil pressure-sensitive adhesive tape.

There are many methods for mounting this dish antenna to your elevation boom. You must give consideration to the placement of the dish to reduce the wind loading and off-balance to the rotator system. In WD4FAB's FABStar installation, the off-balance issue was not a major factor, as the dish was placed near the center of the elevation boom, between the pillow-block bearing supports. Since there is already a sizeable aluminum plate for these bearings, the dish was located to "cover" part of that plate, so as to not add measurably to the existing wind-loading area of the overall assembly.

A mounting bracket provided with the stock dish clamps to the end of a standard 2-inch pipe stanchion (actual measure: 2.38 inches in diameter). This bracket was turned around on the dish and clamped to the leg of a welded-pipe Tee assembly. See **Fig 46**. Pipe-reducing fittings were machined and fitted in the Tee-top bar, which was sawn in half for clamping over the $1^1/_2$ inch pipe used for the elevation boom. Bolts were installed through drilled holes and used to clamp this assembly.

Patch Feeds for Dish Antennas

Patch feeds are almost as simple as helix feeds. A patch is typically an N connector on a flat reflector plate with a tuned flat-metal plate soldered to the inner terminal. Sometimes the flat plate is square; sometimes it is rectangular; sometimes it is round. It could have two feed points, 90° out of phase for circular polarization, as used in the construction of the AO-40 U-band antennas. Some patches are rectangular with clipped corners to create a circular radiation pattern.

On 2401 MHz, the plate is 57 mm square and spaced 3 mm away from the reflector. The point of attachment is about halfway between the center and the edge. A round patch for 2401 MHz is about 66 mm in diameter. These patches work well on the shorter focal length center-fed MMDS and TVRO dishes. G3RUH made a CP patch feed for these short f/D dishes, shown in Fig 31 and **Fig 47**.

Fig 46—Welded pipefitting mount bracket for FABStar dish antenna. (*WD4FAB photo*.)

Robert, WØLMD, has done a considerable amount of experimenting with patch feeds for his dish antennas. One tri-band feed is shown in **Fig 48**. These are circular patches that have CP properties through the arrangement of the feed point and a small piston-variable capacitor that is offset from the feed point. **Fig 49** shows some of the many patches that Robert has created for his trials.

A No-Tune Dual-Band Feed for Mode L/S

Jerry, K5OE, notes that the AO-40 transponder has two uplink receivers active most of the time for CW/SSB activity. Most operators use U band at 435 MHz (70 cm). Also available, however, are two L-band (23-cm) receivers: L1 at 1269 MHz and L2 at 1268 MHz. The reasons for going to L band can be varied, but there is no arguing the benefits in reduced antenna size and AGC suppression. The types of L-band antennas are varied as well. Many use helices. Others use beams and arrays of beams. Still others use dishes, small and large.

K5OE recently acquired an old UHF TV dish measuring 1.2 meters in diameter. He wanted to use it both to receive on S band at 2401 MHz (13cm) and to transmit on the uplink on L band. He covered it with aluminum mesh and built a dual-helix feed for it, but was unhappy with the L-band performance. It seems the concentric helices interacted with each other substantially. Having had good success with patch feeds on S band, he designed, built and installed a dual-patch feed on a 1.5-meter solid dish for Field Day 2002. This arrangement worked superbly on uplink (with 25 W), but was embarrassingly deaf on receive. This second dual-band feed failure led him to experiment for months with different configurations, leading ultimately to the design presented here. The project goals were:

- Good performance on both S-band receive and L-band uplink.
- An easy-to-produce model using common hardware and simple hand tools.

Patches are better than helices as dish feeds. This revelation came to K5OE while doing investigation and

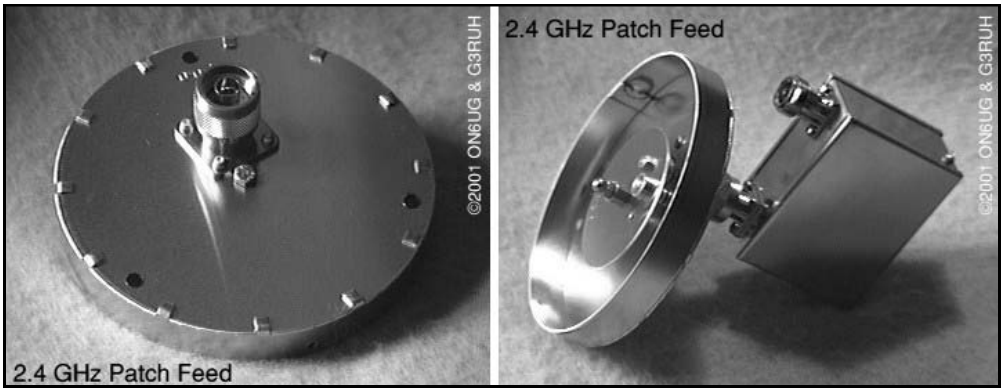


Fig 47—Details of CP-patch feed for short f/D dish antennas by G3RUH and ON6UG.

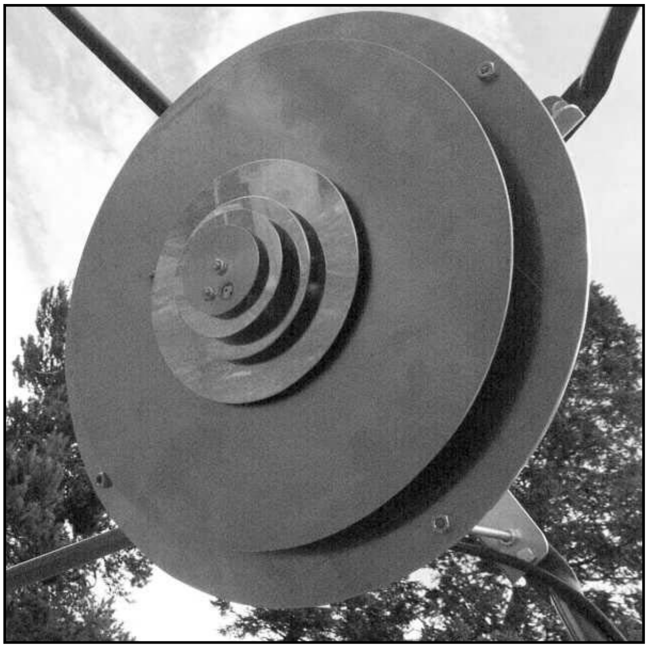


Fig 48—A triband (U, L and S bands) patch-CP feed for large dish antennas for AO-40 service. (*WØLMD photo.*)

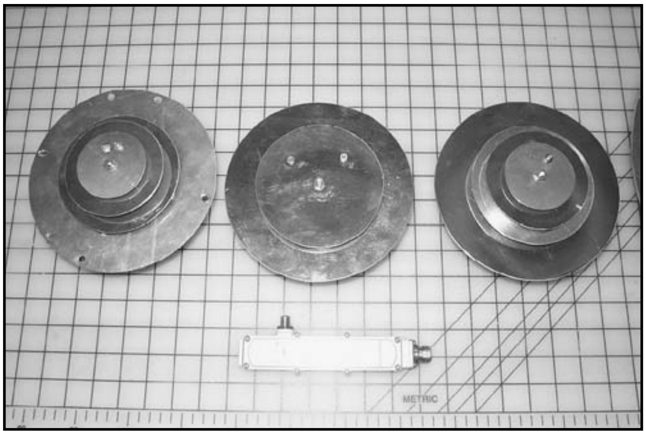


Fig 49—Some of the many experimental CP-patch-feed antennas by WØLMD. (*WØLMD photo.*)

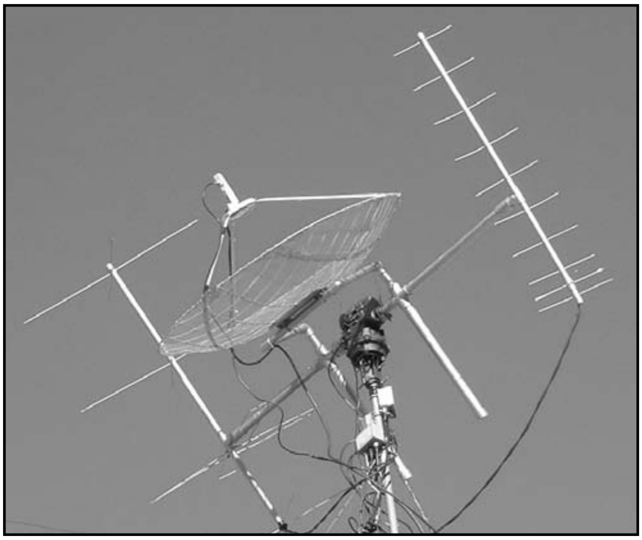


Fig 50—The 1.2-meter dish with dual-band patch feed installed. (*K5OE photo; courtesy of* The AMSAT Journal.)

experimenting with helix antennas. In the middle of this investigative foray, he saw the radiation pattern for the G3RUH patch feed published on James Miller's web site. When he modeled that pattern and input it into the W1GHZ feed pattern program, it produced an amazing 72% efficiency. The best helix he ever modeled has about 60% efficiency. I8CVS recently ran his own antenna range tests of a design similar to the G3RUH patch and produced a similarly impressive pattern.

Then K5OE came across the *truncated corners* square patch design popularized by K3TZ. This AO-40 design here is attributed to 7N1JVW, JF6BCC and JG1IIK. There are references in the literature going back over a decade for this now-common commercial design. The first model K5OE built outperformed his best helix-in-cup design by a full S unit (delta over the noise) on his FT-100 portable setup. Compared to a helix, the patch simply has better illumination efficiency with less spillover from side lobes.

Patch theory is beyond the scope of this article, but can be summarized as building a shape that resonates at the desired frequency, compensated in size by the capacitive inductance between itself and the reflector. A patch can be practically any shape since it basically acts like a parallel-plate transmission line. Current in the patch flows from the feed point to the outer edge(s), where all the radiation occurs. The reputed, but often disputed, circularity of the truncated corner patch is accomplished by effectively designing two antennas into the patch element (of two different diagonal lengths) and feeding them 90º out of phase.

For K5OE's 1.2-meter dish, shown in **Fig 50**, computations predicted 21-dBi gain on L band and almost 27 dBi on S band, with an assumed 50% efficiency:

$$G = 10\log_{10}\left[\eta A\left(\frac{4\pi}{\lambda^2}\right)\right] \qquad \text{(Eq 8)}$$

where

η = efficiency

λ = wavelength in meters.

A = aperture of the dish in meters = $\pi \times r^2$

r = dish radius in meters = diameter/2 in meters = 0.6 meters

At 1269 MHz, λ= 300/1269 = 0.236 meters:

$$G = 10\log_{10}\left[0.50 \times \left(3.14 \times 0.6^2\right) \times \frac{4 \times 3.14}{0.236^2}\right] = 21.1\,\text{dBi}$$

At 2401.5 MHz, $\lambda = 300/2401.5 = 0.125$ meters:

$$G = 10\log_{10}\left[0.50 \times \left(3.14 \times 0.6^2\right) \times \frac{4 \times 3.14}{0.125^2}\right] = 26.6\,\text{dB}^2$$

Where does the feed get mounted? The *focal point* is where the parabolic shape of the dish concentrates the reflected signal. In K5OE's case the antenna was placed flat on the garage floor to measure the depth:

$f = D^2 / 16d$ (Eq 9)

where

D = diameter of the dish in inches
d = depth of the dish in inches
$f = 48^2 / (16 \times 7.25) = 19.8$ inches (50.5 cm)

This is just one example of countless combinations of hardware and patch designs. Inherent in this design, however, are five key design and construction features developed from building and empirical testing of a number of patch feeds.

1. The specified dimensions are critical for no-tune operation. **Fig 51** shows the dimensions necessary to build the dual-feed patch. (K5OE recommends you reproduce this sketch accurately on graph paper. When you cut your patches you can lay them on the paper template for checking.) Repeat: These dimensions are critical. Even a 0.5-mm error will throw your resonance off considerably—patches are not broadband.
2. The reflector must be rigid. Spacing between the driven element (patch) and the reflector affects the resonant frequency. K5OE found 0.025-inch aluminum sheet and 26-gauge copper sheet acceptable for a single S-band patch feed, but too flimsy for an L-band reflector. Use more rigid material or provide additional stiffening for the L-band reflector, as shown in Figs **52**, **53** and **54**.
3. The patches must be electrically isolated from each other. A metallic center support works for a single patch but creates harmonic-coupling problems when patches are stacked for multiband use. The use of nylon machine screws and nuts helps solve the vexing problem of the S-band patch coupling to the L-band patch.
4. The "straight corners" of the truncated corner patch must be kept clear of any nearby metal. This includes the edges of the feed support or cup, if used. See Fig 54.
5. Feeding the patches at 90° to each other minimizes the electromagnetic interaction between the two antenna fields.

One final design issue deals with the first harmonic of the L-band antenna. You must significantly reduce the potentially destructive effect from the 1269-MHz signal's second harmonic. Severe desense of your receive signal could occur and potentially even overload and damage the first active device in your system. Sensitive preamps and downconverters without a pre-RF-amplifier filter will need an external filter. K5OE has used a G3WDG stub filter rated at 100-dB rejection with good success ahead of his preamp. His current setup, however, uses a AIDC-3731AA downconverter with its internal combline filter providing adequate filtering. Using the downconverter directly at the

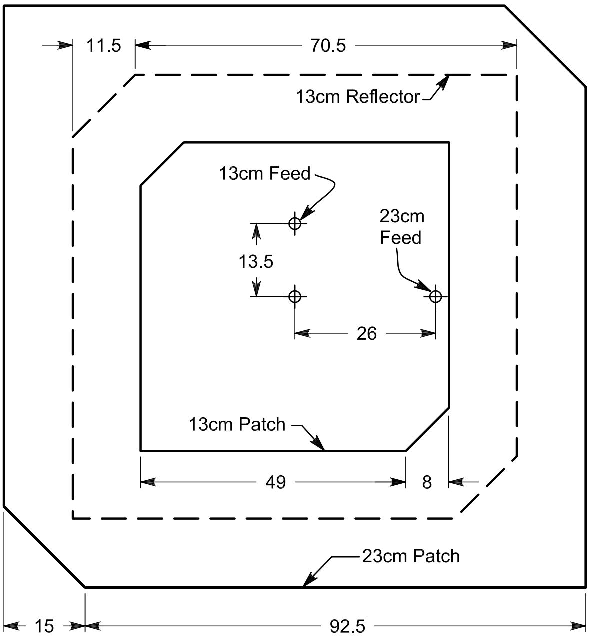


Fig 51—Dual-band patch feed dimensions, in millimeters. (*K5OE diagram; courtesy of* The AMSAT Journal.)

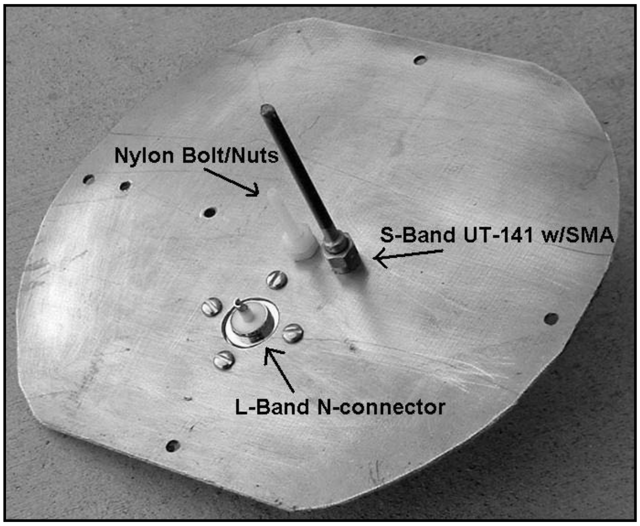


Fig 52—Assembly of the L band reflector. (*K5OE photo; courtesy of* The AMSAT Journal.)

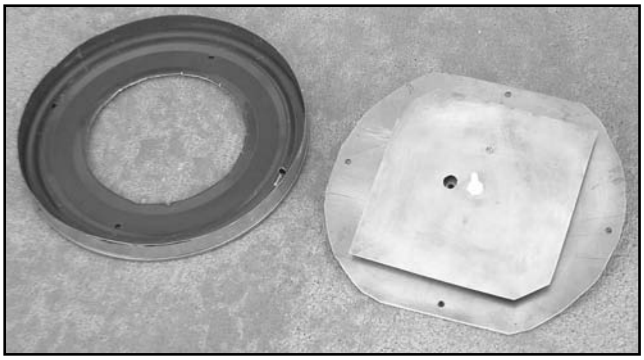


Fig 53—The support, L-band reflector and patch. (*K5OE photo; courtesy of* The AMSAT Journal.)

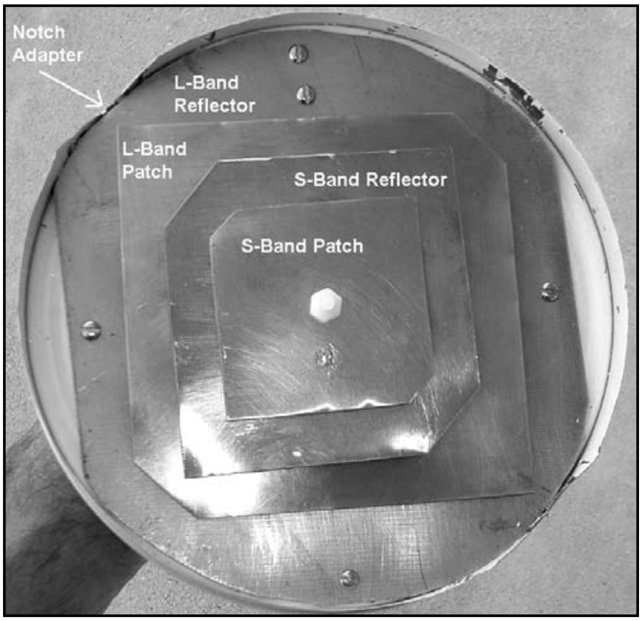


Fig 54—The completed dual-band patch feed. (*K5OE photo; courtesy of* The AMSAT Journal.)

feed point has a noise figure (NF) of 1.0 dB, compared to the cumulative NF of 1.6 dB using a filter and a preamp.

Construction of the feed begins with selection of material for both the electrical parts (the antennas) and the mechanical parts (the support structure). The L-band antenna is constructed using a 6 × 6-inch double-sided circuit board for the reflector and a piece of 26-gauge copper sheet for the driven element (patch). A flanged female type-N connector is used for the feed connection. The S-band antenna is constructed of two pieces of 26-gauge copper sheeting and the feed connection is made with a short piece of UT-141 (0.141-inch copper-clad semirigid coax) terminated in a male SMA fitting. Fig 52 illustrates the assembly of the L-band reflector with the nylon-center support bolt, the L-band N-connector, and the S-band semirigid coax terminated onto an SMA-to-N adapter through the circuit board.

The support structure began life as a paint can, measuring 155 mm in diameter. It was cut down to a 15-mm depth. Cut a hole in the middle of the bottom of the can and trim the PC board to fit inside the can bottom. Use stainless-steel $^{3}/_{8}$-inch 4-40 bolts, washers and nuts to secure the PC board to the can bottom. A $1^{1}/_{2}$-inch 6-32 nylon bolt is secured through the center of the PC board with two nylon nuts to provide the 6-mm spacing for the L-band patch. Fig 53 shows the L-band patch in position and ready to be soldered to the N-connector. Note the hole through the L-band patch allowing the S-band UT-141 coax to pass (without making contact).

The remainder of the antenna is then assembled in order: First the L-band patch is secured with two nylon nuts and soldered to the N-connector. Then the S-band reflector is secured with one nylon nut to provide 3-mm spacing, and the UT-141 coax shield is soldered to the S-band reflector. Finally, the S-band patch is secured with a single nylon nut (3-mm spacing) and soldered to the center conductor of the UT-141 coax. To summarize the overall order of assembly: L-band reflector, two nylon nuts, L-band patch, two nylon nuts, S-band reflector, one nylon nut, S-band patch, and one nylon nut.

An electrical check with an ohmmeter of the completed feed should show the two reflectors connected, with the patches isolated from the reflectors and from each other. Fig 54 shows the completed feed. Note how the sides of the support are cut out to avoid proximity to the L-band patch and how the L-band and S-band patches are at 90º to each other. **Fig 55** shows the back of the feed, complete with an angle support for the downconverter. The flanged N-connector is for the L-band coax and the male-N adapter is secured from the other side of the feed with the SMA fitting on the UT-141 coax.

For those who are tempted to tune the patch, K5OE recommends doing it with the feed installed on the antenna—since the dish surface affects the feed-point impedance slightly. The feed-point impedance, and thus the resonant frequency, can be changed quite a bit by adjustment of the spacing of just the straight corners. There is no need to change the spacing at the center or the feed—just a slight up or down bending of the straight corners will change the tuning. Do this carefully: a little bit goes a long way. This patch design is very repeatable and will work adequately (an SWR below 1.5:1) with no adjustments.

The antenna performs to the calculated predictions above. On receive, this antenna is 4 S units better than K5OE's 45-cm dish and 3 S units above his 65-cm dish (both other dishes have similar patch feeds and the same downconverter). It also clearly outperforms his previous dual-helix arrangement on the 1.2-meter dish, but he was unable to do a side-by-side comparison.

On transmit, it does equally well, with a decent signal into the satellite with only 10 W measured at the

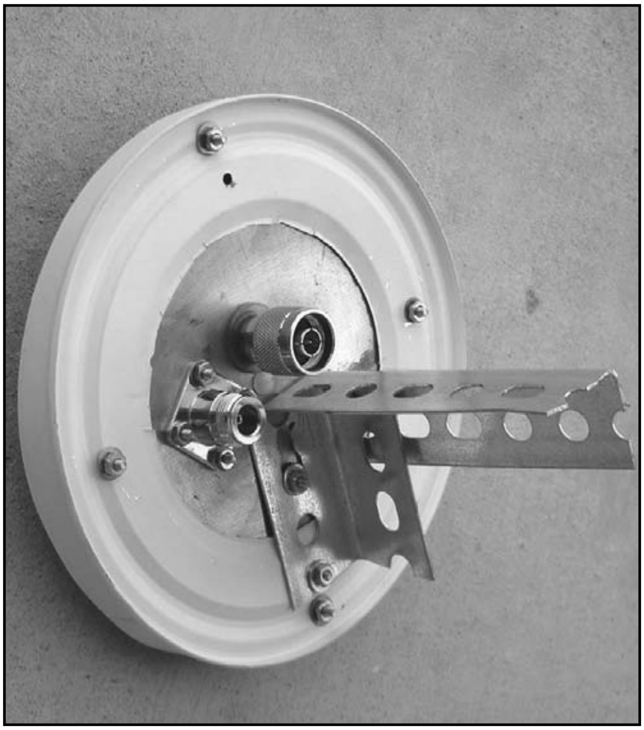


Fig 55—Rear of the completed feed. (K5OE photo; courtesy of *The AMSAT Journal.*)

Fig 56—The portable 435-MHz helix assembled and ready for operation. (*W0CY photo.*)

antenna. The L band is noticeably improved over the helix predecessor. At low squint angles K5OE finds the L-band uplink to be about 1 S unit weaker than his U-band uplink. He later added a small plastic hat to extend over the top of the patches to keep the rain and bird droppings off—both detune the patches when built up between the patch and the reflector.

Though simple and effective, this is merely one way to construct a dual feed. Cookie-tin lids also make excellent supports. Tin snips are a good investment and much easier to use than a hacksaw. Use a flat file to remove burrs from the edges of the patches. Use stainless-steel hardware, most notably 3/8-inch 4-40 machine bolts and nuts for the antenna hardware and 1/2-inch 6-32 for the support-structure connections to the support arms (1/2-inch aluminum tubing). The copper sheet is much easier to solder to than aluminum. Once completed, the feed received a few coats of white enamel paint to protect the copper and to minimize the visual reflections.

This is not the only dual-band antenna on AO-40. There are many varied, innovative designs available, including G6LVB's simple and effective 1.2-meter home-brew stressed *chicken wire* dish with a dual-G3RUH helix feed. G3WDG has a 3-meter dish with L/S-band helices and a K-band (1.3-cm) feed horn, and W0LMD has developed some popular dual- and tri-band "round" patch feeds. (See the Notes and References, as well as the CD-ROM bundled with this book.)

For additional information on constructing antennas, feeds and equipment techniques for use at microwave frequencies, see *The ARRL UHF/Microwave Experimenter's Manual* and *The ARRL UHF/Microwave Projects Manual*. Both of these books have a wealth of information for the experimenter.

PORTABLE HELIX FOR 435 MHZ

Helical antennas for 435 MHz are excellent uplinks for U-band satellite communications. The true circular polarization afforded by the helix minimizes signal *spin fading* that is so predominant in these applications. The antenna shown in **Fig 56** fills the need for an effective portable uplink antenna for OSCAR operation. Speedy assembly and disassembly and light weight are among the benefits of this array. This antenna was designed by Jim McKim, W0CY.

As mentioned previously, the helix is about the most tolerant of any antenna in terms of dimensions. The dimensions given here should be followed as closely as possible, however. Most of the materials specified are available in any well supplied do-it-yourself hardware or building supply store. The materials required to construct the portable helix are listed in **Table 1**.

The portable helix consists of eight turns of 1/4-inch soft-copper tubing spaced around a 1-inch fiberglass tube or maple dowel rod 4 feet, 7 inches long. Surplus aluminum jacket Hardline can be used instead of the copper tubing if necessary. The turns of the helix are supported by 5-inch lengths of 1/4-inch maple dowel mounted through the 1-inch rod in the center of the antenna. **Fig 57A** shows the overall dimensions of the antenna. Each of these support dowels has a V-shaped notch in the end to locate the tubing, as shown in Fig 57B.

The rod in the center of the antenna terminates at the feed-point end in a 4-foot piece of 1-inch ID galva-

Table 1

Parts List for the Portable 435-MHz Helix

Qty	*Item*
1	Type N female chassis mount connector
18 feet	1/4-in. soft copper tubing
4 feet	1-inch ID galvanized steel pipe
1	5 feet × 1-inch fiberglass tube or maple dowel
14	5-inch pieces of 1/4-inch maple dowel (6 feet total)
1	1/8-inch aluminum plate, 10 inches diameter
3	2 × 3/4-inch steel angle brackets
1	30 × 30-inch (round or square) aluminum screen or hardware cloth
8 feet	1/2 × 1/2 × 1/2-inch aluminum channel stock or old TV antenna element stock
3	Small scraps of Teflon or polystyrene rod (spacers for first half turn of helix)
1	1/8 × 5 × 5-inch aluminum plate (boom-to-mast plate)
4	1½-inch U bolts (boom-to-mast mounting)
3 feet	#22 bare copper wire (helix turns to maple spacers)

Assorted hardware for mounting connector, aluminum plate and screen, etc.

nized steel pipe. The pipe serves as a counterweight for the heavier end of the antenna. The 1-inch rod material inside the helix must be nonconductive. Near the point where the nonconductive rod and the steel pipe are joined, a piece of aluminum screen or hardware cloth is used as a reflector screen.

If you have trouble locating the 1/4-inch soft copper tubing, try a refrigeration supply house. The perforated aluminum screening can be cut easily with tin snips. This material is usually supplied in 30 × 30-inch sheets, making this size convenient for a reflector screen. Galvanized 1/4-inch hardware cloth or copper screen could also be used for the screen, but aluminum is easier to work with and is lighter.

A 1/8-inch-thick aluminum sheet is used as the support plate for the helix and the reflector screen. Surplus rack panels provide a good source of this material. **Fig 58** shows the layout of this plate.

Fig 59 shows how aluminum channel stock is used to support the reflector screen. (Aluminum tubing also works well for this. Discarded TV antennas provide plenty of this material if the channel stock is not available.) The screen is mounted on the bottom of the 10-inch aluminum center plate. The center plate, reflector screen and channel stock are connected together with plated hardware or pop rivets. This support structure is very sturdy. Fiberglass tubing is the best choice for the center rod material although maple dowel can be used.

Mount the type-N connector on the bottom of the center plate with appropriate hardware. The center pin should be exposed enough to allow a flattened end of the copper tubing to be soldered to it. Tin the end of the tubing after it is flattened so that no moisture can enter it. If the helix is to be removable from the ground-plane screen, do not solder the copper tubing to the connector. Instead, prepare a small block of brass, drilled and tapped at one side for a 6-32 screw. Drill another hole in the brass block to accept the center pin of the type-N connector, and solder this connection. Now the connection to the copper tubing helix can be made in the field with a 6-32 screw instead of with a soldering iron.

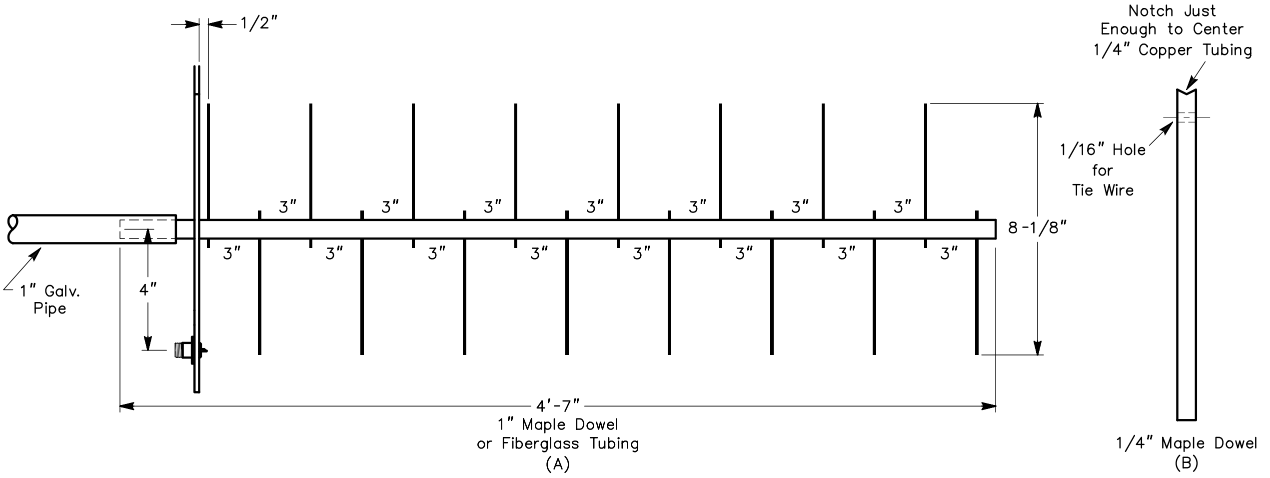


Fig 57—At A, the layout of the portable 435-MHz helix is shown. Spacing between the first 5-inch winding-support dowel and the ground plane is 1/2 inch; all other dowels are spaced 3 inches apart. At B, the detail of notching the winding-support dowels to accept the tubing is shown. As indicated, drill a 1/16-inch hole below the notch for a piece of small wire to hold the tubing in place.

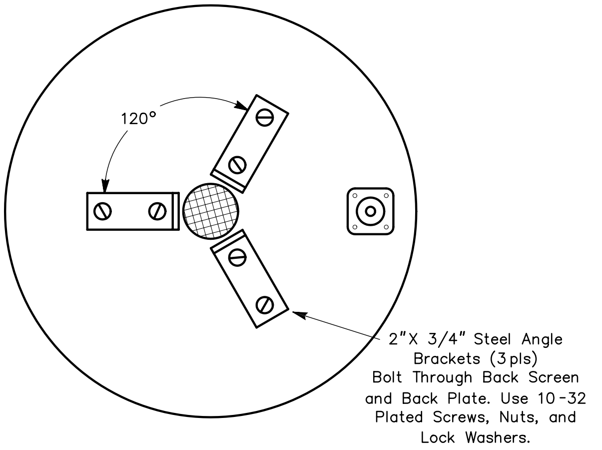


Fig 58—The ground plane and feed-point support assembly are shown. The circular piece is a 10-inch diameter, 1/8-inch thick piece of aluminum sheet. (A square plate may be used instead.) Three 2 × 3/4-inch angle brackets are bolted through this plate to the backside of the reflector screen to support the screen on the pipe. The type-N female chassis connector is mounted in the plate 4 inches from the 1-inch diameter center hole.

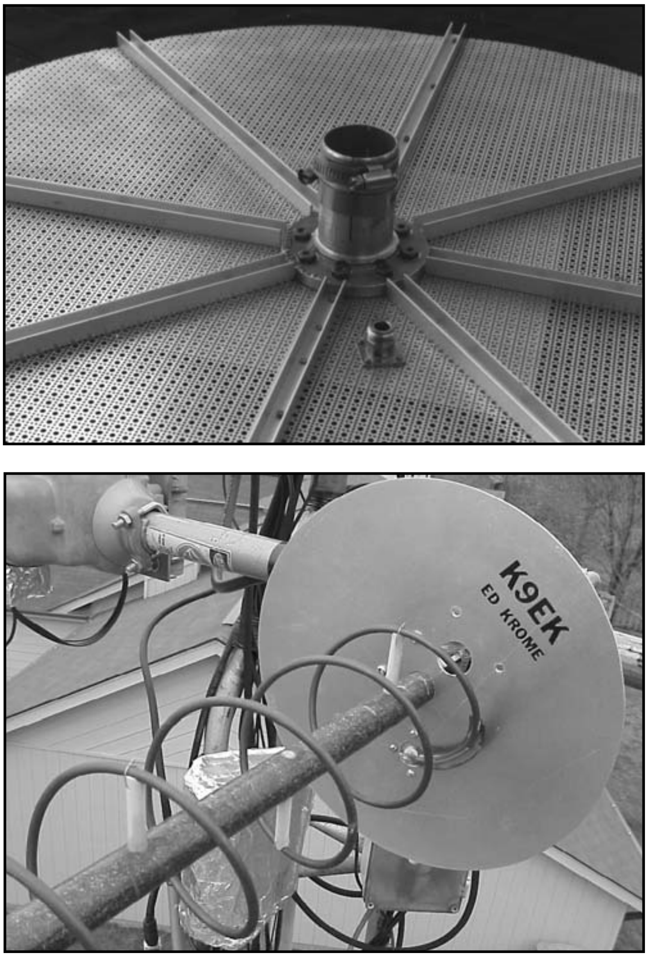


Fig 59—At top, the method of reinforcing the reflector screen with aluminum channel stock is shown. In this version of the antenna, the three angle brackets of Fig 58 have been replaced with a surplus aluminum flange assembly. (*W0CY photo.*) At bottom, this helix view shows the details of a 1/4-turn matching transformer, as discussed in the text. (*K9EK photo.*)

Refer to Fig 57A. Drill the fiberglass or maple rod at the positions indicated to accept the 5-inch lengths of 1/2-inch dowel. (If maple doweling is used, the wood must be weatherproofed as described below before drilling.) Drill a 1/16-inch hole near the notch of each 5-inch dowel to accept a piece of #22 bare copper wire. (The wire is used to keep the copper tubing in place in the notch.) Sand the ends of the 5-inch dowels so the glue will adhere properly, and epoxy them into the main support rod.

Begin winding the tubing in a clockwise direction from the reflector screen end. First drill a hole in the flattened end of the tubing to fit over the center pin of the type-N connector. Solder it to the connector, or put the screw into the brass block described earlier. Carefully proceed to bend the tubing in a circular winding from one support to the next.

See the earlier section entitled "50-Ω Helix Feed" and Figs 19 and 20 to see how the first half-turn of the helix tubing must be positioned close above the reflector assembly. **Fig 59B** shows also an excellent example by K9EK on matching his U-band helical antenna to a 52-Ω feed line. It is important to maintain this spacing, since extra capacitance between the tubing and ground is required for impedance-matching purposes.

Insert a piece of #22 copper wire in the hole in each support as you go. Twist the wire around the tubing and the support dowel. Solder the wire to the tubing and to itself to keep the tubing in the notches. Continue in this way until all eight turns have been wound. After winding the helix, pinch the far end of the tubing together and solder it closed.

Weatherproofing the Wood

A word about preparing the maple doweling is in order. Wood parts must be protected from the weather to ensure long service life. A good way to protect wood is to boil it in paraffin for about half an hour. Any holes to be drilled in the wooden parts should be drilled after the paraffin is applied, since epoxy does not adhere well to wood after it has been coated with paraffin. The small dowels can be boiled in a saucepan. Caution must be exercised here—the wood can be scorched if the paraffin is too hot. Paraffin is sold for canning purposes at most grocery stores. Wood parts can also be protected with three or four coats of spar varnish. Each coat must be allowed to dry fully before another coat is applied.

The fiberglass tube or wood dowel must fit snugly with the steel pipe. The dowel can be sanded or turned down to the appropriate diameter on a lathe. If fiberglass is used, it can be coupled to the pipe with a piece of wood dowel that fits snugly inside the pipe and the tubing. Epoxy the dowel splice into the pipe for a permanent connection.

Drill two holes through the pipe and dowel and bolt them together. The pipe provides a solid mount to the boom of the rotator, as well as most of the weight needed to counterbalance the antenna. More weight can be added to the pipe if the assembly is "front-heavy." (Cut off some of the pipe if the balance is off in the other direction.)

The helix has a nominal impedance of about 105 Ω in this configuration. By varying the spacing of the first half turn of tubing, a good match to 52-Ω coax should be obtainable. When the spacing has been established for the first half turn to provide a good match, add pieces of polystyrene or Teflon rod stock between the tubing and the reflector assembly to maintain the spacing. These can be held in place on the reflector assembly with silicone sealant. Be sure to seal the type-N connector with the same material.

Exposed Antenna Relays and Preamplifiers

For stations using crossed Yagi antennas for CP operation, one feature that has been quite helpful for communicating through most of the LEO satellites, has been the ability to switch polarization from RHCP to LHCP. In some satellite operation this switchable CP ability has been essential. Operation through AO-40 has not shown a great need for such CP agility, since if the satellite is seriously off-pointed the signals are not particularly useable. When AO-40's squint angle is less than 25° the need for LHCP has not been observed. For those using helical antennas or helical-fed dish antennas, we just would not have the choice to switch CP unless an entirely new antenna is added to the cluster for that purpose. Not many of us have the luxury of that kind of space available on our towers.

For stations with switchable-circularity Yagi antennas, experience with exposed circularity switching relays and preamplifiers mounted on antennas have shown that they are prone to failure caused by an elusive mechanism known as *diurnal pumping*. Often these relays are covered with a plastic case, and the seam between the case and PC board is sealed with a silicone sealant. Preamps may also have a gasket seal for the cover, while the connectors can easily leak air. None of these methods create a true hermetic seal and as a result the day/night temperature swings pump air and moisture in and out of the relay or preamp case. Under the right conditions of temperature and moisture content, moisture from the air will condense inside the case when the outside air cools down. Condensed water builds up inside the case, promoting extensive corrosion and unwanted electrical conduction, seriously degrading component performance in a short time.

A solution for those antennas with "sealed" plastic relays, such as the KLM CX series; you can avoid problems by making the modifications shown in **Fig 60**. Relocate the 4:1 balun as shown and place a clear polystyrene plastic refrigerator container over the relay. Notch the container edges for the driven element and the boom so the container will sit down over the relay, sheltering it from the elements. Bond the container in place with a few dabs of RTV adhesive sealant. Position the antenna in an "X" orientation, so neither set of elements is parallel to the ground. The switcher board should now be canted at an angle, and one side of the relay case should be lower than the other. An example for the protective cover for an S-band preamp can be seen in the discussion on feeds for parabolic antennas.

For both the relay and preamp cases, carefully drill a 3/32-inch hole through the low side of the case to provide the needed vent. The added cover keeps rainwater off the

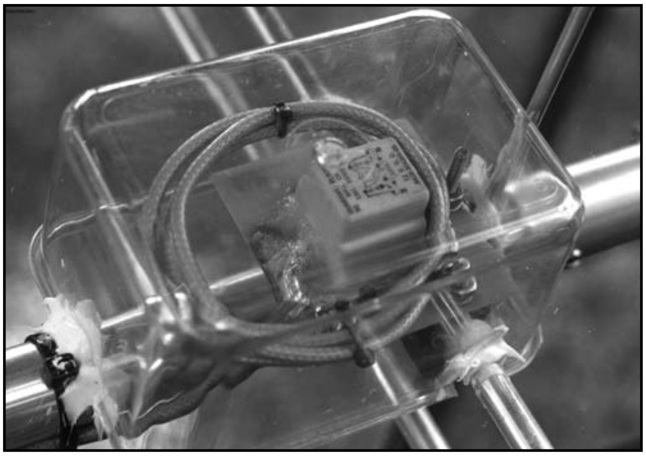


Fig 60—KLM 2M-22C antenna CP switching relay with relocated balun. The protective cover is needed for rain protection, be sure to use a polystyrene kitchen box, see text. (*WD4FAB photo.*)

Fig 61—A NEMA4 box is used to shelter the L-band electronics and power supply. The box flanges are convenient for mounting preamplifiers. The box is shown inverted since it is on a tilt-over tower. (*WD4FAB photo.*)

relay and preamp, and the holes will prevent any buildup of condensation inside the relay case. Relays and preamplifiers so treated have remained clean and operational over periods of years without problems.

Another example for the protection of remotely, tower-mounted equipment is shown in Fig 50, illustrating the equipment box and mast-mounted preamplifiers at the top of WD4FAB's tower. The commercial NEMA4-rated equipment box, detailed in **Fig 61** (shown inverted), is used to protect the 23-cm power amplifier and its power supply, as well as a multitude of electrical connections. This steel box is very weather resistant, with an exceptionally good epoxy finish, but it is not sealed and so it will not trap moisture to be condensed with temperature changes. Be sure to use a box with at least a NEMA3 rating for rainwater and dust protection. The NEMA4 rating is just a little better protection than the NEMA3 rating. Using a well-rated equipment box is very well worth the expense of the box. As you can see, the box also provides some pretty good flanges to mount the mast-mounted preamplifiers for three bands. This box is an elegant solution for the simple need of rain shelter for your equipment. See **Fig 62**.

Elevation Control

Satellite antennas need to have elevation control to point up to the sky. This is the "El" part of Az-El control of satellite antennas. Generally, elevation booms for CP satellite antennas need to be non-conducting so that the boom does not affect the radiation pattern of the antenna. In the example shown next, the elevation boom center section is a piece of extra-heavy-wall $1^1/_2$-inch pipe (for greater strength) coupled with a tubular fiberglass-epoxy boom extension on the 70-cm end and a home-brew long extension on the 2-meter end. This uses large PVC pipe reinforced with four braces of Phillystran non-metallic guy cable. (PVC pipe is notoriously flexible, but the Phillystran cables make a quite stiff and strong boom of the PVC pipe.) For smaller installations, a continuous piece of fiberglass-epoxy boom can be placed directly through the elevation rotator.

Elevation boom motion needs to be powered, and one solution by WD4FAB, shown in **Fig 63**, uses a surplus jackscrew drive mechanism. I8CVS has also built his own robust elevation mechanism. See **Fig 64**. Note in each of these applications the methods used to provide bearings for the elevation mechanism. In WD4FAB's case, the elevation axis is a piece of heavy-duty $1^1/_2$-inch pipe,

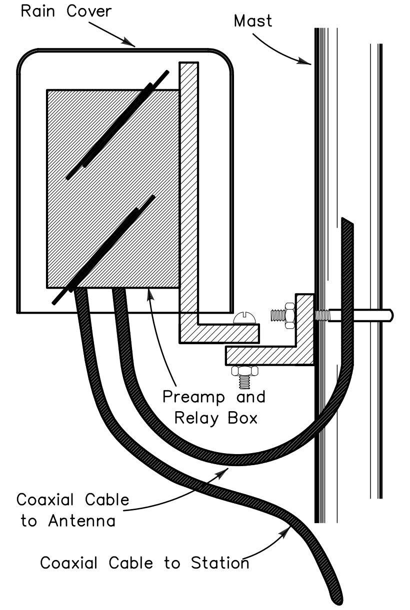


Fig 62—Protection for tower-mounted equipment need not be elaborate. Be sure to dress the cables as shown so that water drips off the cable jacket before it reaches the enclosure. One hazard for such open-bottom enclosures is that of animals liking the cable insulation as a delicacy. Flying insects also like to build their houses in these enclosures.

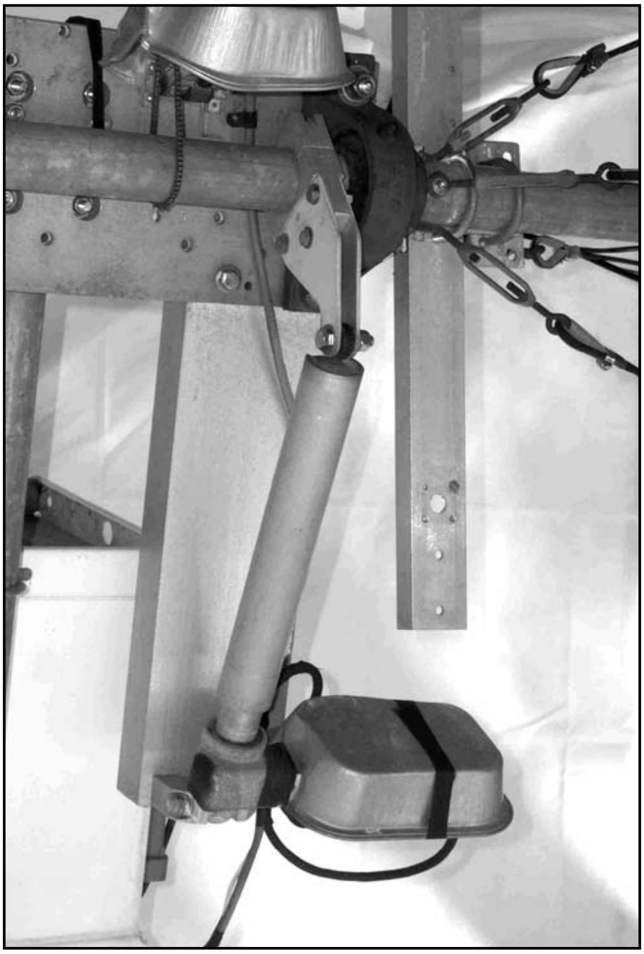


Fig 63—WD4FAB's homebrew elevation rotator drive using a surplus-store drive screw mechanism. Note also the large journal bearing supporting the elevation axis pipe shaft. (*WD4FAB photo.*)

($1^{15}/_{16}$-inch OD) and large 2 inch journal bearings are used for the motion. I8CVS uses a very large hinge to allow his motion.

Robust commercial solutions for Az-El rotators have given operators good service over the years. **See Fig 65**. Manufacturers such as Yaesu and M^2 are among these suppliers. One operator, VE5FP, found a solution for his Az-El needs by using two low-cost, lightweight TV rotators. See Fig 65B.

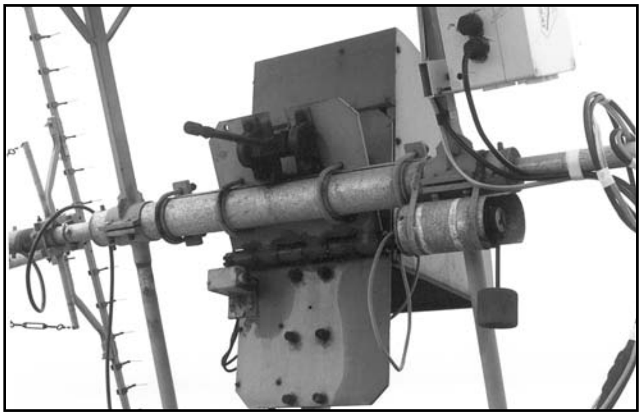


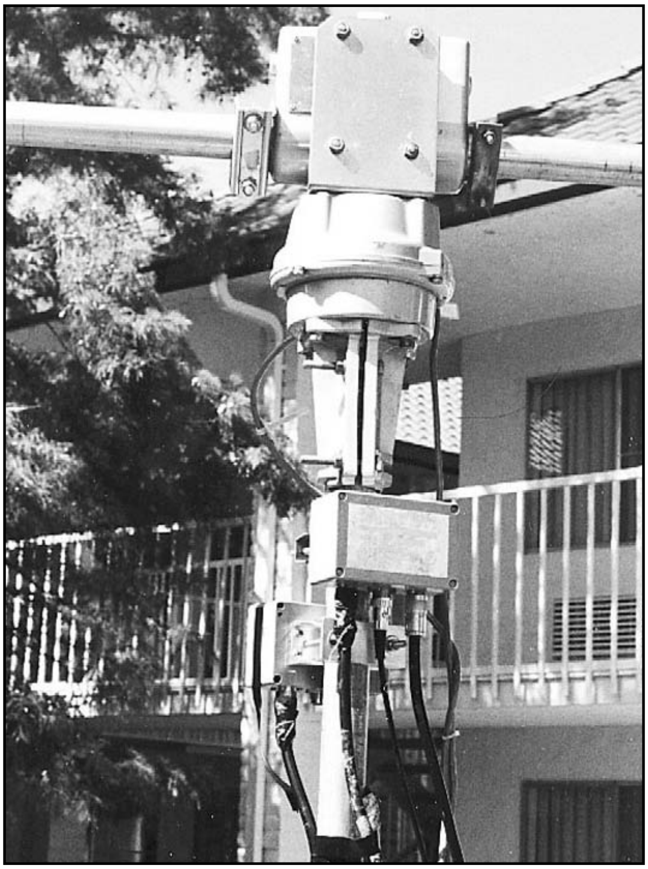
Fig 64—I8CVS's homebrew elevation mechanism using a very large, industrial hinge as the pivot and a jackscrew drive. (*I8CVS photo.*)

CONVERTED C-BAND TVRO DISHES

In working with larger, converted C-band TVRO dishes for AO-40, some operators have used only the polar mount with its jack-screw mechanism. See **Fig 66**. This dish is called *Big Ugly Dish* or just "BUD" by their users. Only using the polar mount mechanism limits the operator in the range of motion, as previously discussed. W0LMD provides for a greater degree of articulation of these dishes through several mechanisms. One of these is a sector-gear elevation drive, shown in **Fig 67**.

For the azimuth motion of our satellite antennas, most use motorized rotator drives, mainly the commercial sources previously mentioned. Most antennas are tower-mounted, allowing the placement of the rotator inside the tower. For the large wind loads of satellite antennas, these commercial rotators become rather expensive.

High loads are also prominent with the use of BUD



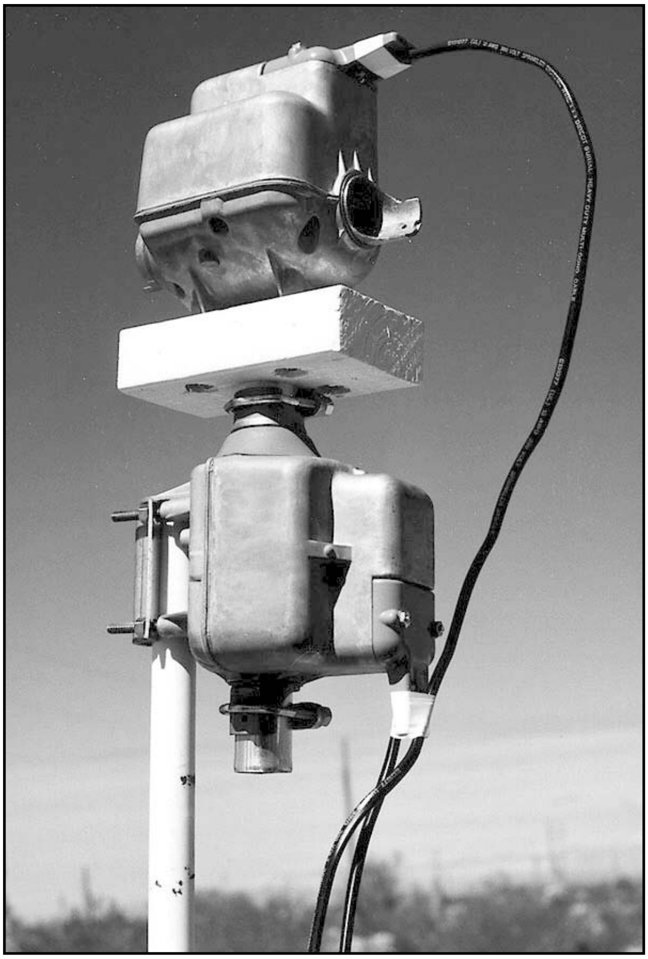


Fig 65—At left, Yaesu Az-El antenna-rotator mounting system is shown. Note that antenna loads must be more carefully balanced on this rotator than in the previously shown systems. At right, VE5FP has a solution for his Az-El rotators by bolting two of them together in his "An Inexpensive Az-El Rotator System", *QST*, December 1998.

Fig 66—A TVRO dish-drive system is shown on its polar mount, using a protected drive-screw mechanism. (*WØLMD photo.*)

Fig 67—A modified TVRO dish mount is shown using an Az-El mount and a sector-gear drive for the elevation. (*WØLMD photo.*)

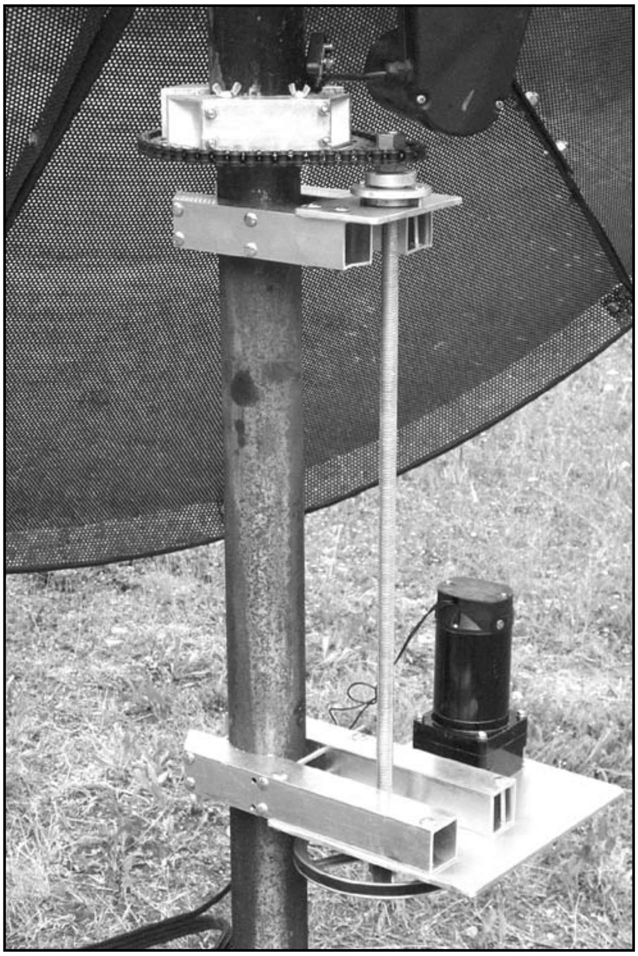


Fig 68—WØLMD constructed a very robust and low-cost Az drive mechanism. (*WØLMD photo.*)

antennas, and WØLMD has again engineered some very robust mechanisms using combinations of motorcycle-chain drives, V-belt drives and gear-head motors, as seen in **Fig 68**. An overall view of one of his BUD antennas is shown in **Fig 69**, showing the Az drive with an El drive that uses a jackscrew mechanism.

Operators through the years have employed many methods for the control of their antenna positions, ranging from true *arm-strong* manual positioning, to manual operation of the powered antenna azimuth and elevation rotators, to fully automated computer control of the rotators. While computer control of the rotators is not essential, life is greatly assisted with their use. For many years, one of the keystone control units for rotators has been the *Kansas City Tracker* (KCT) board installed in your computer. Most satellite-tracking programs can connect to the KCT with ease. One difficulty with the KCT unit is that they are 8-bit digital units, providing positioning precision of 0.35° in elevation and 1.41° in azimuth. For the larger dishes, with their narrow beamwidths, these values of precision are unacceptable. There are other options to replace the KCT unit.

A recent trend for amateur antenna control has been evolving in the form of a standalone controller that translates computer antenna-position information into controller commands with an understanding of antenna-position limits. These boxes, represented by the *EasyTrak* unit, **Fig 70**, from the Tucson Amateur Packet Radio (TAPR) group, have made this capability readily available for many amateurs. This unit is a 10-bit encoder, providing precisions of 0.09° in elevation and 0.35° in azimuth. The computer can also control the operation of your station transceiver through the radio interface provided in *EasyTrak*; you will not need any other radio interface.

Other position readout and control options are available. For many years ham operators have employed synchros, or *selsyns*, for their position readouts. These are

Fig 69—A completed TVRO dish Az-El mounting system is shown, using a jackscrew elevation drive. (*W0LMD photo.*)

Fig 70—The EasyTrak automated antenna rotator and radio controller by TAPR. (*WD4FAB photo.*)

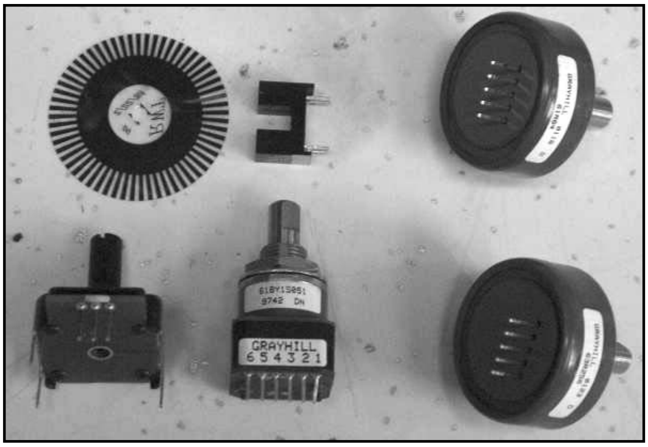


Fig 71—W0LMD has experimented with highly precise optical encoders for his antenna position systems. See text. (*W0LMD photo.*)

specialized transformers, using principles developed over sixty years ago and employed in such devices as surplus "radio compass" steering systems for aircraft. While the position readout of these devices can be quite precise, in general they only provide a visual position indication, one that is not easily adapted to computer control. I8CVS employs such a system at his station and his elevation synchro can be seen in Fig 64, using a weighted arm on the synchro to provide a constant reference to the Earth's gravity vector.

The more up-to-date, computer-friendly position readout methods used these days are usually based on precision potentiometers or digital code wheels. **Fig 71** shows such a digital code-wheel system employed by W0LMD. He notes that such systems, while providing a very high precision of angular position, they are not absolute systems and that once calibrated, they must be continually powered so they do not lose their calibration. Precision potentiometers, on the other hand, provide an absolute position reference, but with a precision that is limited to the quality of the potentiometer, typically 0.5% (0.45° in El and 1.80° in Az) to 1.0%. So the choices have their individual limits, unless a lot of money is spent for very precise commercial systems.

NOTES AND REFERENCES, SATELLITE ANTENNAS

AO-40 frequencies, "Official Transponder Frequency Bandplan for P-3D"; **www.amsat-dl.org/p3dqrg.html**.

Brown, Gerald R., K5OE, "A Helix Feed for Surplus MMDS, Antennas" *Proceedings of the 2001AMSAT-NA Symposium*, October 2001, pp 89-94, also: **members.aol.com/k5oe**.

Brown, Jerry, K5OE, "A K-Band Receiver for AO-40", *Proceedings for the AMSAT-NA Space Symposium, 2002*.

Brown, Gerald R., K5OE, "Build This No-Tune Dual-Band Feed for Mode L/S" *The AMSAT Journal*, Vol 26, No 1, Jan/Feb 2003.

Brown, Gerald R., K5OE, "Dual-Band Dish Feeds for 13/23 cm," *Proceedings of the 2002AMSAT-NA Symposium*, October 2002, pp 123-131.

Brown, Jerry, K5OE, **members.aol.com/k5oe/** MMDS Dishes.

Brown, Gerald R., K5OE, "Patch Feeds," **members.aol.com/k5oe**.

Brown, Jerry, K5OE, "The Texas Potato Masher: A Medium-Gain Directional Satellite Antenna For

LEOs," *The AMSAT Journal*, Vol 22, No. 1, Jan/Feb 1999.

Jansson, Dick, WD4FAB, *QST*, Sep 2002, "Product Review", "M^2 23CM22EZA 1.2 GHz Antenna", p 59.

Kingery, Mike, KE4AZN, "Setting Up for AO-40 L-Band Uplink," *The AMSAT Journal*, May/Jun 2002, pp 14-16, also: **web.infoave.net/~mkmk518/**.

Koehler, Jim, VE5FP, "An Inexpensive Az-El Rotator System", *QST*, Dec 1998.

Kraus, John D., "The Helical Antenna", Chapter 7, *Antennas*, McGraw-Hill Book Company, 1988.

Kraus, John D., W8JK, "16-12, Patch or Microstrip Antennas," *Antennas,* 1988, pp 745-749.

Krome, Ed, K9EK, "Development of a Portable Mode S Ground Station." *The AMSAT Journal*, Vol 16, No. 6, Nov/Dec 1993, pp 25-28.

Krome, Ed, K9EK, "S band Reception: Building the DEM Converter and Preamp Kits," *The AMSAT Journal*, Vol 16, No. 2, Mar/Apr 1993, pp 4-6.

Krome, Ed., K9EK, *Mode S—The Book*, p 96, 109.

Krome, Ed, K9EK, "Mode S: Plug and Play!" *The AMSAT Journal*, Vol 14, No. 1, Jan 1991, pp 21-23, 25.

Long, Howard, G6LVB, "My Shack Configuration—Spring 2002": **www.g6lvb.com/g6lvb_shack_spring_2002.htm**.

McCaa, William D., K0RZ, "Hints on Using the AMSAT-OSCAR 13 Mode S Transponder," *The AMSAT Journal*, Vol 13, No. 1, Mar 1990, pp 21-22.

MacAllister, Andy, W5ACM, "Field Day 2002," *73 Amateur Radio Today,* Sept. 2002, pp 48-52.

Miller, James, G3RUH, "Mode S — Tomorrow's Downlink?" *The AMSAT Journal*, Vol 15, No. 4, Sep/Oct 1992, pp 14-15.

Miller, James S., G3RUH, "'Patch' Feed For S-Band Dish Antennas"; **www.jrmiller.demon.co.uk/products/patch.html**.

Miller, James, G3RUH, "A 60-cm S-Band Dish Antenna," *The AMSAT Journal*, Vol 16 No. 2, Mar/Apr 1993, pp 7-9.

Miller, James, G3RUH, "Small is Best," *The AMSAT Journal*, Vol 16, No. 4, Jul/Aug 1993, p 12.

Monteiro, Anthony, "Work OSCAR 40 with Cardboard-box Antennas!," *QST*, Mar 2003, pp 57-62.

Orban Microwave, "The Basics of Patch Antennas: **www.orbanmicrowave.com/antenna_application_notes.htm**.

Seguin, Mike, N1JEZ, "OSCAR 40 on 24GHz", *QST*, Dec 2002, pp 55-56.

Seydler, Robert, K5GNA,"Modifications of the AIDC 3731 Downconverters", **members.aol.com/k5gna/AIDC3731modifications.doc**.

Suckling, Charles, G3WDG, "K-Band Results From AO-40": **www.g3wdg.free-online.co.uk/kband.htm**.

Suckling, Charles, G3WDG "Notch Filters for AO-40 Mode L/S": **www.g3wdg.free-online.co.uk.notch.htm**.

Suding, Dr. Robert, W0LMD, "Converting TVRO Dish & Dishes For Amateurs" **www.ultimatecharger.com/dish.html**.

Thiel, David & Smith, Staphani, *Switched Parasitic Antennas for Cellular Communications*, Artech House, 2002, "Chapter 3, Patch Antennas," pp 79-96.

Wade, Paul, N1BWT (W1GHZ), *Online Microwave Antenna Handbook*, "Chapter 4, Parabolic Dish Antennas," **www.w1ghz.cx/antbook/chap4.pdf**, Mar. 98. (See CD-ROM bundled with this book.)

Zibrat,Timothy S, K3TZ, "2.4 GHz Patch Design": **www.qsl.net/k3tz/**.

Antenna Systems for EME Communications

This section was updated by David Hallidy, K2DH. As mentioned earlier, the tremendous path loss incurred over an EME circuit places stringent requirements on Earth-station performance. Low-noise receiving equipment, maximum available power and high-gain antenna arrays are required for successful EME operation. Although it is possible to copy some of the better-equipped stations with a low-gain antenna, it is unlikely that such an antenna can provide reliable two-way communications. Antenna gain of at least 20 dBi is required for reasonable EME success. Generally speaking, more antenna gain yields the most noticeable improvement in station performance, since the increased gain improves both the received and transmitted signals.

VHF/UHF EME ANTENNAS

Several types of antennas for 2 meters and 70 cm are popular among EME enthusiasts. Perhaps the most popular antenna for 144-MHz work is an array of either 4 or 8 long-boom (14 to 15 dBi gain) Yagis. The 4-Yagi array provides approximately 20 dB gain, and an 8-Yagi array gives an approximate 3 dB increase over the 4-antenna array. **Fig 72** shows the computed response at a 30° tilt above the horizon for a stack of four 14-element 2-meter Yagis, each with a boomlength of 3.1 λ (22 feet).

At 432 MHz, EME enthusiasts often use 8 or 16 long-boom Yagis in an array. Such Yagis are commercially available or they can be constructed from readily available materials. Chapter 18, VHF and UHF Antenna Systems, has details on some popular Yagi designs.

The main disadvantage of Yagi arrays is that the polarization plane of the individual Yagis cannot be conveniently changed. One way around this is to use cross-polarized Yagis and a relay switching system to select the desired polarization, as described in the previous section. This represents a considerable increase in system complexity to select the desired polarization. Some amateurs have gone so far as to build complicated mechanical systems to allow constant polarization adjustment of all the Yagis in a large array. **Fig 73** shows the K1FO 70-cm EME 16-Yagi array with full polarization control, described in *The ARRL Antenna Compendium, Vol 3*. This 432-MHz EME array uses open-wire phasing lines to minimize feed-line losses. **Fig 74** shows the computed response for this array, which employs rugged but lightweight 14-element Yagis on 3.1 λ (7.1 foot) booms. Feed-line losses are not explicitly accounted for in the *EZNEC Professional* computer model, but are estimated to be less than 0.25 dB.

Polarization shift of EME signals at 144 MHz is fairly rapid, and the added complexity of a relay-controlled cross-polarized antenna system or a mechanical polarization adjustment scheme is probably not worth the effort. At 432 MHz, however, where the polarization shifts at a much slower rate, an adjustable polarization system does offer a definite advantage over a fixed one.

The Yagi antenna system used by Ed Stallman, N5BLZ, is shown in **Fig 75**. His system employs twelve 144-MHz long-boom 17-element Yagi antennas. The monster 48-Yagi 2-meter array of Gerald Williamson, K5GW, is shown in **Fig 76**, and the huge 48-Yagi 70-cm EME array of Frank Potts, NC1I, is shown in **Fig 77**.

Although not as popular as Yagis, Quagi antennas (made from both quad and Yagi elements) are sometimes used for EME work. Slightly more gain per unit boom length is possible as compared to the conventional Yagi, at the expense of some robustness. Additional information on the Quagi is presented in Chapter 18, VHF and UHF Antenna Systems.

The collinear array is an older type of antenna for EME work. A 40-element collinear array has approximately

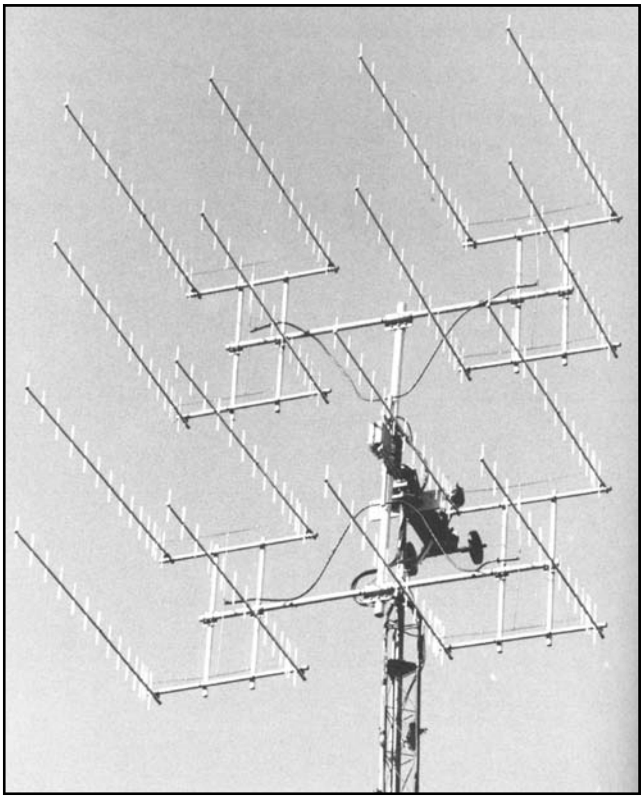


Fig 73—K1FO's variable polarization 16 × 14-element (3.6-λ boom lengths) 432-MHz EME array shown at 2° elevation and vertical polarization. (See *The ARRL Antenna Compendium, Vol 3*.)

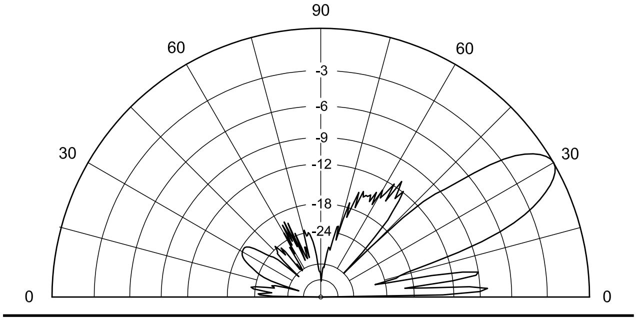


Fig 72—*EZNEC Pro* elevation pattern for four 14-element 2-meter Yagis (3.6-λ boom lengths) at an elevation angle of 30° above the horizon. The computed system gain is 21.5 dBi, suitable for 2-meter EME. This assumes that the phasing system is made of open-wire transmission lines so that feed-line losses can be kept below 0.25 dB.

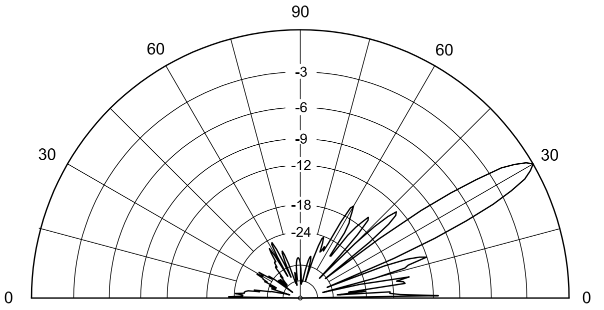


Fig 74—Computed elevation response for K1FO 16-Yagi 432-MHz array shown in Fig 73. (The *EZNEC Pro* model required 2464 segments!) With assumed phasing harness feed-line losses of 0.25 dB, the overall gain exceeds 27.5 dBi.

the same frontal area as an array of four Yagis, but produces approximately 1 to 2 dB less gain. One attraction to a collinear array is that the depth dimension is considerably less than the long-boom Yagis. An 80-element collinear is marginal for EME communications, providing approximately 19 dB gain. As with Yagi and Quagi antennas, the collinear cannot be adjusted easily for polarity changes. From a construction standpoint, there is little difference in complexity and material costs between the collinear and Yagi arrays.

DISH ANTENNAS FOR EME

On 2 meters the minimum antenna gain for reliable EME communications is about 20 dBi. While a few amateurs have had access to parabolic dishes large enough for EME work at 144 and 222 MHz, at those frequencies an array of four long Yagis is equal in gain to a dish 24 feet in diameter! To achieve truly high-gain performance from a dish on 2 meters would require a reflector diameter of nearly 96 feet (providing 32 dBi gain). Such undertakings are generally beyond amateur means, so there has been little work done with dishes at low frequencies, except for the occasional expedition to one of the large radio telescopes that have accommodated amateur EME work.

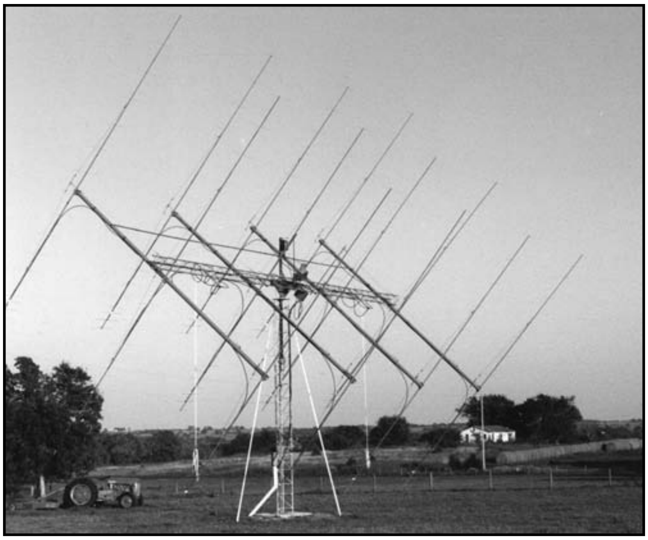


Fig 75—The EME array used at N5BLZ consists of twelve long-boom 144-MHz Yagis. The tractor, lower left, really puts this array into perspective! (*Photo courtesy N5BLZ.*)

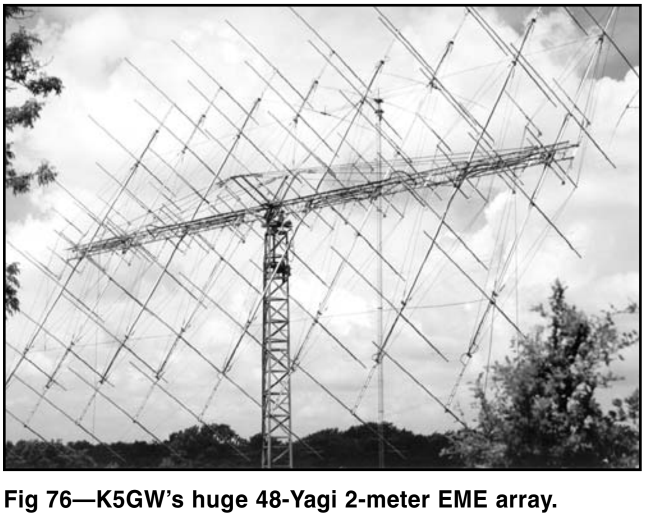


Fig 76—K5GW's huge 48-Yagi 2-meter EME array. (*Photo courtesy K5GW.*)

Microwave Parabolic Dish Antennas

The major problems associated with parabolic dish antennas are mechanical ones. A dish of about 16 feet in diameter is the minimum size required for successful EME operation on 432 MHz. With wind and ice loading, structures of this size place a real strain on the mounting and positioning system. Extremely rugged mounts are required for large dish antennas, especially when used in windy locations. **Fig 78** shows the impressive 7-meter diameter

Fig 77—NC1I's magnificent 48-Yagi 70-cm EME array. (*Photo courtesy NC1I.*)

dish built by David Wardley, ZL1BJQ.

Several aspects of parabolic dish antennas make the extra mechanical problems worth the trouble, however. For example, the dish antenna is inherently broadband, and may be used on several different amateur bands by simply changing the feed. An antenna that is suitable for 432 MHz work will most likely be usable on several of the higher amateur bands too. Increased gain is available as the frequency of operation is increased.

Another advantage of a dish is the flexibility of the feed system. The polarization of the feed, and therefore the polarization of the antenna, can be changed with little difficulty. It is a relatively easy matter to devise a system to rotate the feed remotely from the shack to change polarization. Because polarization changes can account for as much as 30 dB of signal attenuation, the rotatable feed can make the difference between consistent communications and no communications at all. Further information on Parabolic Antennas can be found in Chapter 18, VHF and UHF Antenna Systems as well as in the section below.

A 12-FOOT STRESSED HOMEBREW PARABOLIC DISH

Very few antennas evoke as much interest among UHF amateurs as the parabolic dish, and for good reason. First, the parabola and its cousins—Cassegrain, hog horn and Gregorian—are probably the ultimate in high-gain antennas. One of the highest-gain antennas in the world (148 dB) is a parabola. This is the 200-inch Mt. Palomar telescope. (The very short wavelength of light rays causes such a high gain to be realizable.)

Second, the efficiency of the parabola does not change as size increases. With Yagis and collinear arrays, the losses in the phasing harness increase as the array size increases. The corresponding component of the parabola is lossless air between the feed horn and the reflecting surface. If there are a few surface errors, the efficiency of the system stays constant regardless of antenna size. This project was presented by Richard Knadle, K2RIW, in August 1972 *QST*.

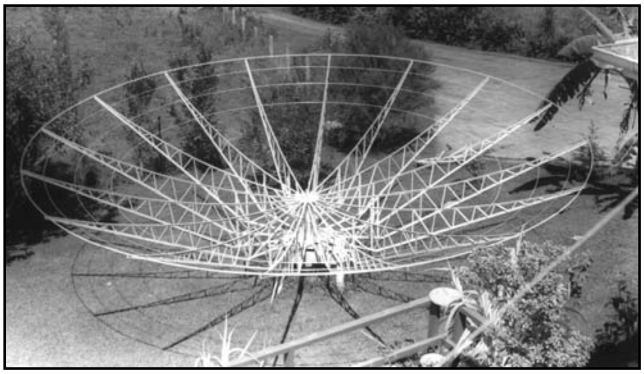


Fig 78—ZL1BJQ's homemade 7-meter (23-foot) parabolic dish, just prior to adding 1/2-inch wire mesh. (*Photo courtesy ZL1BJQ.*)

Some amateurs reject parabolic antennas because of the belief that they are all heavy, hard-to-construct, have large wind-loading surfaces and require precise surface accuracy. However, with modern construction techniques, a prudent choice of materials and an understanding of accuracy requirements, these disadvantages can be largely overcome. A parabola may be constructed with a 0.6 f/D (focal length/diameter) ratio, producing a rather flat dish, which makes it easy to surface and allows the use of recent advances in high-efficiency feed horns. This results in greater gain for a given dish size over conventional designs.

Such an antenna is shown in **Fig 79**. This parabolic dish is lightweight, portable, easy to build, and can be used for 432 and 1296-MHz mountain topping, as well as on 2304, 3456 and 5760 MHz. Disassembled, it fits into the trunk of a car, and can be assembled in 45 minutes.

The usually heavy structure that supports the surface of most parabolic dish antennas has been replaced in this design by aluminum spokes bent into a near parabolic shape by string. These strings serve the triple function of guying the focal point, bending the spokes and reducing the error at the dish perimeter (as well as at the center) to nearly zero. By contrast, in conventional designs, the dish perimeter (which has a greater surface area than the center) is farthest from the supporting center hub. For these reasons, it often has the greatest error. This error becomes more severe when the wind blows.

Here, each of the spokes is basically a cantilevered beam with end loading. The equations of beam bending

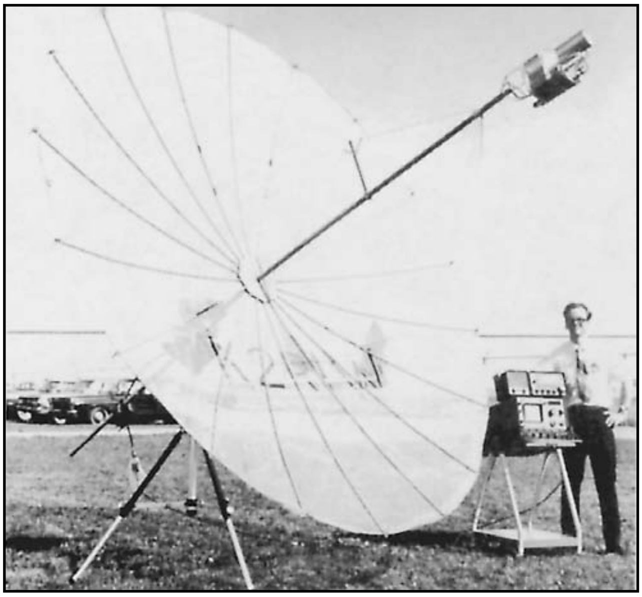


Fig 79—A 12-foot stressed parabolic dish set up for satellite signals near 2280 MHz. A preamplifier is shown taped below the feed horn. The dish was designed by K2RIW, standing at the right. From *QST*, August 1972.

predict a near-perfect parabolic curve for extremely small deflections. Unfortunately the deflections in this dish are not that small and the loading is not perpendicular. For these reasons, mathematical prediction of the resultant curve is quite difficult. A much better solution is to measure the surface error with a template and make the necessary correction by bending each of the spokes to fit. This procedure is discussed later.

The uncorrected surface is accurate enough for 432 and 1296-MHz use. Trophies taken by this parabola in antenna-gain contests were won using a completely natural surface with no error correction. By placing the transmission line inside the central pipe that supports the feed horn, the area of the shadows or blockages on the reflector surface is much smaller than in other feeding and supporting systems, thus increasing gain. For 1296 MHz, a backfire feed horn may be constructed to take full advantage of this feature. At 432 MHz, a dipole and reflector assembly produces 1.5 dB additional gain over a corner-reflector feed system. Because the preamplifier is located right at the horn on 2300 MHz, a conventional feed horn may be used.

Construction

Table 2 is a list of materials required for construction. Care must be exercised when drilling holes in the connecting center plates so assembly problems will not be experienced later. See **Fig 80**. A notch in each plate allows them to be assembled in the same relative positions. The two plates should be clamped together and drilled at the same time. Each of the 18$^1/_2$-inch diameter aluminum spokes has two no. 28 holes drilled at the base to accept no. 6-32 machine screws that go through the center plates. The 6-foot long spokes are cut from standard 12-foot lengths of tubing. A fixture built from a block of aluminum assures that the holes are drilled in exactly the same position in each spoke. The front and back center plates constitute an I-beam type of structure that gives the dish center considerable rigidity.

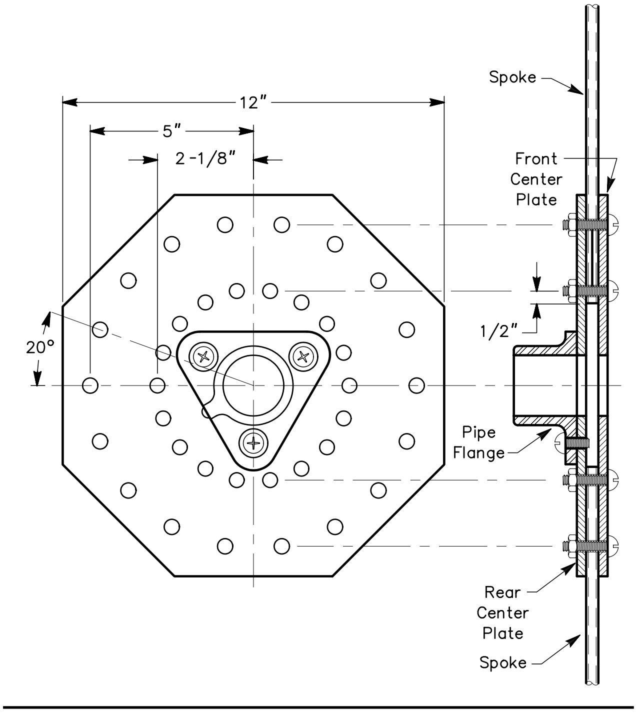


Fig 80—Center plate details. Two center plates are bolted together to hold the spokes in place.

A side view of the complete antenna is shown in **Fig 81**. Aluminum alloy (6061-T6) is used for the spokes, while 2024-T3 aluminum alloy sheet, $^1/_8$ inch thick, is used for the center plates. (Aluminum has approximately three times the strength-to-weight ratio of wood, and aluminum cannot warp or become water logged.) The end of each of the 18 spokes has an eyebolt facing the dish focal point, which serves a dual purpose:

1) To accept the #9 galvanized fence wire that is routed through the screw eyes to define the dish perimeter, and
2) To facilitate rapid assembly by accepting the S hooks which are tied to the end of each of the lengths of 130-pound test Dacron fishing string.

The string bends the spokes into a parabolic curve; the dish may be adapted for many focal lengths by tightening or slackening the strings. Dacron was chosen because it has the same chemical formula as Mylar. This is a low-stretch material that keeps the dish from changing shape. The galvanized perimeter wire has a 5-inch overlap area that is bound together with baling wire after the spokes have been hooked to the strings.

The aluminum window screening is bent over the perimeter wire to hold it in place on the back of the spokes. Originally, there was concern that the surface perturbations (the spokes) in front of the screening might decrease the gain. The total spoke area is so small, however, that

Table 2

Materials List for the 12-Foot Stressed Parabolic Dish

1) Aluminum tubing, 12 ft × $^1/_2$ in. OD × 0.049-in. wall, 6061-T6 alloy, 9 required to make 18 spokes.
2) Octagonal mounting plates 12 × 12 × $^1/_8$ in., 2024-T3 alloy, 2 required.
3) 1$^1/_4$ in. ID pipe flange with setscrews.
4) 1$^1/_4$ in. × 8 ft TV mast tubing, 2 required.
5) Aluminum window screening, 4 × 50 ft.
6) 130-pound test Dacron trolling line.
7) 38 ft #9 galvanized fence wire (perimeter).
8) Two hose clamps, 1$^1/_2$ in.; two U bolts; $^1/_2$ × 14 in. Bakelite rod or dowel; water-pipe grounding clamp; 18 eye bolts; 18 S hooks.

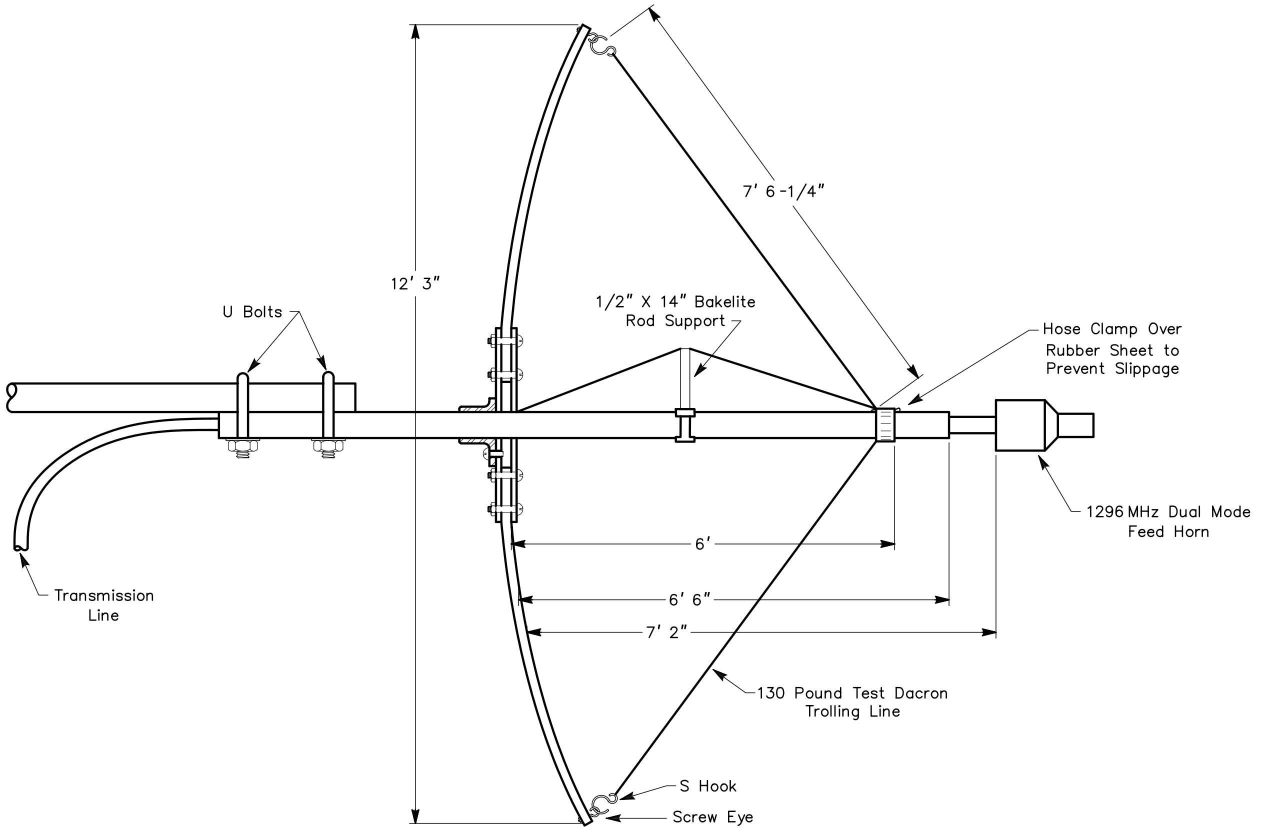


Fig 81—Side view of the stressed parabolic dish.

this fear proved unfounded.

Placing the aluminum screening in front of the spokes requires the use of 200 pieces of baling wire to hold the screening in place. This would increase the assembly time by at least an hour. For contest and mountaintop operation (when the screening is on the back of the spokes) no fastening technique is required other than bending the screen to overlap the wire perimeter.

The Parabolic Surface

A 4-foot wide roll of aluminum screening 50 feet long is cut into appropriate lengths and laid parallel, with a 3-inch overlap between the top of the unbent spokes and hub assembly. The overlap seams are sewn together on one half of the dish using heavy Dacron thread and a sailmaker's curved needle. Every seam is sewn twice; once on each edge of the overlapped area. The seams on the other half are left open to accommodate the increased overlap that occurs when the spokes are bent into a parabola. The perimeter of the screening is then trimmed. Notches are cut in the 3-inch overlap to accept the screw eyes and S hooks.

The first time the dish is assembled, the screening strips are anchored to the inside surface of the dish and the seams sewn in this position. It is easier to fabricate the surface by placing the screen on the back of the dish frame with the structure inverted. The spokes are sufficiently strong to support the complete weight of the dish when the perimeter is resting on the ground.

The 4-foot wide strips of aluminum screening conform to the compound bend of the parabolic shape very easily. If the seams are placed parallel to the E-field polarization of the feed horn, minimum feedthrough will occur. This feedthrough, even if the seams are placed perpendicular to the E field, is so small that it is negligible. Some constructors may be tempted to cut the screening into pie-shaped sections. This procedure will increase the seam area and construction time considerably. The dish surface appears most pleasing from the front when the screening perimeter is slipped between the spokes and the perimeter wire, and is then folded back over the perimeter wire. In disassembly, the screening is removed in one piece, folded in half, and rolled.

The Horn and Support Structure

The feed horn is supported by $1\frac{1}{4}$-inch aluminum television mast. The Hardline that is inserted into this tubing is connected first to the front of the feed horn, which then slides back into the tubing for support. A setscrew assures that no further movement of the feed horn occurs. During antenna-gain competition the setscrew is omit-

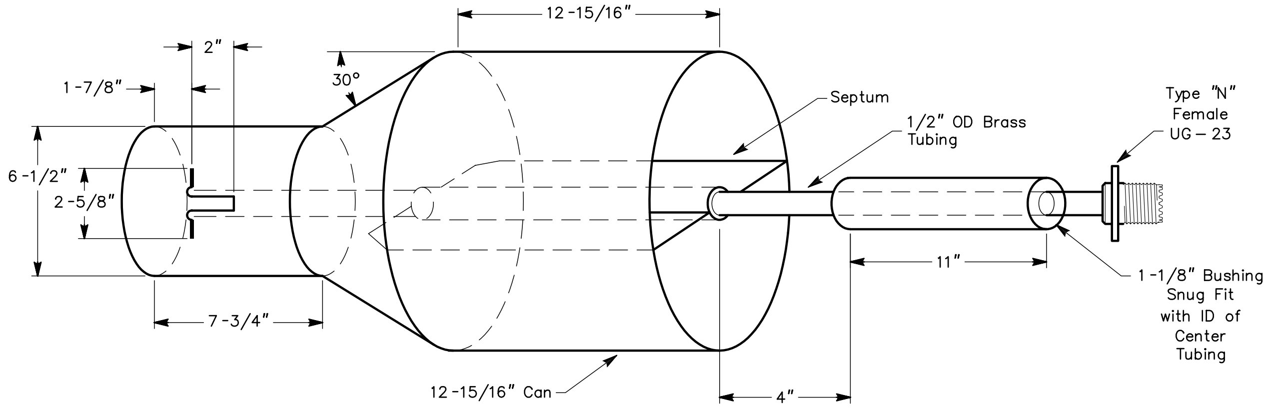


Fig 82—Backfire type 1296-MHz feed horn, linear polarization only. The small can is a Quaker State oil container; the large can is a 50-pound shortening container (obtained from a restaurant, Gold Crisp brand). Brass tubing, $\frac{1}{2}$-inch OD extends from UG-23 connector to dipole. Center conductor and dielectric are obtained from $\frac{3}{8}$-inch Alumafoam coaxial cable. The dipole is made from 3/32-inch copper rod. The septum and 30° section are made from galvanized sheet metal. Styrofoam is used to hold the septum in position. The primary gain is 12.2 dBi.

ted, allowing the $\frac{1}{2}$-inch semirigid CATV transmission line to move in or out while adjusting the focal length for maximum gain. The TV mast is held firmly at the center plates by two setscrews in the pipe flange that is mounted on the rear plate. At 2300 MHz, the dish is focused for best gain by loosening these setscrews on the pipe flange and sliding the dish along the TV mast tubing. (The dish is moved instead of the feed horn.)

The fishing strings are held in place by attaching them to a hose clamp that is permanently connected to the TV tubing. A piece of rubber sheet under the hose clamp prevents slippage and keeps the hose clamp from cutting the fishing string. A second hose clamp is mounted below the first as extra protection against slippage.

The high-efficiency 1296-MHz dual mode feed horn, detailed in **Fig 82**, weighs $5\frac{3}{4}$ pounds. This weight causes some bending of the mast tubing, but this is corrected by a $\frac{1}{2}$-inch diameter bakelite support, as shown in Fig 81. This support is mounted to a pipe grounding clamp with a no. 8-32 screw inserted in the end of the rod. The bakelite rod and grounding clamp are mounted midway between the hose clamp and the center plates on the mast. A double run of fishing string slipped over the notched upper end of the bakelite rod counteracts bending.

The success of high-efficiency parabolic antennas is primarily determined by feed horn effectiveness. The multiple diameter of this feed horn may seem unusual. This patented dual-mode feed, designed by Dick Turrin, W2IMU, achieves efficiency by launching two different kinds of waveguide modes simultaneously. This causes the dish illumination to be more constant than conventional designs.

Illumination drops off rapidly at the perimeter, reducing spillover. The feed backlobes are reduced by at least 35 dB because the current at the feed perimeter is almost zero; the phase center of the feed system stays constant across the angles of the dish reflector. The larger diameter section is a phase corrector and should not be changed in length. In theory, almost no increase in dish efficiency can be achieved without increasing the feed size in a way that would increase complexity, as well as blockage.

The feed is optimized for a 0.6 f/D dish. The dimensions of the feeds are slightly modified from the original design in order to accommodate the cans. Either feed type can be constructed for other frequencies by changing the scale of all dimensions.

Multiband Use

Many amateurs construct multiband antenna arrays by putting two dishes back to back on the same tower. This is cost inefficient. The parabolic reflector is a completely frequency independent surface, and studies have shown that a 0.6 f/D surface can be steered seven beamwidths by moving the feed horn from side to side before the gain diminishes by 1 dB. Therefore, the best dual-band antenna can be built by mounting separate horns side by side. At worst, the antenna may have to be moved a few degrees (usually less than a beamwidth) when switching between horns, and the unused horn increases the shadow area only slightly. In fact, the same surface can function simultaneously on multiple frequencies, making crossband duplex operation possible with the same dish.

Order of Assembly

1) A single spoke is held upright behind the rear center plate with the screw eye facing forward. Two no. 6-

32 machine screws are pushed through the holes in the rear center plate, through the two holes of the spoke, and into the corresponding holes of the front center plate. Lock washers and nuts are placed on the machine screws and hand tightened.

2) The remaining spokes are placed between the machine screw holes. Make sure that each screw eye faces forward. Machine screws, lock washers and nuts are used to mount all 18 spokes.
3) The no. 6-32 nuts are tightened using a nut driver.
4) The mast tubing is attached to the spoke assembly, positioned properly, and locked down with the setscrews on the pipe flange at the rear center plate. The S hooks of the 18 Dacron strings are attached to the screw eyes of the spokes.
5) The ends of two pieces of fishing string (which go over the bakelite rod support) are tied to a screw eye at the forward center plate.
6) The dish is laid on the ground in an upright position and #9 galvanized wire is threaded through the eyebolts. The overlapping ends are lashed together with baling wire.
7) The dish is placed on the ground in an inverted position with the focus downward. The screening is placed on the back of the dish and the screening perimeter is fastened as previously described.
8) The extension mast tubing (with counterweight) is connected to the center plate with U bolts.
9) The dish is mounted on a support and the transmission line is routed through the tubing and attached to the horn.

Parabola Gain Versus Errors

How accurate must a parabolic surface be? This is a frequently asked question. According to the Rayleigh limit for telescopes, little gain increase is realized by making the mirror accuracy greater than ± $^{1}/_{8}\ \lambda$ peak error. John Ruze of the MIT Lincoln Laboratory, among others, has derived an equation for parabolic antennas and built models to verify it. The tests show that the tolerance loss can be predicted within a fraction of a decibel, and less than 1 dB of gain is sacrificed with a surface error of $\pm^{1}/_{8}\ \lambda$. (A $^{1}/_{8}\ \lambda$ is 3.4 inches at 432 MHz, 1.1 inches at 1296 MHz and 0.64 inch at 2300 MHz.)

Some confusion about requirements of greater than $^{1}/_{8}$-λ accuracy may be the result of technical literature describing highly accurate surfaces. Low sidelobe levels are the primary interest in such designs. Forward gain is a much greater concern than low sidelobe levels in amateur work; therefore, these stringent requirements do not apply.

When a template is held up against a surface, positive and negative (±) peak errors can be measured. The graphs of dish accuracy requirements are frequently plotted in terms of RMS error, which is a mathematically derived function much smaller than ± peak error (typically $^{1}/_{3}$). These small RMS accuracy requirements have discouraged many constructors who confuse them with ± peak errors.

Fig 83 may be used to predict the resultant gain of various dish sizes with typical errors. There are a couple of surprises, as shown in **Fig 84**. As the frequency is increased for a given dish, the gain increases 6 dB per octave until the tolerance errors become significant. Gain deterioration then increases rapidly. Maximum gain is realized at the frequency where the tolerance loss is 4.3 dB. Notice that at 2304 MHz, a 24-foot dish with ±2-inch peak errors has the same gain as a 6-foot dish with ±1-inch peak errors. This is quite startling, when it is realized that a 24-foot dish has 16 times the area of a 6-foot dish. Each time the diameter or frequency is doubled or halved, the gain changes by 6 dB. Each time all the errors are halved, the frequency of maximum gain is doubled. With this information, the gain of other dish sizes with other tolerances can be predicted.

These curves are adequate for predicting gain, assuming a high-efficiency feed horn is used (as described earlier), which realizes 60% aperture efficiency. At frequencies below 1296 MHz where the horn is large and causes considerable blockage, the curves are somewhat optimistic. A properly built dipole and splasher feed will have about 1.5 dB less gain when used with a 0.6 f/D dish than the dual-mode feed system described.

The worst kind of surface distortion is where the surface curve in the radial direction is not parabolic but gradually departs in a smooth manner from a perfect parabola. The decrease in gain can be severe, because a large area is involved. If the surface is checked with a template, and if reasonable construction techniques are employed, deviations are controlled and the curves represent an upper limit to the gain that can be realized.

If a 24-foot dish with ±2-inch peak errors is being used with 432 and 1296-MHz multiple feed horns, the constructor might be discouraged from trying a 2300-MHz feed because there is 15 dB of gain degradation. The dish will still have 29 dBi of gain on 2300 MHz, however, making it worthy of consideration.

The near-field range of this 12-foot stressed dish (actually 12 feet 3 inches) is 703 feet at 2300 MHz. By using the sun as a noise source and observing receiver noise power, it was found that the antenna had two main lobes about 4° apart. The template showed a surface error (insufficient spoke bending at $^{3}/_{4}$ radius), and a correction was made. A recheck showed one main lobe, and the solar noise was almost 3 dB stronger.

Other Surfacing Materials

The choice of surface materials is a compromise between RF reflecting properties and wind loading. Aluminum screening, with its very fine mesh (and weight of 4.3 pounds per 100 square feet) is useful beyond 10 GHz because of its very close spacing. This screening is easy to roll up and is therefore ideal for a portable dish. This close spacing causes the screen to be a 34% filled aperture, bring-

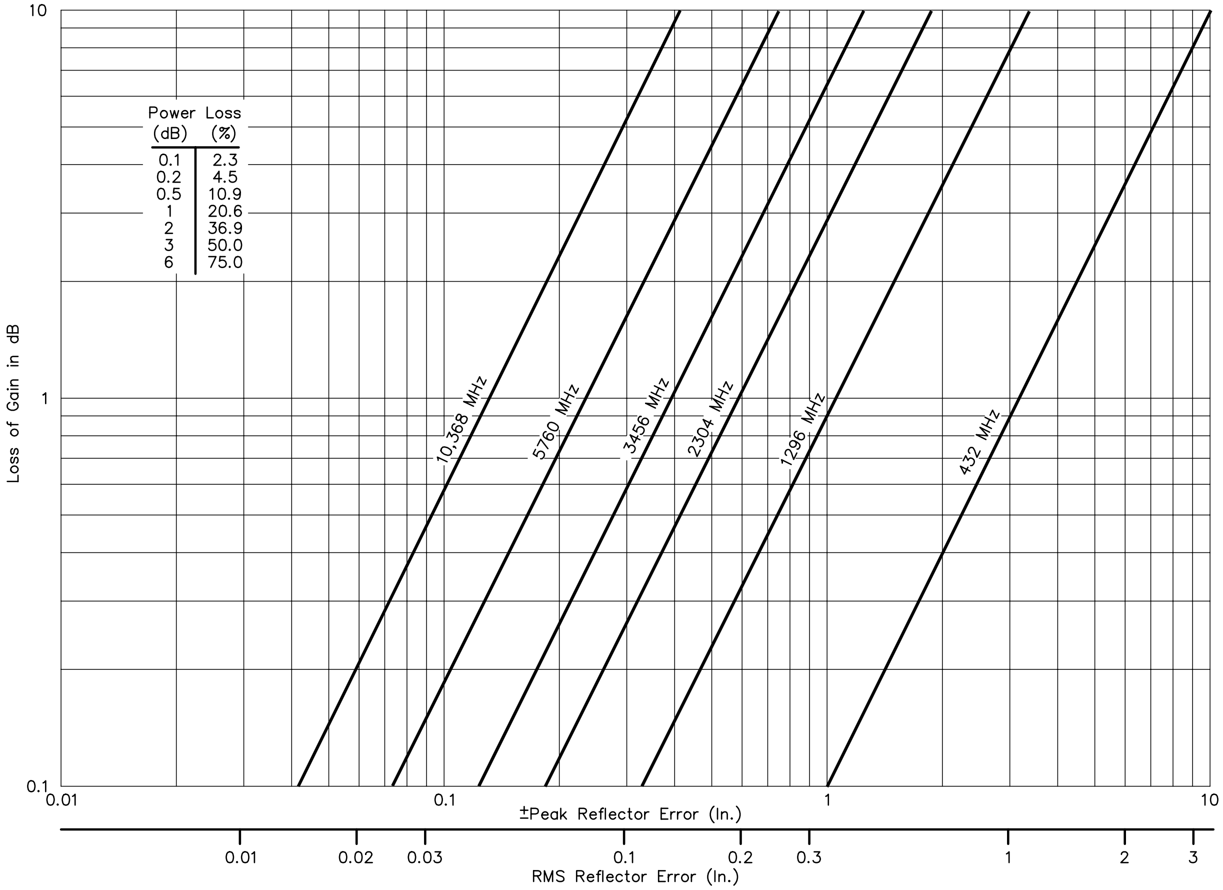


Fig 83—Gain deterioration versus reflector error. By Richard Knadle, K2RIW.

ing the wind force at 60 mph to more than 400 *pounds* on this 12-foot dish. Those considering a permanent installation of this dish should investigate other surfacing materials.

Hexagonal 1-inch poultry netting (chicken wire), which is an 8% filled aperture, is nearly ideal for 432-MHz operation. It weighs 10 pounds per 100 square feet, and exhibits only 81 pounds of force with 60 mph winds. Measurement on a large piece reveals 6 dB of feedthrough at 1296 MHz, however. Therefore, on 1296 MHz, one fourth of the power will feed through the surface material. This will cause a loss of only 1.3 dB of forward gain. Since the low-wind loading material will provide a 30-dBi gain potential, it is still a very good tradeoff.

Poultry netting is very poor material for 2300 MHz and above, because the hole dimensions approach $^1/_2$ λ. As with all surfacing materials, minimum feedthrough occurs when the E-field polarization is parallel to the longest dimension of the surfacing holes.

Hardware cloth with $^1/_2$-inch mesh weighs 20 pounds per 100 square feet and has a wind loading characteristic of 162 pounds with 60 mph winds. The filled aperture is 16%, and this material is useful to 2300 MHz.

A rather interesting material worthy of investigation is $^1/_4$-inch reinforced plastic. It weighs only 4 pounds per 100 square feet. The plastic melts with many universal solvents such as lacquer thinner. If a careful plastic-melting job is done, what remains is the $^1/_4$-inch spaced aluminum wires with a small blob of plastic at each junction to hold the matrix together.

There are some general considerations to be made in selecting surface materials:

1) Joints of screening do not have to make electrical contact. The horizontal wires reflect the horizontal wave. Skew polarizations are merely a combination of horizontal and vertical components which are thus reflected by the corresponding wires of the screening. To a horizontally polarized wave, the spacing and diameter of only the horizontal wires determine the reflection coefficient (see **Fig 85**). Many amateurs have the mistaken impression that screening materials that do not make electrical contact at their junctions are poor reflectors.
2) By measuring wire diameter and spacings between the wires, a calculation of percentage of aperture that is filled can be made. This will be one of the major determining factors of wind pressure when the surfacing material is dry.

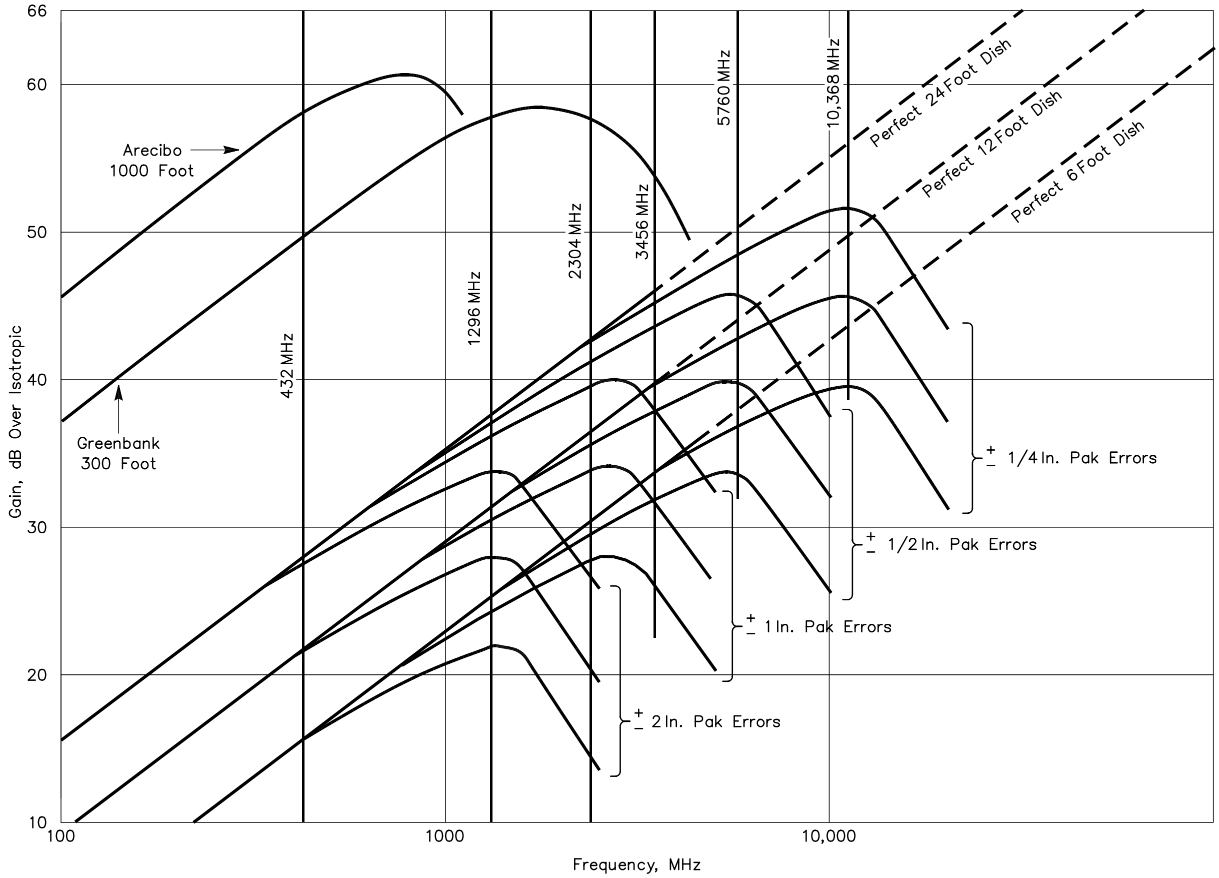


Fig 84—Parabolic-antenna gain versus size, frequency and surface errors. All curves assume 60% aperture efficiency and 10-dB power taper. Graph by K2RIW for ham bands, using display technique of J. Ruze, British IEE.

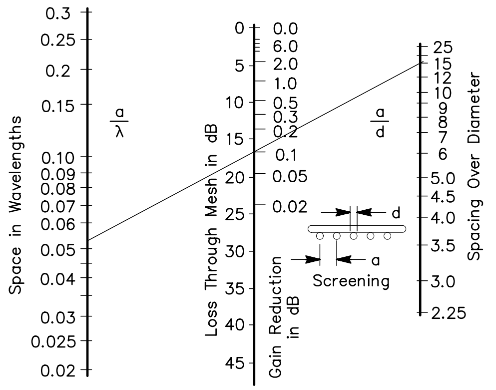


Fig 85—Surfacing material quality.

A Parabolic Template

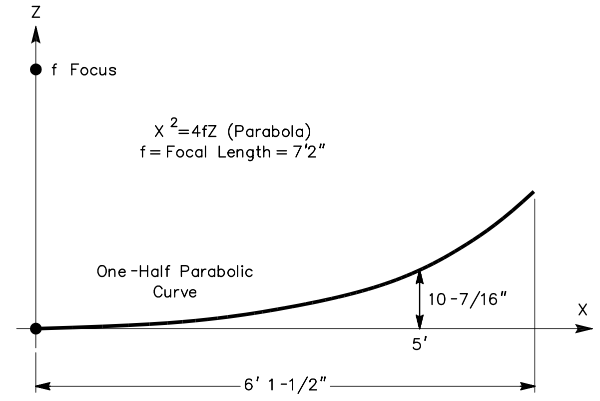
At and above 2300 MHz (where high surface accuracy is required), a parabolic template should be constructed to measure surface errors. A simple template may be constructed (see **Fig 86**) by taking a 12-foot 3-inch length of 4-foot wide tar paper and drawing a parabolic shape on it with chalk. The points for the parabolic shape are calculated at 6-inch intervals and these points are connected with a smooth curve. For those who wish to use the template with the surface material installed, the template should be cut along the chalk line and stiffened by cardboard or a wood lattice frame. Surface error measurements should take place with all spokes installed and deflected by the fishing lines, as some bending of the center plates does take place. **Fig 87** shows the 12-foot stressed dish built by Franco Marcelo, N2UO.

Variations

All the possibilities of the stressed parabolic antenna have not been explored. For instance, a set of fishing lines or guy wires can be set up behind the dish for error correction, as long as this does not cause permanent bending of the aluminum spokes. This technique also protects the dish against wind loading from the rear. An extended piece of TV mast is an ideal place to hang a counterweight and attach the rear guys. This strengthens the structure considerably.

EME USING SURPLUS TVRO DISH ANTENNAS

Since the 1990s, there has been a significant change



X	Z (to Nearest 1/16")	X	Z
0.5'	1/8"	3.5'	5-1/8"
1.0'	7/16"	4.0'	6-11/16"
1.5'	15/16"	4.5'	8-1/2"
2.0'	1-11/16"	5.0'	10-7/16"
2.5'	2-5/8"	5.5'	12-11/16"
3.0'	3-3/4"	6.0'	15-1/16"

Fig 86—Parabolic template for 12-foot, 3-inch dish.

Fig 87—N2UO's homemade 12-foot stressed dish. (*Photo courtesy N2UO.*)

in the systems people use to watch satellite TV broadcasts. Formerly, C-band satellite receivers were used, along with parabolic dish antennas in the 3- to 5-meter diameter range. Now, Ku-band (12-GHz) receivers are the norm, with their associated small (usually 18-inch) dish antennas. This has provided a large body of surplus C-band dishes, which can be used for EME—certainly on the bands at 33 cm and above, and for the larger dishes (5 meters), even at 70 cm. Many times, these dishes and their mounts can be had for the asking, so they truly become an inexpensive way to build a multi-band EME antenna.

This updated article, first presented by David Hallidy, K2DH (ex-KD5RO) in the ARRL *UHF/Microwave Projects Manual*, describes the use of a 3-meter (10-foot) TVRO antenna in such an application. (Also see earlier in this chapter the section describing converted C-Band TVRO Dishes for satellite work.)

Background

Calculations show that a 3-meter dish will have about 30 dBi gain at 1296 MHz. With a state-of-the-art LNA (Low-Noise Amplifier or preamp) at the feed, an efficient feed horn illuminating the dish surface, and 200 W at 1296 MHz, lunar echoes should be easily detected and many stations can be worked. The biggest challenges to such a system are assembling the dish to its mount and steering it to track the Moon. As much as possible, the KISS ("Keep It Simple, Stupid") principle was used to accomplish this task.

In 1987, WA5TNY, KD5RO, KA5JPD, and W7CNK proved that such an EME system could work, even as high as 3.4 and 5.7 GHz, to provide the first EME contacts on those bands. An additional advantage to this (or any) small dish is its ability to be mounted to a trailer and taken out on EME expeditions. It can also be easily disassembled and stored, if necessary.

As can be seen from **Fig 88**, the entire setup is very simple, using a standard amateur tower as the main support for the dish.

Azimuth Drive

In azimuth, direct drive of the main rotating shaft was selected, and a small prop-pitch motor was used. These motors, while not as plentiful as they were some years ago, still turn up with some regularity at flea markets for very little money. The beauty of the prop-pitch motor is that it turns slowly, is reversible, provides very high torque, and requires no braking system (the gear reduction, on the order of 4000:1, provides the necessary braking). Prop-pitch motors are dc motors, and were designed to vary the pitch of propeller blades at start-up, take-off and landing of older large airplanes. Thus, they can be run at different speeds merely by varying the dc voltage to the motor, and can be reversed by reversing the polarity of the dc voltage. By mounting a thrust bearing of the appropriate size at the top of the tower, and mounting the motor directly below it at the end of the rotating shaft that turns the antenna, a simple direct-drive system can be constructed.

The dc power supply and control relays are located in a weatherproof box on the side of the tower, next to the motor. This system requires only 9 V dc at about 5 A to adequately start, turn and stop the prop-pitch motor, and this voltage turns the antenna through 360° of rotation in about 2$^1/_2$ minutes. Azimuth position sensing is also a simple task. See **Fig 89**. A linear multi-turn potentiometer is driven by the rotating shaft, using a simple friction drive.

A strip of rubber is attached to the rotating shaft and a wheel is connected to the shaft of the pot. The pot is then mounted so that it presses against the rubber strip, and as the shaft turns so does the pot. If a ten-turn pot is used, and the system is aligned such that the pot is at the center of its rotation when the antenna is pointed approximately south, the pot will not rotate past the end at either extreme of the antenna's rotation (CW/CCW north), and absolute alignment is a simple task of calibrating the change in resistance (change in voltage, when the pot is fed from a constant voltage source) with degrees of rotation (see the discussion on Position Readout for details).

Elevation Drive

The elevation drive is also very simple. Most (nearly all) TVRO setups have a means of moving the dish across the sky to align it with various satellites. To do this, most companies use a device called a *Linear Actuator*. This is a dc motor to which is attached a long lead screw that pulls (or pushes) the outer shell of the actuator in or out to make it longer or shorter. The movable end of the actuator is attached to the dish and the motor end is fixed to the mount. The dish rests on pivots, which allow it to move as the actuator extends/retracts. To convert this type of mount (called a *Polar Mount*) to an Az/El mount is usually very simple.

Fig 90 shows how this can be done. Simply breaking the welds that held the mount in a polar fashion allows the mount to be turned on its side and used to pivot the dish vertically with the linear actuator. Another feature of linear actuators is that they also have some means of feeding their relative position to the satellite receiver. This is usually just a multi-turn potentiometer geared to the lead screw. All we have to do is connect this pot to a readout system, and we can calibrate the lift of the actuator in degrees. We thus have a simple means of rotating the dish and elevating it—but how do we know that it's pointed at the Moon?

Position Readout

Readout of the position of the antenna, in both azimuth and elevation is also a relatively simple task. On the

Fig 88—View of K2DH's (ex-KD5RO) complete TVRO antenna installation. (*K2DH photo.*)

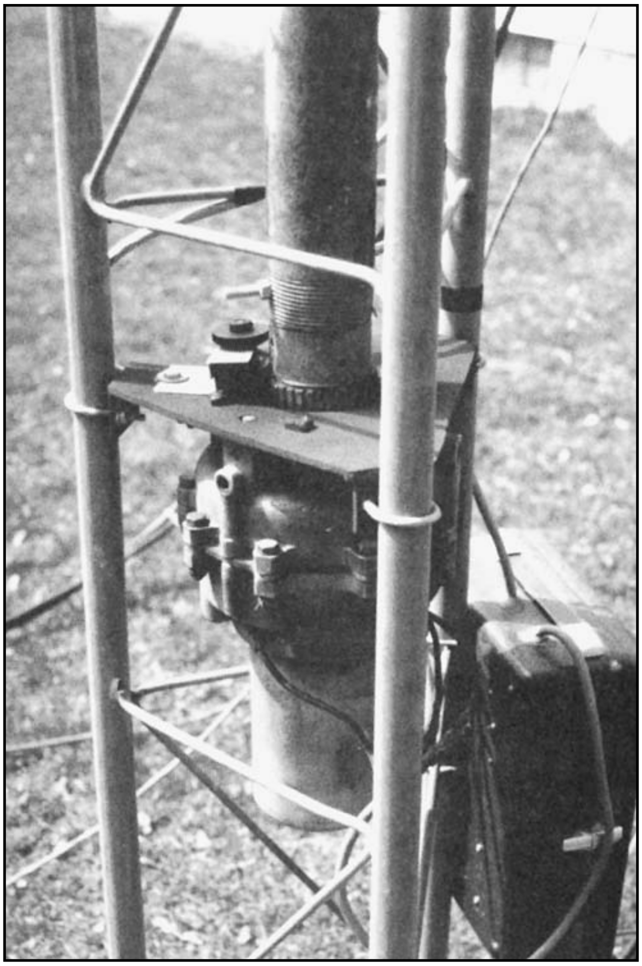


Fig 89—Azimuth rotation systems, showing prop-pitch motor and position sensor.

Fig 90—Elevation system, showing modified TVRO mount.

surplus market there are available Digital Volt Meters (DVMs) using LED or LCD displays that can do this job nicely, and that have more precision than is probably necessary for a dish (or Yagi array) of small size. As mentioned earlier, a multi-turn potentiometer on the elevation-drive mechanism can be used to readout elevation, and the same technique can be used for azimuth readout—a potentiometer coupled to the main rotating shaft that turns the antenna.

When using a pot for readout, the most important thing to know is how many degrees of antenna position change occur (in Az or El) for each turn of the pot. This then can be used to calibrate a voltmeter to read volts directly as degrees—for example, 3.60 V could correspond to 360° azimuth (Clockwise North), and 9.0 V could correspond

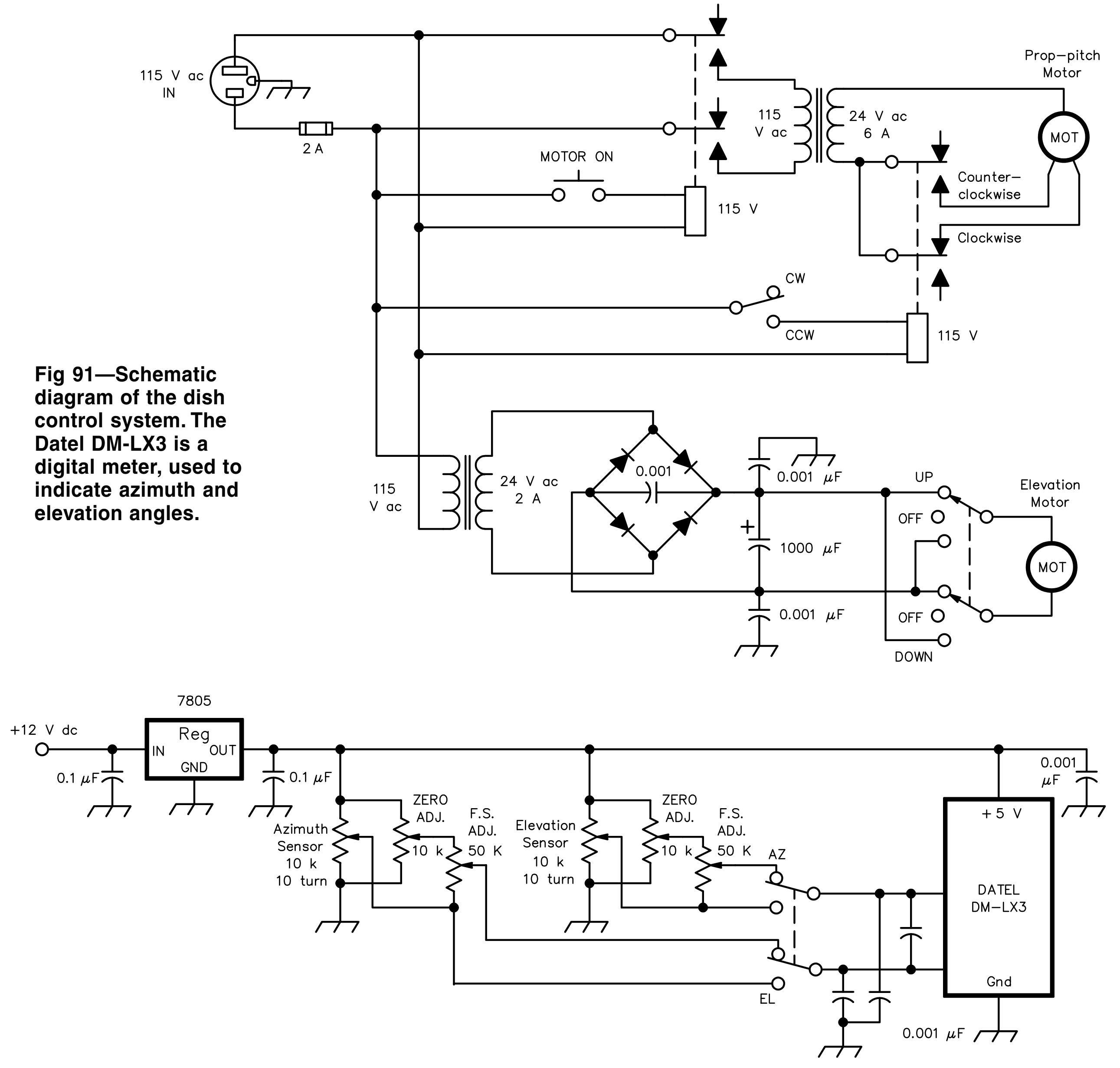


Fig 91—Schematic diagram of the dish control system. The Datel DM-LX3 is a digital meter, used to indicate azimuth and elevation angles.

to 90° elevation (straight up).

A resistance bridge circuit is best used in this application, since it is less sensitive to changes in the supply voltage. The only thing to be careful about is that the DVM must have both the positive (high) and negative (low) inputs isolated from ground (assuming the power supply used to power the DVM is grounded). You could also use a pair of small, cheap Digital Multi-Meters (DMMs), which can sometimes be found for under $10. Because they are battery powered, the isolation issue just discussed is eliminated.

Please see **Fig 91** for a complete schematic of the azimuth, elevation and readout electronics for this antenna-drive system. Also note that while this discussion is geared towards the use of a small dish, the same positioning and readout systems could be used in a Yagi array for 2 meters or 70 cm.

Now that we know where the dish is pointed, how do we know where the Moon is? There are several software programs available to the Amateur for tracking celestial bodies such as the Moon, the Sun, certain stars (usable as noise sources), and even Amateur Satellites. Programs by W9IP, VK3UM, F1EHN and others can be obtained very reasonably and these work well to provide highly accurate position information for tracking.

Feeding the Surplus TVRO Dish

An area that needs particular attention when attempting EME with a small dish is an efficient feed system. An efficient feed system can be a real challenge with TVRO dishes, because many are "deep"—that is, their f/D (focal length to Diameter ratio) is small.

The satellite TV industry used deep dishes because they tend to be quieter, picking up less Earth noise due to spillover effects. A deep dish has a short focal length, and therefore, the feed is relatively close to the surface of the dish. To properly illuminate the reflector out to its edges, a feed horn of relatively wide beamwidth must be used. The feeds designed several years ago by Barry Malowanchuk, VE4MA, are intended for use with just such dishes, and have the advantage of being adjustable to optimize their pattern to the dish in use.

The feed that was used with this dish was modeled after VE4MA's 1296-MHz feed, and a version was even scaled for use at 2304 MHz that worked as well as the original. See **Fig 92** and also see the Notes and References section at the end of this chapter. (Also see the earlier section in the satellite portion of this chapter describing patch feeds for small dishes.)

SHF EME CHALLENGES

The challenges met when successfully building a station for EME at 900 MHz to 5.7 GHz only become more significant on the SHF bands at 10 GHz and above. Absolute attention to detail is the primary requirement, and this extends to every aspect of the EME antenna system. The dish surface is probably the most difficult problem to solve. As was discussed earlier in this chapter, the shape and accuracy of the reflector contribute directly to the overall gain of the antenna.

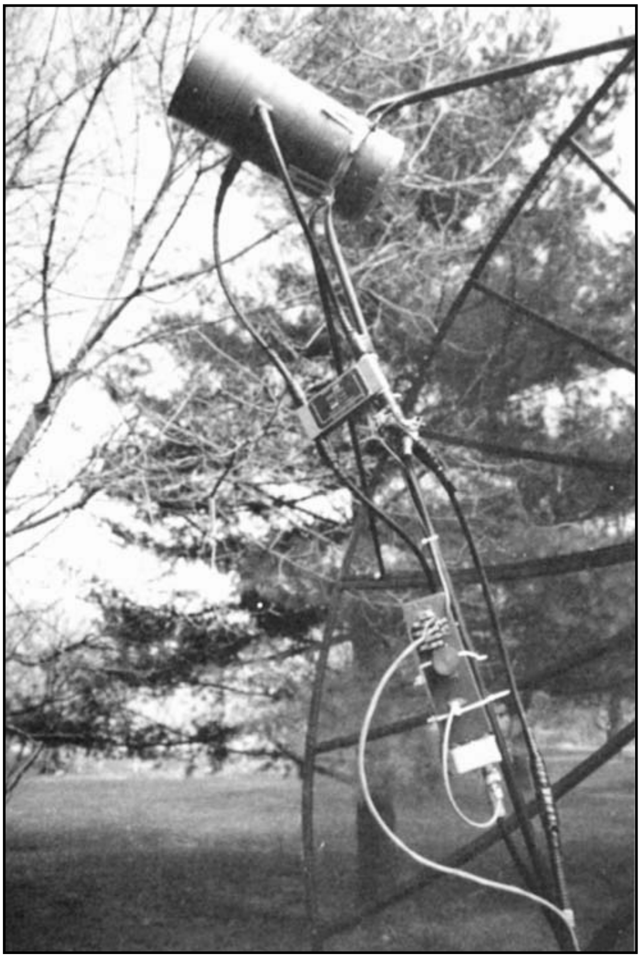


Fig 92—View of feed, showing coffee-can feed horn and hybrid coupler.

But where slight errors in construction can be tolerated at the lower frequencies, the same cannot be said at millimetric wavelengths. Those who have attempted EME on 10 and 24 GHz have discovered that the weight of the dish reflector itself will distort its shape enough to lower the gain to the point where echoes are degraded. Stiffening structures at the back of such dishes are often found necessary. **Fig 93** illustrates the back struts added by Al Ward, W5LUA, to strengthen his dish.

Pointing accuracy is also paramount—a 16-foot dish at 10 GHz has a beamwidth about equal to the diameter of the Moon—0.5°. This means that the echo degradation due to the Moon's movement away from where the dish is pointed is almost immediate, and autotracking systems become more of a necessity than a luxury. At these frequencies, most amateurs actually peak their antennas on

Fig 93—Strengthening struts W5LUA added to the back of his dish to hold down distortion. (*Photo courtesy W5LUA.*)

Moon Noise—the black-body Radiation from the Moon that becomes the dominant source of noise in space.

At these frequencies, the elevation of the Moon above the horizon also plays a role in the ability to communicate, since tropospheric absorption due to water vapor is greatest at low elevation angles (the signal must pass through a greater portion of the troposphere than when the Moon is highly elevated). It is beyond the abilities of most Amateurs to construct their own dishes for these frequencies, so surplus dishes for Ku-band satellite TV (typically 3 meters in diameter) are usually employed, as have high-performance dishes designed for millimetric radar and point-to-point communications at 23 and 38 GHz.

NOTES AND REFERENCES, EME ANTENNAS

W. Allen, "A Mode J Helix," *AMSAT Newsletter*, Jun 1979, pp 30-31.

D. J. Angelakos and D. Kajfez, "Modifications on the Axial-Mode Helical Antenna," *Proc. IEEE*, Apr 1967, pp 558-559.

A. L. Bridges, "Really Zap OSCAR With this Helical Antenna," *73*, in three parts, Jul, Aug and Sep 1975.

K. R. Carver, "The Helicone—A Circularly Polarized Antenna with Low Sidelobe Level," *Proc. IEEE*, Apr 1967, p 559.

M. R. Davidoff, "A Simple 146-MHz Antenna for Oscar Ground Stations," *QST*, Sep 1974, pp 11-13.

M. R. Davidoff, *The Radio Amateur's Satellite Handbook* (Newington: ARRL, 1998-2000).

D. DeMaw, "The Basic Helical Beam," *QST*, Nov 1965, pp 20-25, 170.

D. Evans and G. Jessop, *VHF-UHF Manual, 3rd ed.* (London: RSGB), 1976.

N. Foot, "WA9HUV 12-Foot Dish for 432 and 1296 MHz," The World Above 50 Mc., *QST*, Jun 1971, pp 98-101, 107.

N. Foot, "Cylindrical Feed horn for Parabolic Reflectors," *Ham Radio*, May 1976.

O. J. Glasser and J. D. Kraus, "Measured Impedances of Helical Beam Antennas," *Journal of Applied Physics*, Feb 1948, pp 193-197.

D. Hallidy, "Microwave EME Using A Ten-Foot TVRO Antenna," *The ARRL UHF/Microwave Projects Manual*, 1994 pp 10-9 to 10-13.

G. R. Isely and W. G. Smith, "A Helical Antenna for Space Shuttle Communications," *QST*, Dec 1984, pp 14-18.

H. Jasik, *Antenna Engineering Handbook*, 1st ed. (New York: McGraw-Hill, 1961).

R. T. Knadle, "A Twelve-Foot Stressed Parabolic Dish," *QST*, Aug 1972, pp 16-22.

J. D. Kraus, "Helical Beam Antenna," *Electronics*, Apr 1947, pp 109-111.

J. D. Kraus and J. C. Williamson, "Characteristics of Helical Antennas Radiating in the Axial Mode," *Journal of Applied Physics*, Jan 1948, pp 87-96.

J. D. Kraus, "Helical Beam Antenna for Wide Band Applications," *Proc of the IRE*, Oct 1948, pp 1236-1242.

J. D. Kraus, *Antennas* (New York: McGraw-Hill Book Co., 1950).

J. D. Kraus, "A 50-Ohm Input Impedance for Helical Beam Antenna," *IEEE Transactions on Antennas and Propagation*, Nov 1977, p 913.

J. D. Kraus, *Big Ear* (Powell, OH: Cygnus-Quasar Books, 1976).

T. S. M. MacLean, "Measurements on High-Gain Helical Aerial and on Helicals of Triangular Section," *Proc. of IEE* (London), Jul 1964, pp 1267-1270.

D. M. Mallozzi, "The Tailored Helical," *AMSAT Newsletter*, Mar 1978, pp 8-9.

B. Malowanchuk, "Use of Small TVRO Dishes for EME," *Proceedings of the 21st Conference of The Central States VHF Society*, 1987 pp 68-77.

B. Malowanchuk, "Selection of An Optimum Dish Feed," *Proceedings of the 23rd Conference of The Central States VHF Society*, 1989 pp 35-43.

M. W. Maxwell, *Reflections—Transmission Lines and Antennas* (Newington, CT: ARRL, 1990) [out of print].

T. Moreno, *Microwave Transmission Design Data* (New York: McGraw-Hill, 1948).

K. Nose, "Crossed Yagi Antennas for Circular Polarization," *QST*, Jan 1973, pp 11-12.

K. Nose, "A Simple Az-El Antenna System for Oscar," *QST*, Jun 1973, pp 11-12.

S. Powlishen, K1FO, "432-MHz EME 1990s Style," Parts 1 and 2, *Communications Quarterly*, Oct 1990, pp 29-39; Oct 1991, pp 33-48.

S. Powlishen, K1FO, "Rear-Mount Yagi Arrays for 432-MHz EME: Solving the EME Polarization Problem," *The ARRL Antenna Compendium, Vol 3* (Newington:

ARRL, 1992), pp 79-98.

C. Richards, "The 10 Turn Chopstick Helical (Mk2) for OSCAR 10 432 MHz Uplink," *Radio Communication*, Oct 1984, pp 844-845.

S. Sander and D. K. Cheng, "Phase Center of Helical Beam Antennas," *IRE National Convention Record Part 6*, 1958, pp 152-157.

E. A. Scott and H. E. Banta, "Using the Helical Antenna at 1215 Mc.," *QST*, Jul 1962, pp 14-16.

R. Soifer, W2RS, "More 'QRP' EME on 144 MHz," *QST*, Oct 1990, pp 36-38.

G. Southworth, *Principles and Applications of Waveguide Transmission* (New York: D. Van Nostrand Co., 1950).

B. Sykes, "Circular Polarization and Crossed-Yagi Antennas," Technical Topics, *Radio Communication*, Feb 1985, p 114.

H. E. Taylor and D. Fowler, "A V-H-F Helical Beam Antenna," *CQ*, Apr 1949, pp 13-16.

G. Tillitson, "The Polarization Diplexer—A Polaplexer," *Ham Radio*, Mar 1977.

P. P. Viezbicke, "Yagi Antenna Design," *NBS Technical Note 688* (U. S. Dept. of Commerce/National Bureau of Standards, Boulder, CO), Dec 1976.

D. Vilardi, "Easily Constructed Antennas for 1296 MHz," *QST*, Jun 1969.

D. Vilardi, "Simple and Efficient Feed for Parabolic Antennas," *QST*, Mar 1973.

J. L. Wong and H. E. King, "Broadband Quasi-Tapered Helical Antenna," *IEEE Transactions on Antennas and Propagation*, Jan 1979, pp 72-78.