Contents

Space Communications

Radio amateur satellite operation is increasingly popular as inexpensive equipment and antennas have become widely available. Organizations around the world are delivering more amateur satellites to space, providing more and more communication opportunities. CubeSats built and operated by student groups support both communications and scientific telemetry. EME operation using the Moon as a reflector has become accessible to a wide range of amateurs using basic equipment and digital modes optimized for this difficult path. This chapter of the *Handbook* will help you understand the basics of space communications so that you can participate, too.

The chapter's initial section on satellite operation was provided by Patrick Stoddard, WD9EWK, and previously, Steve Ford, WB8IMY. The section provides background on satellites in general and presents material on how to access and communicate via satellites. The EME section has been updated for the 2023 edition by Doug Grant, K1DG, from material originally provided by Joe Taylor, K1JT, including material from Alan Katz, K2UYH; Marc Franco, N2UO; PK Blair, G3LTF; F5VHX; Lionel Edwards, VE7BQH; GM3SEK (SK); Leif Sbrink, SM5BSZ; and VK7MO. The basics of EME communication are presented along with current practices and requirements for basic EME stations. Unless otherwise noted, references to other chapters refer to the chapters in the print version of the *ARRL Handbook*.

1 Amateur Satellite History

The story of amateur radio satellites is as old as the Space Age itself. The Space Age is said to have begun on October 4, 1957. That was the day when the Soviet Union shocked the world by launching Sputnik 1, the first artificial satellite. Hams throughout the world monitored Sputnik's telemetry beacons at 20.005 and 40.002 MHz as it orbited the Earth. During Sputnik's 22-day voyage, amateur radio was in the media spotlight since hams were among the few civilian sources of news about the revolutionary spacecraft.

Almost four months later, the United States responded with the launch of the Explorer 1 satellite on January 31, 1958. At about that same time, a group of amateur radio operators on the West Coast began considering the possibility of a ham radio satellite. This group later organized itself as Project OSCAR (OSCAR is an acronym meaning Orbiting Satellite Carrying Amateur Radio) with the expressed aim of building and launching amateur satellites. (See the sidebar "When Does a Satellite Become an OSCAR?")

After a series of high-level exchanges with the American Radio Relay League and the United States Air Force, Project OSCAR secured a launch opportunity. The first amateur radio satellite, known as OSCAR 1, would "piggyback" with the Discoverer 36 spacecraft being launched from Vandenberg Air Force Base in California. Both "birds" (as satellites are called among their builders and users) successfully reached low Earth orbit on the morning of December 12, 1961.

OSCAR 1 weighed only 10 pounds. It was built, quite literally, in the basements and garages of the Project OSCAR team. It carried a small beacon transmitter that allowed ground stations to measure radio propagation through the ionosphere. The beacon also transmitted telemetry indicating the internal temperature of the satellite.

OSCAR 1 was an overwhelming success. More than 570 amateurs in 28 countries forwarded observations to the Project OSCAR data collection center. OSCAR 1 lasted only 22 days in orbit before burning up as it reentered the atmosphere, but amateur radio's "low tech" entry into the high tech world of space travel had been firmly secured. When scientific groups

When Does a Satellite Become an OSCAR?

While worldwide AMSAT organizations are largely responsible for the design and construction of the modern day amateur radio satellites, the original "OSCAR" designation is still being applied to many satellites carrying amateur radio. However, most amateur radio satellites are not usually assigned their sequential OSCAR numbers until *after* they successfully achieve orbit and become operational. Even then, an OSCAR number is only assigned after its sponsor formally requests one.

For example, let's make up a satellite and call it ROVER. The ROVER spacecraft won't receive an OSCAR designation until (1) it reaches orbit and (2) its sponsor submits a request. Now let's presume that ROVER makes it into orbit and the OSCAR request is made and granted. ROVER is now tagged as OSCAR 99 and its full name becomes ROVER-OSCAR 99. You'll find, however, that many hams will abbreviate the nomenclature. Some will simply call the satellite ROVER, or OSCAR 99. They may even abbreviate its full name to just RO-99.

If a satellite subsequently fails in orbit, or it re-enters the Earth's atmosphere, its OSCAR number is usually retired, never to be issued again.

asked the Air Force for advice on secondary payloads, the Air Force suggested they study the OSCAR design. What's more, OSCAR 1's bargain-basement procurement approach and management philosophy would become the hallmark of all the OSCAR satellite projects that followed, even to this day.

Since then, amateurs have successfully built and launched dozens of satellites, each one progressively more sophisticated than the last.

1.1 AMSAT

Much of the amateur satellite progress has been spearheaded by the Radio Amateur Satellite Corporation, better known as *AMSAT*. The original AMSAT was formed in Washington, DC in 1969 as an organization dedicated to fostering an amateur radio presence in space. The AMSAT model quickly became international with many countries creating their own AMSAT organizations, such as AMSAT-UK in England, AMSAT-DL in Germany, BRAMSAT in Brazil and AMSAT-LU in Argentina. All of these organizations operate independently but may cooperate on large satellite projects and other items of interest to the worldwide amateur radio satellite community. Because of the many AMSAT organizations now in existence, the US AMSAT organization is frequently designated AMSAT-NA.

Since the very first OSCAR satellites were launched in the early 1960s, AMSAT's international volunteers have pioneered a wide variety of new communications technologies. These breakthroughs have included some of the very first satellite voice transponders as well as highly advanced digital "store-and-forward" messaging transponder techniques. All of these accomplishments have been achieved through close cooperation with international space agencies that often have provided launch opportunities at significantly reduced costs in return for AMSAT's technical assistance in developing new ways to launch paying customers.

AMSAT's major source of operating revenue is obtained by offering memberships in the various international AMSAT organizations. Membership is open to radio amateurs and to others interested in the amateur exploration of space. Modest donations are also sought for tracking software and other satellite related items. In addition, specific spacecraft development funds are established from time to time to help fund major AMSAT spacecraft projects through donations. In addition to money, AMSAT makes creative use of leftover materials donated from aerospace industries worldwide.

The AMSAT-NA organization, from the president on down to the workers designing and building space hardware, all donate their time and talents to the organization.

Table 1 — Amateur Satellites

Type of Satellite	*Number Currently Active (Mar 2022)*
FM Repeater Satellites	8
Digital Satellites	9
Telemetry-Only Satellites	10
Transponder Satellites	
LEO	17
Geostationary	1
See the Satellite Info pages at **www.amsat.org** for the operating details of currently active satellites. A current status page is available at **www.amsat.org/status**.	

1.2 Amateur Satellites Today

Today, the number of active amateur radio satellites continually changes. The AMSAT Fox and Golf programs are building and launching a series of satellites focused on communication. Some satellites offer FM repeater operation, very similar to terrestrial repeaters and accessible with a handheld VHF/UHF FM transceiver and simple antennas. Transponder satellites translate ranges of frequencies and can be used by CW, SSB, and digital mode stations. Telemetry-only satellites act as orbiting science experiments for student research teams. **Table 1** lists the types of satellites and the number currently active. AMSAT maintains a list of functioning satellites at **www.amsat.org/status**.

After many attempts to create a high-orbit satellite that would relay communications across entire hemispheres, the Qatari Es'hail-2 carrying QO-100 (Qatar-OSCAR 100: **amsat-uk.org/satellites/geo/eshail-2**) amateur radio transponders was launched in November 2018. It is in a geostationary orbit at 25.9 degrees East and links radio amateurs across ITU regions 1 and 3. (Some Region 2 amateurs in Brazil can also access the satellite.) The transponders operate on the 2.4 and 10.45 GHz bands with transponders for conventional analog modes, digital modulations, and DVB amateur television.

2 Satellite Transponders

In its most basic form, a *transponder* is the satellite communications system that receives signals from the Earth, alters their frequencies, amplifies them, and sends them back to Earth. The word originates from *transmitter* and *responder*. The transponder is at the heart of every satellite's ability to relay signals. There are three transponder types currently in use.

2.1 "Bent Pipe" Transponders

A bent-pipe transponder is the simplest transponder design in terms of function. It receives a signal at one frequency and simultaneously retransmits it at another. The metaphor is that of a U-shaped pipe that captures an object coming toward it and redirects the object back to its source (**Figure 1**).

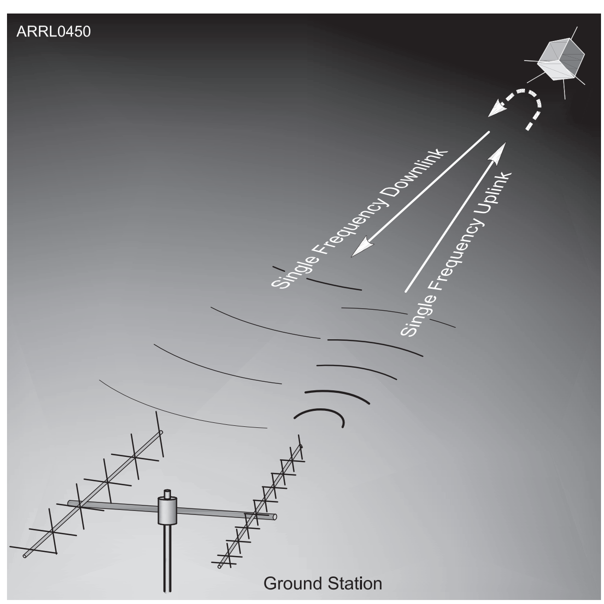


Figure 1 — A bent-pipe transponder gets its name from the way it functions. It takes the received uplink signal and instantly relays it on the downlink back to its source. Bent-pipe transponders are most often found on satellites that function primarily as FM repeaters.

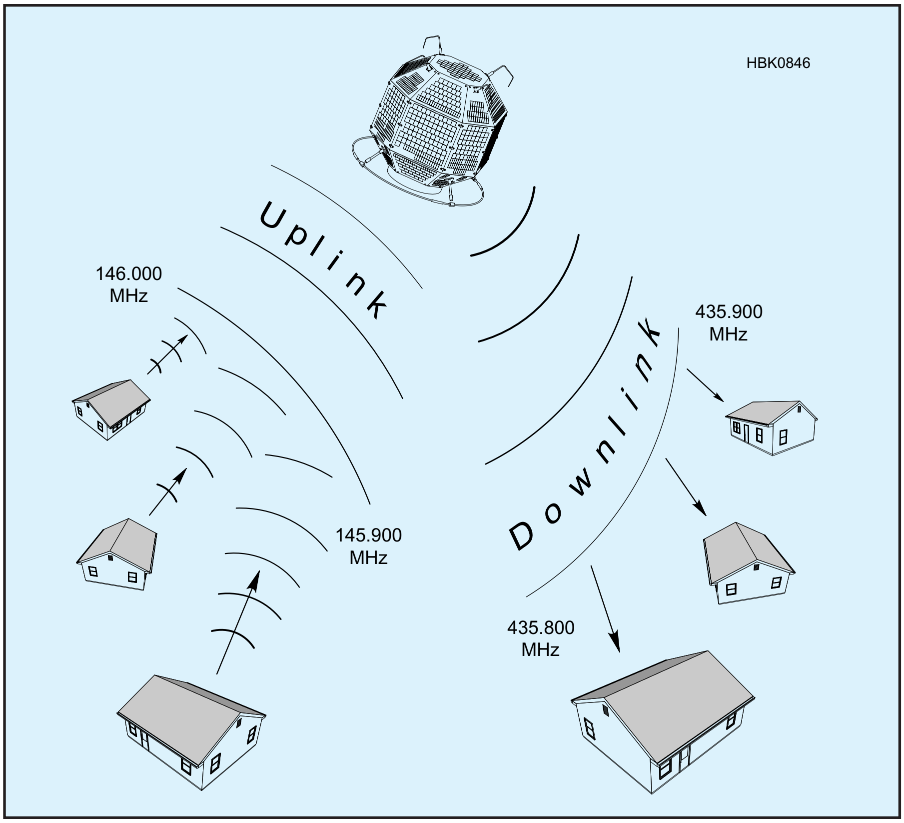


Figure 2 — Linear transponders repeat all signals received in an entire slice of spectrum. This allows the satellite to relay many conversations simultaneously.

A terrestrial FM repeater is a typical example of a bent-pipe transponder. Earthbound repeaters monitor one frequency and retransmit on another, usually (though not always) within the same band. Thanks to their elevated antenna systems, sensitive receivers and considerable output power, terrestrial repeaters can extend the coverage of mobile or handheld FM transceivers over hundreds or even thousands of square miles.

Bent-pipe satellite transponders also function as FM repeaters (although they could just as easily relay other modulation modes such as SSB). Satellite repeaters lack the output power of terrestrial repeaters because power generation in space is a difficult proposition. But what satellite repeaters lack in output power they more than make up for in antenna elevation. Even something as meager as a ¼λ whip antenna can become a transmitting and receiving powerhouse when it is hundreds of miles above the planet.

The principle advantage of a bent-pipe transponder operating in the FM mode is that it is readily compatible with common amateur radio FM transceivers. Satellites such as AMRAD-OSCAR 27 can be easily worked with the same transceivers you'd otherwise use to chat through a local FM repeater. It isn't uncommon to hear mobile and even handheld portable stations communicating through these satellites.

The principle *disadvantage* of a bent-pipe transponder is that it can relay only one signal at a time. Multiple signals on the satellite uplink frequency interfere with each other, usually resulting in an unintelligible cacophony on the downlink. Thanks to the "capture effect" common to FM receivers, only the strongest signal will come through clearly. With only 10 or 15 minutes available during typical low-orbit passes, an inconsiderate operator running high power can use the capture effect to monopolize the satellite, effectively shutting out all other stations.

The solution to the bent-pipe problem is to have a satellite that can relay more than one signal at a time. That requires a completely different sort of transponder.

2.2 Linear Transponders

Unlike a bent-pipe transponder that can relay only one signal at a time, a linear transponder receives signals in a narrow slice of the RF spectrum (the *passband*), shifts the frequency of the passband, amplifies all signals linearly, and then retransmits everything back to Earth. Rather than relaying only one signal, a satellite equipped with a linear transponder can relay many signals at once (**Figure 2**).

From an operator point of view, linear transponders have an enormous advantage. With single-channel bent-pipe transponders, the user is obligated to finish a conversation quickly and clear the frequency so that someone else can make a contact. Not so with linear transponders. With the ample spectrum available through a linear transponder, there is more than enough "room" for everyone to communicate for as long as they please, or at least until the satellite travels out of range.

A linear transponder can be used with any type of signal when real time communication is desired. From the standpoint of conserving valuable spacecraft resources such as power and bandwidth, however, the preferred user modes are SSB and CW. Transponders are specified by first giving the approximate input frequency followed by the output frequency.

Table 2
Satellite Uplink/Downlink Mode Designators

Satellite Band Designations
10 meters (29 MHz): H
2 meters (145 MHz): V
70 centimeters (435 MHz): U
23 centimeters (1260 MHz): L
13 centimeters (2.4 GHz): S
5 centimeters (5.6 GHz): C
3 centimeters (10 GHz): X

Common Operating Modes (Uplink/Downlink)
V/H (2 meters/10 meters)
H/V (10 meters/2 meters)
U/V (70 centimeters/2 meters)
V/U (2 meters/70 centimeters)
U/S (70 centimeters /13 centimeters)
U/L (70 centimeters/23 centimeters)
L/S (23 centimeters/13 centimeters)
L/X (23 centimeters/3 centimeters)
C/X (5 centimeters/3 centimeters)

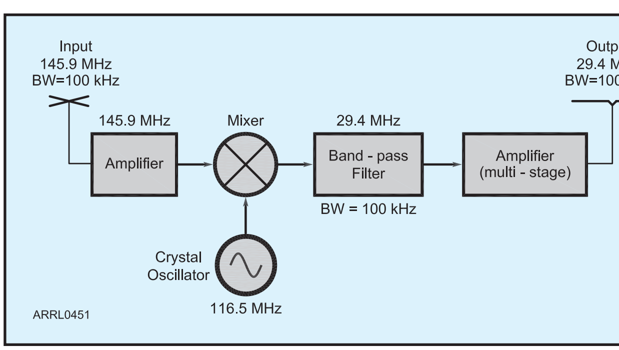


Figure 3 — A simplified block diagram of a linear transponder.

For example, a 146/435-MHz transponder has an input passband centered near 146 MHz and an output passband centered near 435 MHz. The same transponder could be specified in wavelengths, as a 2 meter/70 centimeter unit.

TRANSPONDER MODES

To keep linear transponder specifications as simple as possible, the satellite community often uses so-called *Mode* designators. In the early years of amateur satellite operation, these designations were rather arbitrarily assigned and bore little resemblance to the actual frequencies in use. Fortunately, the amateur satellite community has since settled on a newer series of transponder specifications that are far more intuitive. For instance, in our previous example, the 2 meter band is tagged with the label "V" (for VHF) while the 70 centimeter band is labeled "U" (for UHF). Therefore, a transponder that listens on 2 meters and repeats on 70 centimeter is today usually called a Mode V/U transponder. See **Table 2**.

Transponder design is, in many respects, similar to receiver design. Input signals are typically on the order of 10^{-13} W and the output level can be up to several watts. A major difference, of course, is that the transponder output is at radio frequency while the receiver output is at audio frequency. A block diagram of a simple transponder is shown in **Figure 3**. For several reasons, flight-model transponders are more complex than the one shown.

In spacecraft applications a key characteristic of a linear amplifier is its overall efficiency (RF output/dc input). Once we reach power levels above a few watts the use of class A, AB or B amplifiers cannot be tolerated. The power and bandwidth of a transponder must be compatible with each other and with the mission. That is, when the transponder is fully loaded with equal-strength signals, each signal should provide an adequate signal-to-noise ratio at the ground. Selecting appropriate values accurately on a theoretical basis using only link calculations is error prone. Experience with a number of satellites, however, has provided AMSAT with a great deal of empirical data from which it's possible to extrapolate accurately to different orbits, bandwidths, power levels, frequencies and antenna characteristics.

In general, low-altitude (300 to 1600 km) satellites that use passive magnetic stabilization and omnidirectional antennas can provide reasonable downlink performance with from 1 to 10 W PEP at frequencies between 29 and 435 MHz, using a 50- to 100-kHz-wide transponder. A high-altitude (35,000 km) spin-stabilized satellite that uses modest (7 to 10 dBi) gain antennas should be able to provide acceptable performance with 35 W PEP using a 300-kHz-wide transponder downlink at 146 or 435 MHz. Transponders are usually configured to be *inverting* in order to minimize Doppler shift. This means, for example, that a signal with a frequency at the low end of the uplink passband shifts to a corresponding point on the high end of the downlink passband. In the case of an SSB signal, the sideband modulation inverts as well — lower sideband on the uplink becomes upper sideband on the downlink.

DYNAMIC RANGE

The dynamic range problem for transponders is quite different from that for HF receivers. At first glance it may seem that the situation faced by satellite transponders is simpler. After all, an HF receiver must be designed to handle input signals differing in strength by as much as 100 dB, while a low-altitude satellite will encounter signals in its passband differing by perhaps 40 dB. Good HF receivers solve the problem by filtering out all but the desired signal before introducing significant gain. A satellite, however, has to accommodate all users simultaneously. The maximum overall gain can, therefore, be limited by the strongest signal in the passband.

Considering the state-of-the-art in transponder design and available spacecraft power budgets, an effective dynamic range of about 25 dB is about the most that can be currently obtained. In earlier satellites, the receiver AGC was normally adjusted to accommodate the loudest user. As a result, stations 25 dB weaker were not able to put a usable signal through the spacecraft even though they might be capable of doing so when the AGC is not activated. In the ideal situation users would adjust uplink power so that spacecraft AGC is never activated.

The "power-hog" problem is a serious one. A single station running excessive power can effectively swamp a linear transponder. Far too often, an inexperienced operator may believe that cranking up transmit power will improve downlink signal strength. Instead, that increase in power only serves to depress the downlink signal levels of all other stations.

In the short-lived OSCAR 40 satellite, the designers tried an innovative approach to the power-hog problem with the addition of LEILA (*LEI*stungs *L*imit *A*nzeige [Power Limit Indicator]). LEILA's computer continuously monitored the 10.7 MHz transponder IF passband. When an uplink signal exceeded a predetermined level, the computer inserted a CW message over the offender's downlink. The message indicated to the transmitting station that the transponder was being overloaded, and served as an inducement for the offending station to reduce power until the CW signal disappeared. If the overloading signal continued, or exceeded an even higher preset level, LEILA activated a notch filter tuned to the offending station's frequency. LEILA turned out to be highly effective. If you suddenly heard CW being transmitted over your signal on the downlink, you knew you had to reduce power immediately or face the consequences.

Since the transponder is the primary mission subsystem, reliability is extremely important. One way to improve system reliability is to include at least two transponders on each spacecraft; if one fails, the other would be available full time. And there are significant advantages to *not* using identical units.

2.3 Digital Transponders

Digital transponders differ significantly from linear transponders. A digital transponder demodulates the incoming signal. The data can then be stored aboard the spacecraft (as in a packet mailbox) or used to immediately regenerate a digital downlink signal (as in a digipeater). The mailbox service is best suited to low altitude spacecraft. Digipeating is most effective on high altitude spacecraft. Like linear transponders, digital units are downlink limited. A key step in the design procedure is to select modulation techniques and data rates to maximize the downlink capacity. Using assumptions about the type of traffic expected, the designers select appropriate uplink parameters. An analysis suggests that the uplink data capacity should be about four or five times that of the downlink because of "collisions" among signals trying to access the transponder.

For mailbox operation designers often use a PACSAT (*packet radio satellite*) model with similar data rates for the uplink and downlink, and they couple a single downlink with four uplinks. Fuji-OSCARs 12 and 20, and the MicroSat series ran both links at 1200 bps. These PACSATs contained an FM receiver with a demodulator that accepted Manchester-encoded FSK on the uplink. To produce an appropriate uplink signal, ground stations needed FM transmitters and packet radio modems known as terminal node controllers (TNCs) that were capable of generating the Manchester-encoded signal for the uplink.

The PACSAT downlink used binary phase-shift keying (BPSK) at an output of either 1.5 or 4 W. This modulation method was selected because, at a given power level and bit rate, it provides a significantly better bit error rate than other methods that were considered. One way of receiving the downlink is to use an SSB receiver and pass the audio output to a PSK demodulator. The SSB receiver is just serving as a linear downconverter in this situation. Other methods of capturing the downlink are possible but the two proven systems now operating use this approach.

During the heydays of the PACSATs, there were several TNCs designed specifically for this application. Over time the PACSATs have gradually gone out of service and those specialized TNCs have all but disappeared from the marketplace. The remaining digital satellite transponders use 1200 bps AFSK or 9600 bps FSK data transmissions for both uplink and downlink. This means that ordinary packet radio TNCs — the kind currently used for various terrestrial applications — can be used with these digital satellites as well.

RUDAK

A discussion of digital transponders would not be complete without mentioning RUDAK. RUDAK is an acronym for Regenerativer Umsetzer fur Digitale Amateurfunk Kommunikation (Regenerative Transponder for Digital Amateur Communications). Early RUDAK systems took a different approach to achieving the desired ratio of uplink to downlink capacity. The one flown on OSCAR 13 used one uplink channel and one downlink channel with the data rate on the uplink (2400 bps) roughly six times that on the downlink (400 bps). The 400 bps rate on the downlink was chosen because this was the standard that had been used for downlinking high-orbiting satellite telemetry since the late 1970s. Users already capturing telemetry would be able to capture RUDAK transmissions from day one. Unfortunately, the RUDAK unit on OSCAR 13 failed during launch.

A system known as RUDAK II was flown on RS-14/AO-21 and actually consisted of two units. One unit was similar to the RUDAK flown on OSCAR 13. However, the other unit, known as the RUDAK Technology Experiment (or RTX), was a new experimental transponder using DSP technology. It was essentially a flying test bed for ideas being considered for future high-orbit missions.

The RUDAK-U system flown on OSCAR 40 contained two CPUs, one 153.6 kbaud modem, four hardwired 9600 baud modems and eight DSP modems capable of operating at speeds up to 56 kbaud. The great advantages of modern RUDAK systems are their extraordinary flexibility. Through the use of digital signal processing, the RUDAK is able to configure itself into any type of digital system desired. Had OSCAR 40 survived, the plan was to use its RUDAK system to create a highly capable digital communications platform in space.

3 Satellite Tracking

3.1 Satellite Orbits

Most active amateur satellites are in various types of low Earth orbits (LEOs) at altitudes that vary between approximately 350 km (the International Space Station) and 1300 km (OSCAR 29). There are satellites planned for future launch that will travel in the high Earth orbits (HEOs). At their closest approaches to Earth (their *perigees*), these satellites may come within 1000 km; at the highest points of their orbits (their *apogees*), they will travel as far as 50,000 km into space. Let's take a brief look at several of the most common orbits.

An *inclined* orbit is one that is inclined with respect to the Earth's equator. See **Figure 4A**. A satellite that is inclined 90° would be orbiting from pole to pole; smaller inclination angles mean that the satellite is spending more time at lower latitudes. The International Space Station, for example, travels in an orbit that is inclined about 50° to the equator. Satellites that move in these orbits frequently fall into the Earth's shadow (eclipse), so they must rely on battery systems to provide power when the solar panels are not illuminated. Depending on the inclination angle, some locations on the Earth will never have good access because the satellites will rarely rise above their local horizons. This was true, for example, in the days when the US Space Shuttles carried amateur radio operators. Shuttle orbits were usually inclined at low angles, which meant that Shuttles barely made it above the horizon for hams in the northern US and Canada.

A *sun-synchronous* orbit takes a satellite over the north and south poles. See Figure 4B. There are two advantages to a sun-synchronous orbit: (1) the satellite is available at approximately the same time of day, every day and (2) everyone, no matter where they are, will enjoy at least one high-altitude pass per day. OSCAR 91 is a good example of a satellite that travels in a sun-synchronous orbit.

A *dawn-to-dusk* orbit is a variation on the sun-synchronous model except that the satellite spends most of its time in sunlight and relatively little time in shadow. OSCAR 27 travels in a dawn-to-dusk orbit. See Figure 4C.

The *Molniya* high Earth orbit (Figure 4D) was pioneered by the former Soviet Union. It is an elliptical orbit that carries the satellite far into space at its greatest distance from Earth. To observers on the ground, the satellite at apogee appears to hover for hours at a time before it plunges earthward and sweeps around the Earth at its closest approach. One great advantage of the Molniya orbit is that the satellite is capable of "seeing" an entire hemisphere of the planet while at apogee. Hams can use a Molniya satellite to enjoy long, leisurely conversations spanning thousands of kilometers here on Earth. When this book was written, however, there were no active ham satellites traveling in Molniya orbits.

3.2 Satellite Tracking Software

The key to communicating through a satellite is being able to track its movements and predict when it will appear above your local horizon. Fortunately, we have sophisticated software available that streamlines this task considerably.

You'll find satellite-tracking software written for Windows, macOS and Linux operating systems. Several popular applications are listed in **Table 3**. When computers were first employed to track amateur satellites, they provided only the most basic, essential information: when the satellite will be available (*AOS*, acquisition of signal), how high the satellite will rise in the sky and when

Table 3
A Sampling of Satellite Tracking Software

Name	*Source*	*Operating System*	*Radio Control?*	*Antenna Control?*
Nova	**www.amsat.org** (store)	Windows	No	Yes
SCRAP	**www.amsat.org** (store)	Windows	No	Yes
SatPC32	**www.amsat.org** (store)	Windows	Yes	Yes
SatScape	**www.satscape.co.uk/classic.html**	Windows	Yes	Yes
MacDoppler	**www.dogparksoftware.com/MacDoppler.html**	macOS	Yes	Yes
Ham Radio Deluxe	**hrd.ham-radio.ch**	Windows	Yes	No
Predict	**www.qsl.net/kd2bd/predict.html**	Linux	No	Yes
WinOrbit	**www.sat-net.com/winorbit**	Windows	No	No

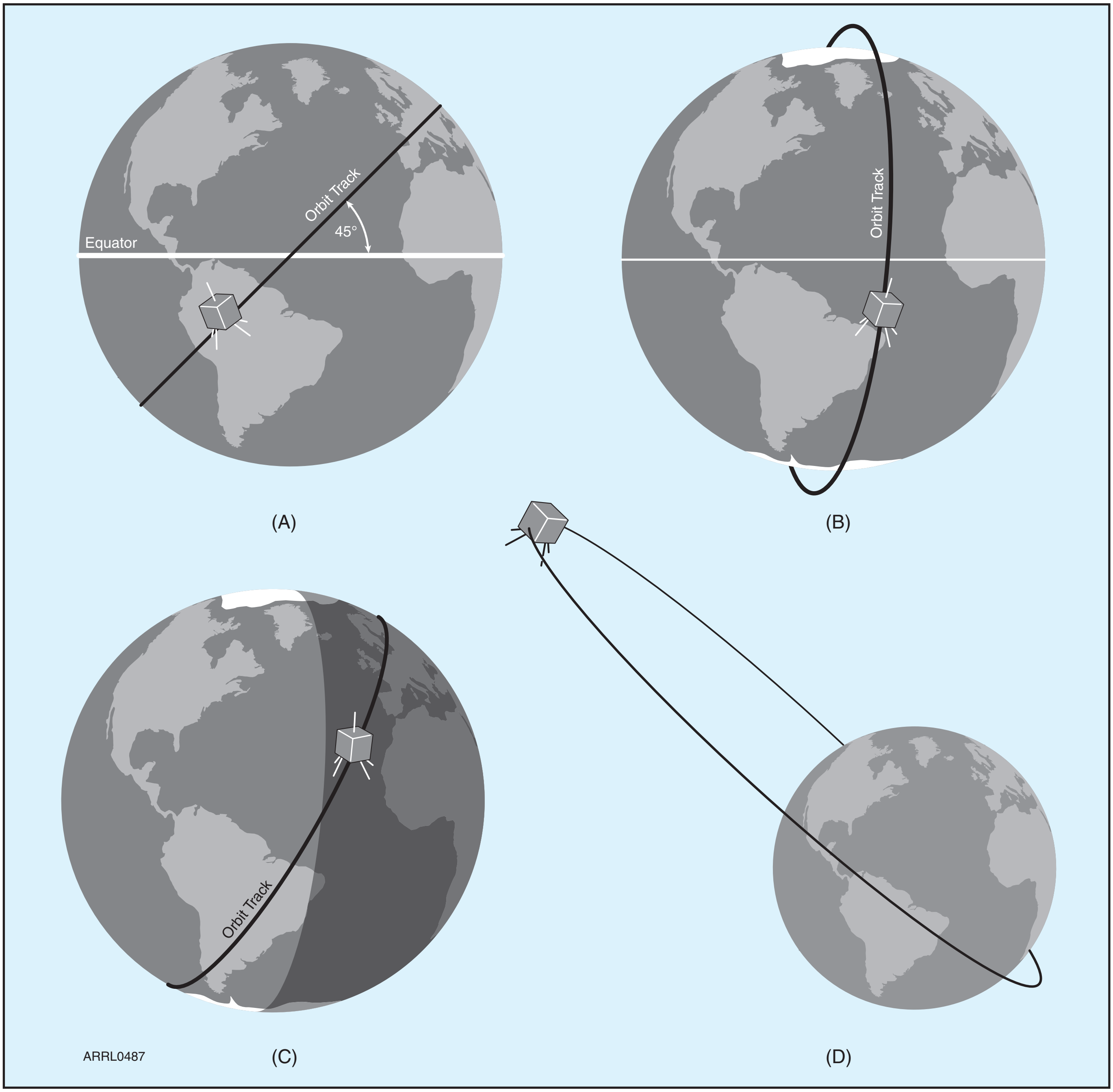


Figure 4 — At A, an *inclined* orbit is one that is inclined with respect to the Earth's equator (in this case, 45°). At B, a *sun-synchronous* orbit takes the satellite over the north and south poles, allowing every station in the world to enjoy at least one high-elevation pass per day. At C, a *dawn-to-dusk* orbit is a variation on the sun-synchronous model except that the satellite spends most of its time in sunlight and relatively little time in eclipse. At D, the *Molniya* orbit is an elliptical orbit that carries the satellite far into space at its greatest distance from Earth (apogee). To observers on the ground, the satellite at apogee appears to hover for hours at a time before it plunges earthward and (often) sweeps within 1000 km at its closest approach (perigee).

the satellite is due to set below your horizon (*LOS*, loss of signal). Today we tend to ask a great deal more of our tracking programs. Modern applications still provide the basic information, but they usually offer many more features such as:

- The spacecraft's operating schedule, including which transponders and beacons are on.
- Predicted frequency offset (Doppler shift) on the link frequencies.
- The orientation of the spacecraft's antennas with respect to your ground station and the distance between your ground station and the satellite.
- Which regions of the Earth have access to the spacecraft; that is, who's in QSO range?
- Whether the satellite is in sunlight or being eclipsed by the Earth. Some spacecraft only operate when in sunlight.
- When the next opportunity to cover a selected terrestrial path (mutual window) will occur.
- Changing data can often be updated at various intervals such as once per minute — or even once per second.

A number of applications do even more.

Some will control antenna rotators, automatically keeping directional antennas aimed at the target satellite. Other applications will also control the radio to automatically compensate for frequency changes caused by Doppler shifting.

Adding additional spacecraft to the scenario suggests more questions. Which satellites are currently in range? How long each will be accessible? Will any new spacecraft be coming into range in the near future? Obviously there is a great deal of information of potential interest. Programmers developing tracking software often find that the real challenge is not solving the underlying physics problems, but deciding what information to include and how to present it in a useful format. This is especially true since users have different interests, levels of expertise and needs. Some prefer to see the information in a graphical format, such as a map showing real-time positions for all satellites of interest. Others may prefer tabular data such as a listing of the times a particular spacecraft will be in range over the next several days.

There are also several internet sites where you can do your tracking online. This eliminates all the hassles associated with acquiring and installing software. The currently available online tracking sites are not as powerful or flexible as the software you can install on your PC, however. One interesting site of this type is maintained by AMSAT-NA and you'll find it at **www.amsat.org/track/**.

3.3 Getting Started With Software

There are so many different types of satellite software, and they change so frequently, it would be foolhardy to attempt to give you detailed operational descriptions in any book. The book would be obsolete a month after it came off the press!

Even so, there are a number of aspects of satellite-tracking software that rarely change. For instance, most programs will ask you to enter your station location as part of the initial setup process. Some applications use the term "observer" to mean "station location," but the terms are synonymous for the sake of our discussion. Sophisticated programs will go as far as to provide you with a list of cities that you can select to quickly enter your location. Other programs will ask you to enter your latitude and longitude coordinates manually.

When entering latitude, longitude (and other angles), make sure you know whether the computer expects degree-minute or decimal-degree notation. Following the notation used by the on-screen prompt usually works. Also make sure you understand the units and sign conventions being used. For example, longitudes may be specified in negative number for locations west of Greenwich (0° longitude). Latitudes in the southern hemisphere may also require a minus sign. Fractional parts of a degree will have very little effect on tracking data so in most cases you can just ignore it.

Dates can also cause considerable trouble. Does the day or month appear first? Can November be abbreviated Nov or must you enter 11? The number is almost always required. Must you write 2010 or will 10 suffice? Should the parts be separated by colons, dashes or slashes? The list goes on and on. Once again, the prompt is your most important clue. For example, if the prompt reads "Enter date (DD:MM:YY)" and you want to enter February 9, 2010 follow the format of the prompt as precisely as possible and write 09:02:10.

When entering numbers, commas should never be used. For example, if a semi-major axis of 20,243.51 km must be entered, type 20243.51 with the comma and units omitted. It takes a little time to get used to the quirks of each software package, but you'll soon find yourself responding automatically.

Once you have your coordinates entered, you're still not quite done. The software now "knows" its location, but it doesn't know the locations of the satellites you wish to track. The only way the software can calculate the positions of satellites is if it has a recent set of *orbital elements*.

3.4 Orbital Elements

Orbital elements are sets of six numbers that completely describe the orbit of a satellite at a specific time. Although scientists may occasionally use different groups of six quantities, radio amateurs nearly always use the six known as Keplerian Orbital Elements, or simply *Keps*.

These orbital elements are derived from very precise observations of each satellite's orbital motion. Using precision radar and highly sensitive optical observation techniques, the North American Aerospace Defense Command (NORAD) keeps a very accurate catalog of almost everything in Earth orbit. Periodically, they issue the unclassified portions of this information to the National Aeronautics and Space Administration (NASA) for release to the general public. The information is listed by individual catalog number of each satellite and contains numeric data that describes, in a mathematical way, how NORAD observed the satellite moving around the Earth at a very precise location in space at a very precise moment in the past.

Without getting into the complex details of orbital mechanics, suffice it to say that your software simply uses the orbital element information NASA publishes that describe where a particular satellite was "then" to solve the orbital math and make a prediction (either graphically or in tabular format) of where that satellite ought to be "now." The "now" part of the prediction is based on the local time and station location information you've also been asked to load into your software.

Orbital elements are frequently distributed with additional numerical data (which may or may not be used by a software tracking program) and are commonly available in two forms, NASA format and AMSAT format.

UNDERSTANDING THE AMSAT FORMAT

Let's use the easier-to-understand AMSAT format example shown in **Table 4** to break down the meaning, line by line.

The first two entries identify the spacecraft. The first line is an informal *satellite name*. The second entry, *Catalog Number*, is a formal ID assigned by NASA.

The next entry, *Epoch Time*, specifies the time the orbital elements were computed. The number consists of two parts, the part to the left of the decimal point that describes the year and day, and the part to the right of the decimal point that describes the (very precise) time of day. For example, 96325.465598 refers to 1996, day 325, time of day .465598.

The next entry, *Element Set*, is a reference used to identify the source of the information. For example, 199 indicates element set number 199 issued by AMSAT. This information is optional.

The next six entries are the six key orbital elements.

Inclination describes the orientation of the satellite's orbital plane with respect to the equatorial plane of the Earth.

RAAN, Right Ascension of Ascending Node, specifies the orientation of the satellite's orbital plane with respect to fixed stars.

Eccentricity refers to the shape of the orbital ellipse. The closer this number is to 0, the more circular the orbit of the satellite tends

Table 4

Example of Elements Used for Satellite Tracking (Download current elements for actual tracking use.)

NASA Two-Line Elements for Fuji-OSCAR 29

```
FO-29
1 24278U 96046B   17095.69822905 -.00000014  00000-0  20017-4 0  9991
2 24278 098.5744 348.5692 0350659 165.0412 196.1426 13.53075024019072
```

to be. Conversely, an eccentricity value approaching 1 indicates the satellite is following a more elliptically shaped orbital path.

Argument of Perigee describes where the perigee of the satellite is located in the satellite orbital plane. Recall that a satellite's perigee is its closest approach to the Earth. When the argument of perigee is between 180 and 360° the perigee will be over the Southern Hemisphere. Apogee — a satellite's most distant point from the Earth — will therefore occur above the Northern Hemisphere.

Mean Anomaly locates the satellite in the orbital plane at the epoch. All programs use the astronomical convention for *mean anomaly (MA) units*. The mean anomaly is 0 at perigee and 180 at apogee. Values between 0 and 180 indicate that the satellite is headed up toward apogee. Values between 180 and 360 indicate that the satellite is headed down toward perigee.

Mean Motion specifies the number of revolutions the satellite makes each day. This element indirectly provides information about the size of the elliptical orbit.

Decay Rate is a parameter used in sophisticated tracking models to take into account how the frictional drag produced by the Earth's atmosphere affects a satellite's orbit. It may also be referred to as rate of change of mean motion, first derivative of mean motion, or drag factor. Although decay rate is an important parameter in scientific studies of the Earth's atmosphere and when observing satellites that are about to reenter, it has very little effect on day-to-day tracking of most amateur radio satellites. If your program asks for drag factor, enter the number provided. If the element set does not contain this information enter zero — you shouldn't discern any difference in predictions. You usually have a choice of entering this number using either decimal form or scientific notation. For example, the number –0.00000039 (decimal form) can be entered as –3.9e–7 (scientific notation). The e–7 stands for 10 to the minus seventh power (or 10^{-7}). In practical terms e–7 just means move the decimal in the preceding number 7 places to the left. If this is totally confusing, just remember that in most situations entering zero will work fine.

Epoch revolution is just another term for the expression "Orbit Number" that we discussed earlier. The number provided here does not affect tracking data, so don't worry if different element sets provide different numbers for the same day and time.

The *Checksum* is a number constructed by the data transmitting station and used by the receiving station to check for certain types of transmission errors in data files. It does not bear any relationship to a satellite's orbit.

In the "old days" of satellite-tracking software you had to enter the orbital elements by hand. This was a tedious and risky process. If you entered an element number incorrectly, you would generate wildly inaccurate predictions.

Today, thankfully, most satellite-tracking programs have greatly streamlined the process. One method of entering orbital elements is to grab the latest set from the AMSAT-NA website at **www.amsat.org** (look under "Keps" in the main menu). You can download the element set as a text file and then tell your satellite-tracking program to read the file and create the database. Another excellent site is CelesTrak at **celestrak.com**. Your program will probably be able to read either the AMSAT or NASA formats.

If you're fortunate to own sophisticated tracking software such as *Nova*, and you have access to the internet, the program will reach into cyberspace, download and process its Keps automatically. All it takes is a single click of your mouse button. Some programs can even be configured to download the latest Keps on a regular basis without any prompting from you.

3.5 Other Tracking Considerations

SATELLITE FOOTPRINTS

Many satellite tracking applications display not only the satellite track, but also the satellite *footprint*. A satellite footprint can be loosely defined as the area on the Earth's surface that is "illuminated" by the satellite's antenna systems at any given time. Another way to think of a footprint is to regard it as the zone within which stations can communicate with each other through the satellite.

Unless the satellite in question is *geostationary*, footprints are constantly moving. Their sizes can vary considerably, depending on the altitude of the satellite. The footprint of the low-orbiting International Space Station is about 600 km in diameter. In contrast, the higher orbiting OSCAR 52 has a footprint that is nearly 1500 km across. See the example of a satellite footprint in **Figure 5**. The amount of time you have available to communicate depends on how long your station remains within the footprint. This time can be measured in minutes, or in the case of a satellite in a highly elliptical orbit, hours.

It is worthwhile to note that the size and even the shape of a footprint can also vary according to the type of antenna the satellite is using. A highly directional antenna with a narrow beamwidth will create a small footprint even though the satellite is traveling in a high-altitude orbit. This usually isn't an issue for amateur satellites, however.

A SATELLITE'S "PHASE"

Some satellites use operating schedules to determine which transponders and antennas are active at any given time. It is based on the *phase* of the satellite's mean anomaly, or MA. Many software applications can use this information to provide detailed predictions that tell you not only when the satellite will appear, but also which transponders will be active at the time.

The expression "anomaly" is just a fancy term for *angle*. Astronomers have traditionally divided orbits into 360 mean-anomaly units, each containing an equal time segment. Because of the architecture of common microprocessors, it was much more efficient to design the computers controlling spacecraft to divide each orbit into 256 segments of equal time duration. Radio amateurs refer to these as mean anomaly or phase units. The duration of

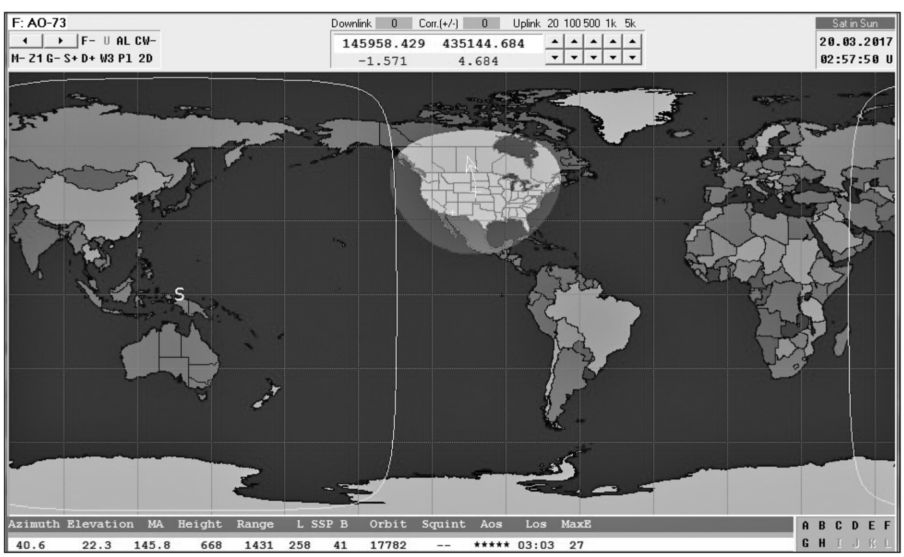


Figure 5 — This image shows the circular footprint as depicted by *NOVA* satellite-tracking software. The footprint indicates the area of the Earth that is visible to the satellite at any given time.

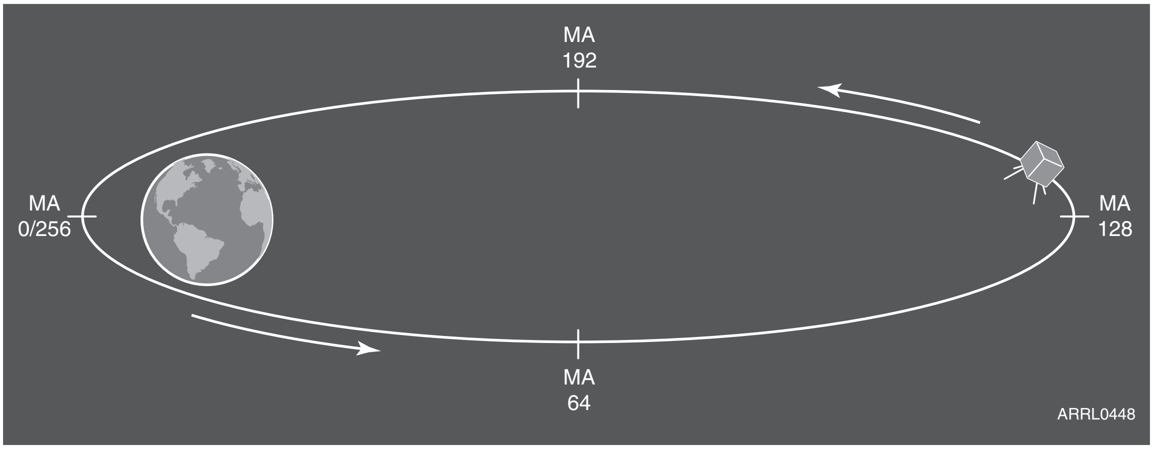


Figure 6 — Mean anomaly (MA) units or phase units divide each orbit into 256 segments of equal time duration. The duration of each segment is the satellite's period divided by 256. For example, a mean anomaly unit for OSCAR 13 was roughly 2.68 minutes. At MA 0 (beginning of orbit) and MA 256 (end of orbit) the satellite is at perigee (its lowest point). At MA 128 (halfway through the orbit) the satellite is at apogee (or its highest point).

each segment is the satellite's period divided by 256. For example, a mean anomaly unit for OSCAR 13 was roughly 2.68 minutes. At MA 0 (beginning of orbit) and MA 256 (end of orbit) the satellite is at perigee (its lowest point). At MA 128 (halfway through the orbit) the satellite is at apogee or high point. See **Figure 6**.

Because radio amateurs and astronomers use the term mean anomaly in a slightly different way, there's sometimes a question as to which system is being used. Any confusion is minor and usually easily resolved. Most OSCAR telemetry with real-time MA values and schedules use the 256 system. The term "phase" — and the fact that no numbers larger than 256 ever appear — are significant hints. Computer tracking programs designed for non-radio amateur audiences generally use the traditional astronomical notation. It's easy to determine when this is the case because the mean anomaly column will contain entries between 257 and 360.

If a satellite is using an MA-based transponder schedule, the schedule will be posted on the AMSAT-NA website at **www.amsat.org**. (When this book was written there were no amateur radio satellites in orbit using MA scheduling, but this may change as currently planned satellites reach orbit.) Depending on its sophistication, your tracking software may allow you to enter this schedule data.

Schedules are generally modified every few months when satellite orientation is adjusted to compensate for changes in the sun angle on the spacecraft. A typical schedule used for OSCAR 13, with its corresponding uplink (transmitting) and downlink (receiving) frequency band requirements, looked like this:

Off: from MA 0 until MA 49

Mode U/V (uplink on 70 centimeters/downlink on 2 meters): on from MA 50 until MA 128

Mode U/S (uplink on 70 centimeters/downlink on 2.4 GHz): on from MA 129 until MA 159

Mode U/V (uplink on 70 centimeters/downlink on 2 meters): on from MA 160 until MA 255

If you wanted to operate Mode U/S, you needed to be at the radio when the satellite was between MA129 and MA159 in its orbit.

SQUINT ANGLE

Another dilemma your software may help resolve is the *squint angle*. The squint angle describes how the directive antennas on a satellite are pointed with respect to your ground station. Squint angle can vary between 0° and 180°. A squint angle of 0° means the satellite antennas are pointed directly at you and that generally indicates that good link performance can be expected (**Figure 7**). When the squint angle is above 20°, signal level

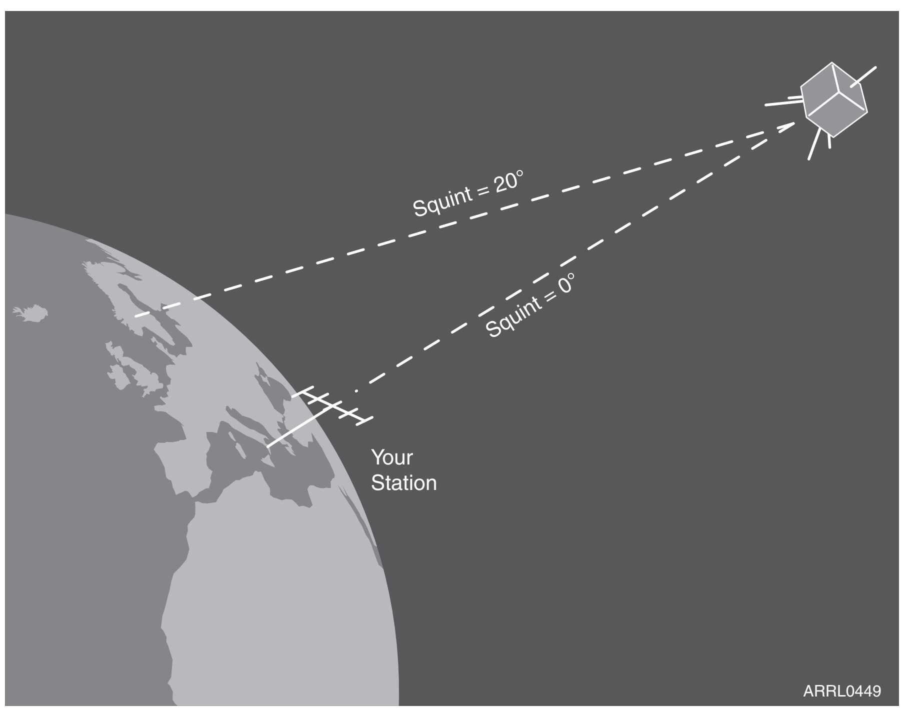


Figure 7 — The squint angle describes how the directive antennas on a satellite are pointed with respect to your ground station. Squint angles can vary between 0° and 180°. A squint angle of 0° means the satellite antennas are pointed directly at you, which, in turn, means good link performance can usually be expected. When the squint angle is above 20° signal level begins to drop.

begins to drop and a disruptive amplitude flutter called spin modulation on uplinks and downlinks may become apparent.

Programs that include algorithms to calculate squint angle require information about the orientation or attitude of the satellite. This information is generally available from sources that provide the basic orbital elements and on telemetry sent directly from the satellite of interest. The parameters needed are labeled *Bahn latitude* and *Bahn longitude*. They are also known as BLAT and BLON or ALAT and ALON where the prefix "A" stands for attitude.

Programs that provide squint angle information may also contain a column labeled *Predicted Signal Level*. Values are usually computed using a simple prediction model that takes into account satellite antenna pattern, squint angle and spacecraft range. The model assumes a 0 dB reference point with the satellite overhead, at apogee and pointing directly at you. At any point on the orbit the predicted level may be several dB above (+) or below (–) this reference level.

You won't need to be concerned about squint angle for most LEO satellites. It only becomes a factor with the high-orbit birds since they generally use directive antennas. As with MA scheduling, you'll want to know that the satellite's antennas are pointing at your location before you fire up your equipment. With the right kind of software, you'll know well ahead of time.

4 Satellite Ground Station Antennas

Assembling a satellite ground station presents a different challenge compared to typical HF station setups. There are a number of variables that change depending on the types of satellites you hope to use. A ground station designed strictly for LEO satellites differs substantially from one intended for HEO birds. There are also issues surrounding computers and software, particularly if you plan to access digital satellites.

One aspect of your ground station with the greatest range of choice is your antenna system. To use most amateur satellites, you must transmit on one band (the uplink) and receive on another band (the downlink). Unless you are using a single, dual-band antenna, your satellite station will require at least two antennas. Some satellite operators have several antennas so that they can operate on various uplink/downlink band combinations as the need arises.

4.1 Antenna Polarization

The *polarization* of a satellite antenna is an important factor, regardless of whether it is used for transmitting or receiving. Polarization is determined by the position of the radiating element or wire with respect to the Earth. A radiator that is parallel to the Earth radiates horizontally, while a vertical radiator radiates a vertical wave. These are so-called *linearly polarized* antennas. If the radiating element is slanted above the Earth, it radiates waves that have *both* vertical and horizontal components.

For terrestrial VHF+ line-of-sight communication, polarization matching is important. If one station is using a horizontally polarized antenna and the other is using a vertically polarized antenna, the mismatch can result in a large signal loss under certain conditions. We don't worry about polarization mismatches on HF frequencies because whenever signals are refracted through the ionosphere, as HF signals usually are, polarization changes anyway.

The problem with applying polarization concerns to spacecraft is that the orientation of a satellite's antennas relative to your ground station is constantly changing. This often results in fading when the polarization of its antennas conflict with yours. This problem doesn't plague satellites exclusively. Aircraft, automobiles and all other moving radio platforms can suffer the same effects.

Fortunately, there is a "cure" known as *circular polarization* (CP). With CP, wave fronts appear to rotate as they pass the receiving station, either clockwise (right-hand or RHCP) or counter clockwise (left-hand or LHCP). See **Figure 8**. The advantage of using circular polarization is that it can substantially reduce the effects of polarization conflict. Since the polarization of a CP antenna rotates through horizontal and vertical planes, the resulting pattern effectively "smoothes" the fading effects, generating consistent signals as a result.

That said, your satellite ground station antennas do *not* need to be circularly polarized to be effective. Linearly polarized antennas, either horizontal or vertical, are perfectly useful. Some ground station antenna designs use slanted or "crossed" elements to mix the horizontal and vertical polarization components as discussed earlier. The goal of fine-tuning your antenna polarization is to give your station an edge, something that is important when you are dealing with weak signals from deep space. But, while circular polarization of your antennas may give your station a definite advantage, it isn't an absolute requirement.

4.2 Omnidirectional Antennas

An ideal omnidirectional antenna radiates and receives signals in all directions equally. In the real world, most "omnidirectional" antennas have a certain amount of directivity. For example, a common ground plane antenna (**Figure 9**) is considered to be omnidirectional, but as you can see in **Figure 10** the radiation pattern is not uniform. Notice the deep null directly overhead. Signals will fade sharply as satellites move through this null, particularly during high-elevation passes.

Despite their low gain, omnidirectional antennas are attractive because they do not need to be aimed at their targets. This means that they don't require mechanical antenna rotators, which can add significant cost and

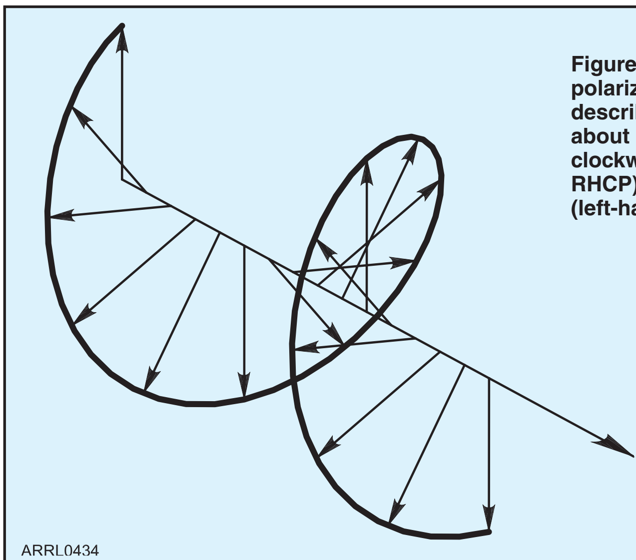


Figure 8 — A circularly polarized wave front describes a rotational path about its central axis, either clockwise (right-hand or RHCP) or counter clockwise (left-hand or LHCP).

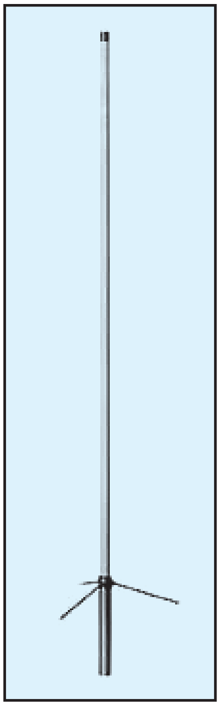


Figure 9 — An ordinary ground plane antenna. This particular model is designed for terrestrial communications on 2 meters.

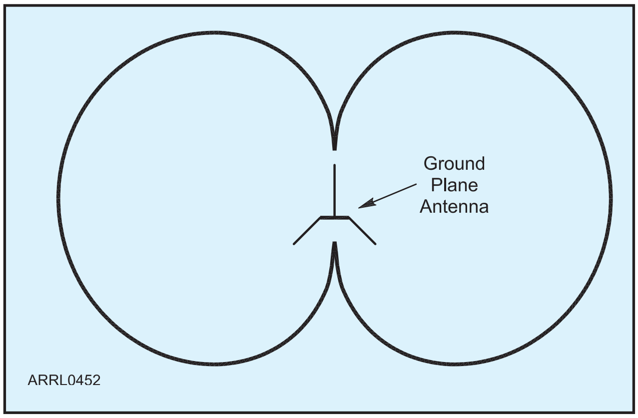


Figure 10 — The simplified radiation pattern of a ground plane antenna. Notice the deep null directly overhead.

complexity to a ground station. Omni antennas are also more compact than directional antennas for the same frequency. On the other hand, their low gain makes them practical only for LEO satellites that have sensitive receivers and relatively strong transmit signals.

Technically speaking, any type of omnidirectional antenna can be used for a satellite ground station. Hams have enjoyed satellite operations with simple ground planes, J-poles, "big wheels" and even automobile antennas. But for best results with an omni-based antenna system, you'll want a radiation pattern that minimizes the polarization conflicts and pattern nulls that can cause signals to fade. To this end, engineers have designed a number of omnidirectional antennas with these issues in mind.

THE EGGBEATER

The *eggbeater* antenna is a popular design named after the old-fashioned kitchen utensil it resembles (**Figure 11**). The antenna is composed of two full-wave loops of rigid wire or metal tubing. Each of the two loops has an impedance of 100 Ω, and when coupled in parallel they offer an ideal 50 Ω impedance for coaxial feed lines. The loops are fed 90° out of phase with each other and this creates a circularly polarized pattern.

An eggbeater may also use one or more parasitic reflector elements beneath the loops to focus more of the radiation pattern upward. This effect makes it a "gain" antenna, but that gain is at the expense of low-elevation reception. Toward the horizon an eggbeater is actually horizontally polarized. As the pattern rises in elevation, it becomes more and more right-hand circularly polarized. Experience has shown that eggbeaters seem to perform best when reflector elements are installed just below the loops.

Eggbeaters can be built relatively easily, but there are also a couple of commercial models available. The spherical shape of the eggbeater creates a fairly compact antenna when space is an issue, which is another reason why it is an attractive design.

THE TURNSTILE

The basic *turnstile* antenna consists of two horizontal half-wave dipoles mounted at right angles to each other (like the letter "X") in the same horizontal plane with a reflector screen beneath (**Figure 12**). When these two antennas are excited with equal currents 90° out of phase, their typical figure-eight patterns merge to produce a nearly circular pattern.

In order to get the radiation pattern in the upward direction for space communications, the turnstile antenna needs a reflector underneath. For a broad pattern it is best to maintain a distance of ⅜ λ at the operating frequency between the reflector and the turnstile. Homebrewed turnstile reflectors often use metal window-screen material that you can pick up at many hardware stores. (Make sure it is a metal, not plastic, screen material.)

Like their cousins the eggbeaters, turnstiles are relatively easy to build. In fact, building

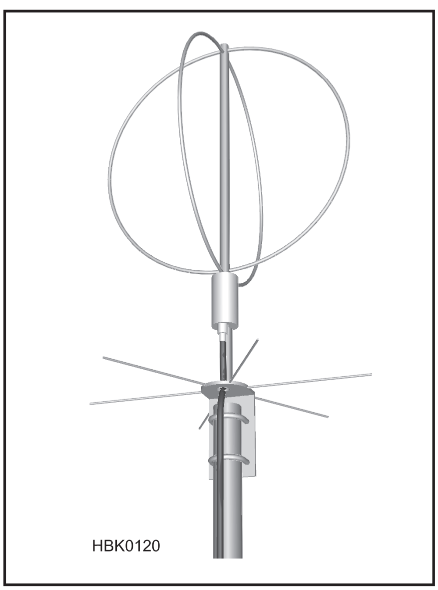


Figure 11 — The eggbeater antenna is a popular design named after the old-fashioned kitchen utensil it resembles. The antenna is composed of two full-wave loops of rigid wire or metal tubing.

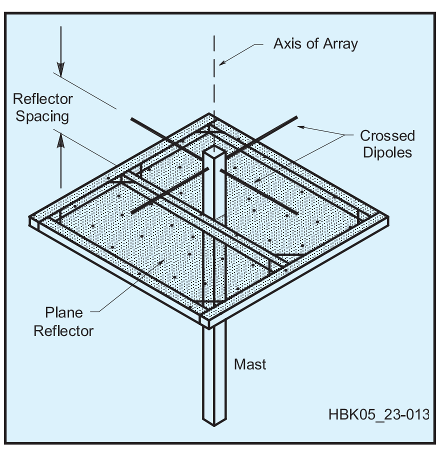


Figure 12 — The basic turnstile antenna consists of two horizontal half-wave dipoles mounted at right angles to each other (like the letter "X") in the same horizontal plane with a reflector screen beneath.

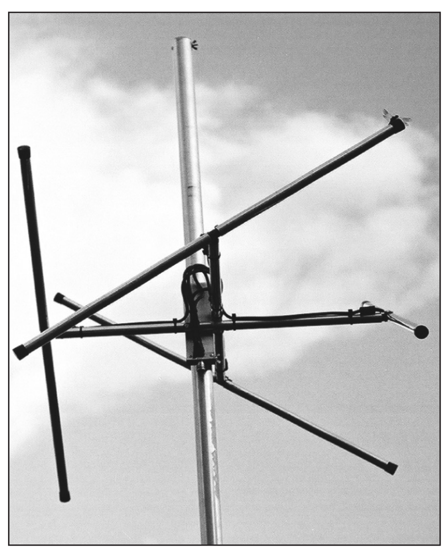


Figure 13 — The EZ Lindenblad antenna designed by Anthony Monteiro, AA2TX.

one may be your only choice since turnstiles are rarely available off the shelf.

THE LINDENBLAD ANTENNA

In a *Lindenblad* antenna (**Figure 13**), each dipole element is attached to a section of shorted open-wire-line, also made from tubing, which serves as a balun transformer. A coaxial cable runs through one side of each open-wire line to feed each dipole. The four coaxial feed cables meet at a center hub section where they are connected in parallel to provide a four-way, in-phase power-splitting function. This cable junction is connected to another section of coaxial cable that serves as an impedance matching section to get a good match to 50 Ω. An innovative solution, the EZ-Lindenblad, is described later in this chapter. While certainly more elaborate than an eggbeater or turnstile, the Lindenblad creates a uniform circularly polarized pattern that is highly effective for satellite applications.

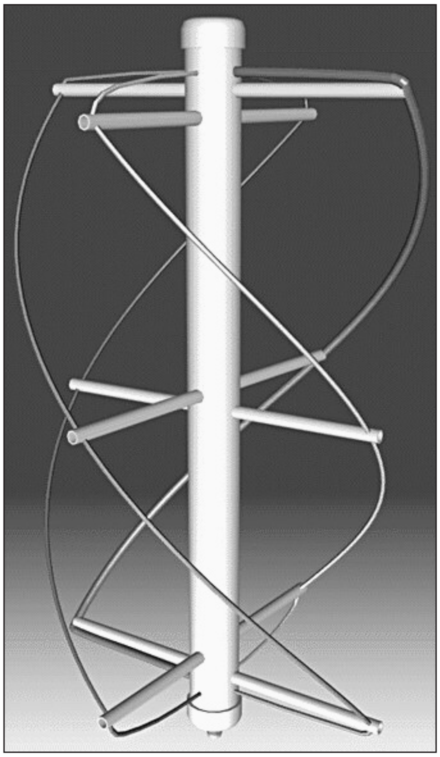


Figure 14 — The quadrifilar helicoidal antenna is comprised of four equal-length conductors (filars) wound in the form of a corkscrew (helix) and fed in quadrature.

THE QUADRIFILAR HELICOIDAL ANTENNA

The quadrifilar helicoidal antenna (QHA) shown in **Figure 14** ranks among the best of the omnidirectional satellite antennas. It is comprised of four equal-length conductors (filars) wound in the form of a corkscrew (helix) and fed in quadrature. The result is a nearly perfect circularly polarized pattern.

QHAs can be challenging to build since the filar lengths and spacing have to be precise. Even so, homebrewing a QHA can save you a substantial amount of money. This antenna is available off the shelf (they are favorites for maritime satellite links), but they can be costly. A version that can be built from readily available materials is described later in this chapter.

4.3 Directional Antennas

Gain and directivity are important antenna factors. These factors are maximized in *directional* antennas. In fact, the design goal of a directional antenna is to create a highly directional pattern along its axis (**Figure 15**). An ordinary flashlight is a reasonable analog for a directional antenna, although the pattern of a directional antenna isn't as well focused as a flashlight beam (antennas with parabolic reflectors come fairly close, though).

The chief advantage of a directional antenna is its considerable directivity and gain. When you are working with weak signals from spacecraft, you need all the gain you can get. Directional antennas are mandatory for high-altitude satellites when they are at apogee, nearly 50,000 km distant. They also are excellent for LEO birds, providing strong, consistent signals that omnidirectional antennas can rarely match.

But, a major disadvantage of a directional antenna is *also* its directivity! To achieve best results with a directional antenna, you must find a way to point it at the satellite you wish to work. This entails pointing it by hand, or by using an antenna rotator. If you were to simply leave a directional antenna fixed in one place, you would enjoy good signals only during the brief moments when satellites passed through the antenna's pattern. A rotator adds significant cost to a ground station and installing one isn't a trivial exercise. On the other hand, there is a way to reduce rotator cost, which we'll discuss later.

If you can afford a directional antenna and rotator system, you'll never regret the investment. When properly installed, it is vastly superior to any omnidirectional antenna you are likely to encounter.

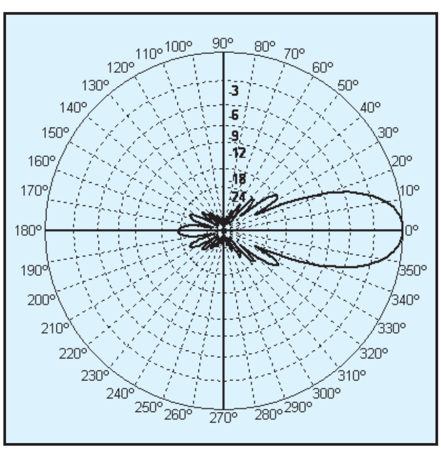


Figure 15 — The design goal of a directional antenna is to create a highly directional pattern along its axis. This example shows the radiation pattern of a high-gain Yagi antenna.

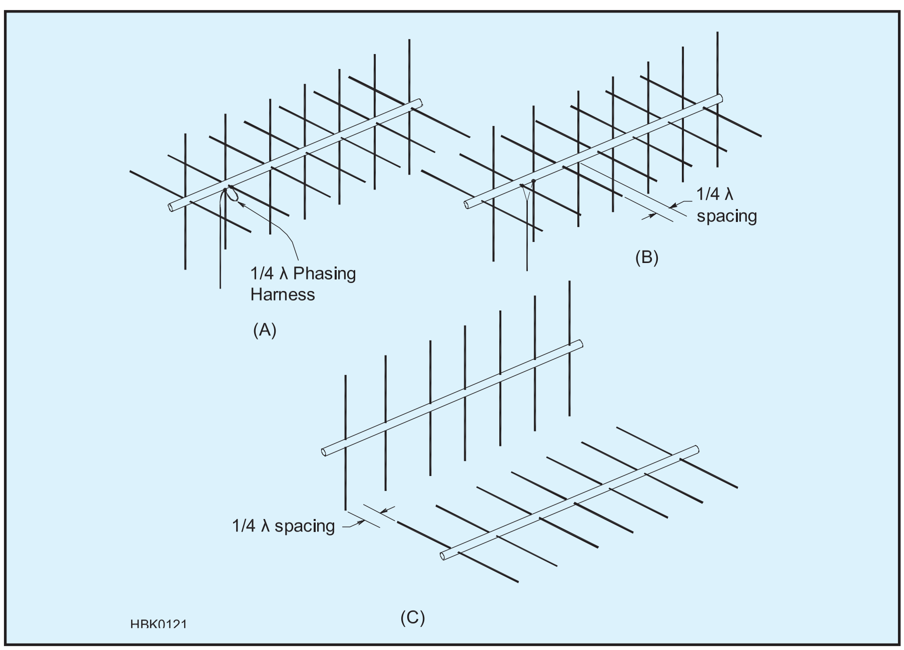


Figure 16 — Evolution of the circularly polarized Yagi. The simplest form of crossed Yagi, A, is made to radiate circularly by feeding the two driven elements 90° out of phase. Antenna B has the driven elements fed in phase, but has the elements of one bay mounted ¼ λ forward from those of the other. Antenna C offers elliptical (circular) polarization using separate booms. The elements in one set are mounted perpendicular to those of the other and are spaced ¼ λ forward from those of the other.

YAGI ANTENNAS

The familiar Yagi antennas used for VHF+ terrestrial operation can be used for satellite applications as well. However, keep in mind that the greater the directivity, the more focused (narrow) the antenna pattern. This translates to an antenna that must be aimed at a satellite with a fair degree of accuracy. This can be a challenge when your target is a rapidly moving LEO bird.

The Yagi antennas you normally see are *linear* designs that are mounted in either horizontal or vertically polarized configurations. These same antennas can be successfully used for satellite work just as they are. However, there are ways you can optimize them to increase their effective performance.

The dipole elements of Yagi antennas radiate linearly polarized signals, but remember that the polarization direction really depends on the orientation of the antenna to the Earth. If two Yagi antennas are mounted on the same support boom, arranged for horizontal and vertical polarization, and combined with the correct phase difference (90°), a circularly polarized wave results. Because the electric fields of the antennas 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. This design is known as a *crossed Yagi*.

A 90° phase shift must exist between the two antennas and the simplest way to obtain this shift is to use two feed lines. One feed-line section is ¼ λ longer than the other, as shown in **Figure 16**. These separate feed lines are then paralleled to a common transmission line to the station. However, 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.) **Figure 17** shows a practical example of offset crossed Yagis for the 23 centimeter band.

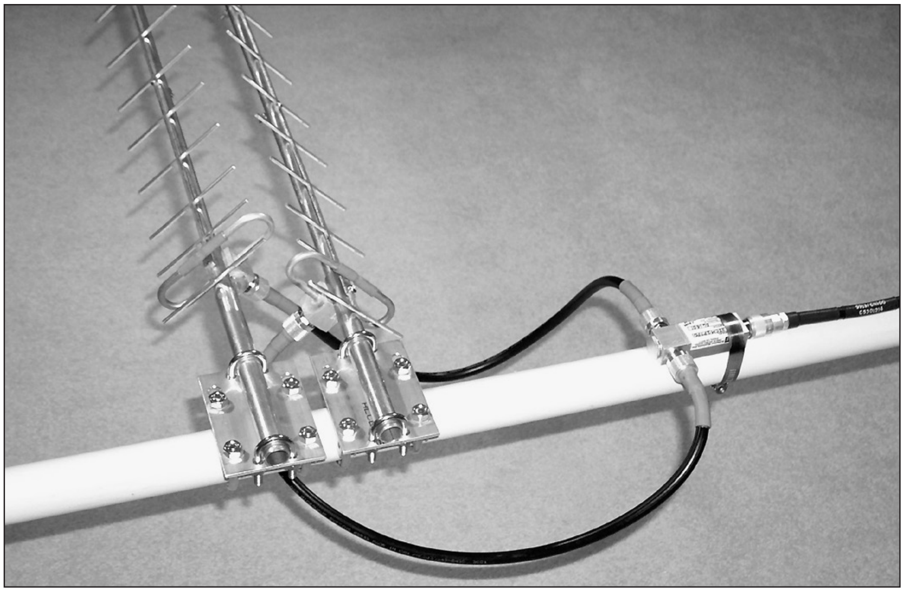


Figure 17 — An example of offset crossed-Yagi circularly polarized antennas with fixed polarization. This example shows a pair of Yagis for L band (1296 MHz) mounted on an elevation boom. [KD1K photo]

So far we've been discussing single-band crossed Yagi designs to achieve circular polarization, or something close to it. If circular polarization isn't a top criterion, you may want to consider a *dual-band Yagi* that places linear Yagi antennas for two separate bands on the same support boom. While this design doesn't produce circular polarization, it partially makes up for that disadvantage in convenience and economics. The most common design combines antennas for 2 meters and 70 centimeters on the same boom (**Figure 18**). You can feed the antennas with two separate feed lines, or use single feed line and a *diplexe*r (some manufacturers incorrectly call them *duplexers*) to separate the signals at the antenna, at the radio or at both locations (**Figure 19**). With a single 2 meter/

Figure 18 — Joe Bottiglieri, AA1GW, uses a dual-band Yagi to work a low-Earth orbiting FM repeater satellite with a handheld transceiver.

Figure 19 — A diplexer made by the Comet Corporation. Diplexers can be used to separate or combine signals on different bands.

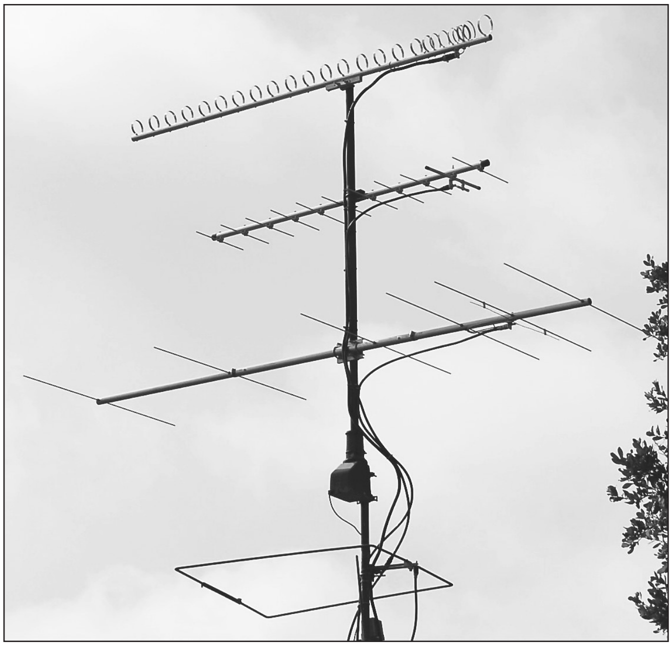


Figure 20 — This antenna stack includes a loop Yagi at the very top.

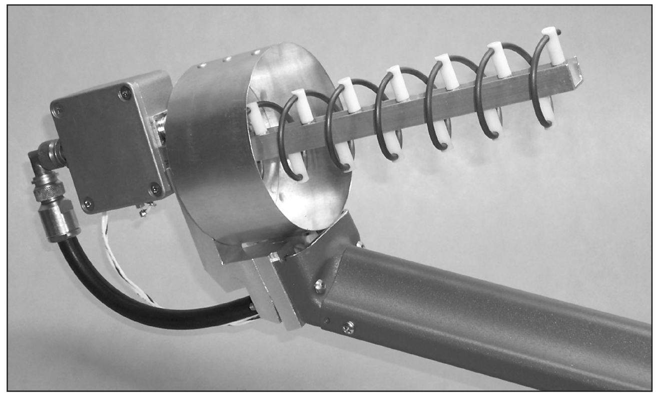


Figure 21 — A seven-turn LHCP helical antenna for a 2.4 GHz dish feed. This helical antenna uses a cupped reflector and has a preamplifier mounted directly to the antenna feed point. [Dick Jansson, KD1K, photo]

70 centimeter Yagi antenna you can enjoy nearly all available amateur satellites. That single-purchase aspect makes them attractive for budget-conscious hams.

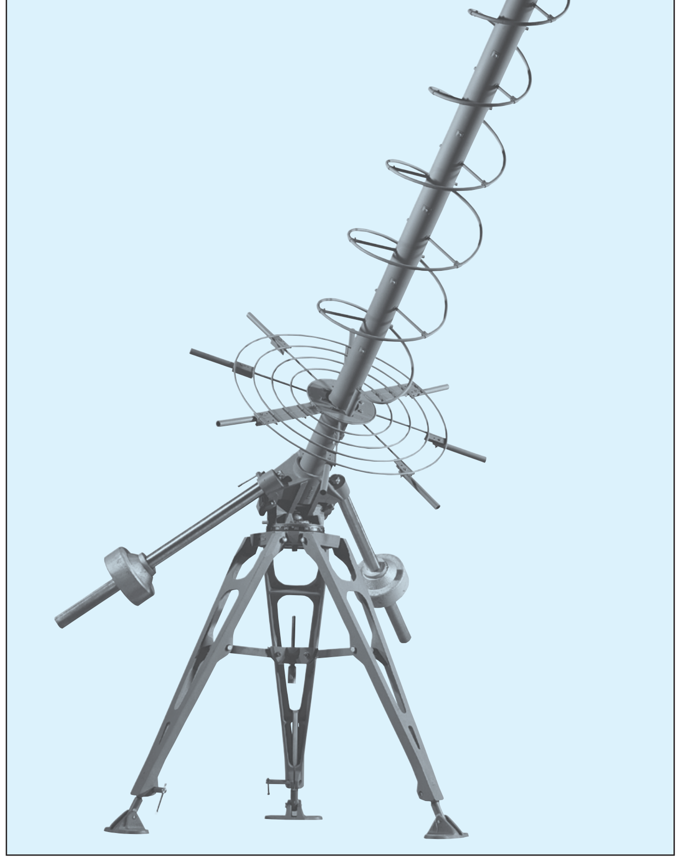
A type of Yagi that you may encounter for higher frequencies (typically 902 MHz and above) is the *loop Yagi* (**Figure 20**). In this design, the individual elements are bent into loops and mounted on a common boom. Despite their appearance, loop Yagis are linearly polarized antennas. Their advantage is that they create a substantial amount of gain in a relatively small physical space. Because of the sizes of the loops, however, loop Yagis are most practical and common at microwave frequencies.

HELICAL ANTENNAS

Another 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. **Figure 21** shows an example of a microwave helical antenna. A larger helical for 70 centimeters is shown in **Figure 22**.

This antenna has two characteristics that make it especially interesting and useful for satellite stations. 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

Figure 22 — A helical antenna for 70 cm.



pattern, gain and impedance characteristics over a wide frequency range. This is one of the few antenna designs that have 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.

Electrically, a helix looks like a large air-wound coil with one of its ends fed against a ground plane. The ground plane often consists of a screen of 0.8 to 1.1 λ diameter (or per side for a square ground plane). The circumference of the coil form must be between 0.75 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 should be in the range of 0.2126 to 0.2867 λ. The winding of the helix comes away from the cupped reflector with a counterclockwise winding direction for LHCP. A clockwise winding direction yields RHCP.

PARABOLIC DISH ANTENNAS

A number of modern ham satellites now include microwave transponders and this has created a great deal of interest in effective microwave antennas. From the ground station “point of view,” antennas for the microwave bands are not only small, they pack a high amount of gain into their compact packages. Among the best high-performance antenna designs for microwave use are those that employ parabolic reflectors (so-called parabolic “dishes”) to concentrate the transmitted and received energy.

Like a bulb in a flashlight, a parabolic antenna must have a *feed source* — the radiating and receiving part of the antenna — “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* (**Figure 23**). 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 **Figure 24**. 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 by 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 dish’s parabola can be designed so the *focus point* — the point where the feed source must be — 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 (F), measure the diameter of the dish (D) and the depth of the dish (d).

$$F = D^2 / 16d$$

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. This is where you want to place the feed source.

To invoke the flashlight analogy again, the feed source should evenly illuminate the entire dish, and none of the feed energy should fall outside the dish’s reflecting surface. However, *no* feed system is perfect in illuminating a dish. These so-called “spillover losses” affect the gain by either under-illuminating or over-illuminating the dish. Typical dish efficiency is 50%. That’s 3 dB of lost gain.

A great feed system for one dish can perform poorly on another. For example, if you can get your hands on a surplus offset-fed satellite TV dish, you may find a helical radiator is the best feed source. Designs range 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 typically longer-focal-length (f/D ~ 0.6), offset-fed dishes. Generally speaking, helix feeds work poorly on the short-focal length dishes, but really perform well on the longer-focal length, offset-fed dishes.

Figure 24 — This is a good example of an offset-fed dish. Note the feed source at the bottom edge of the photo, pointing into the center of the parabola. Also note that this is a DirectTV satellite TV antenna that has been “repurposed” for amateur radio satellites!

Figure 25 — The 2.4 GHz satellite downlink antenna at ARRL Headquarters station W1AW is a so-called “barbeque grill” dish antenna originally designed for the Multi-channel Multipoint Distribution Service (MMDS). These inexpensive antennas can be assembled and installed in minutes.

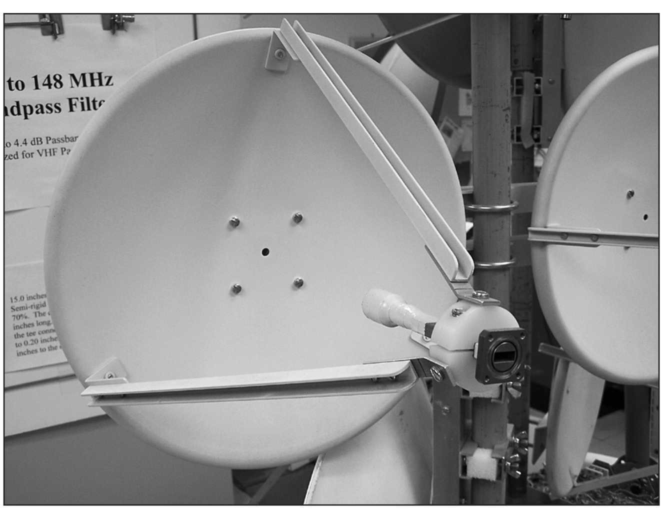


Figure 23 — As you can see, the feed source is directly in front, making this a center-fed dish.

Figure 26 — A basic antenna rotator; the light-duty variety used to turn TV antennas. The wire exiting the bottom of the rotator housing is the multiconductor cable responsible for power and control.

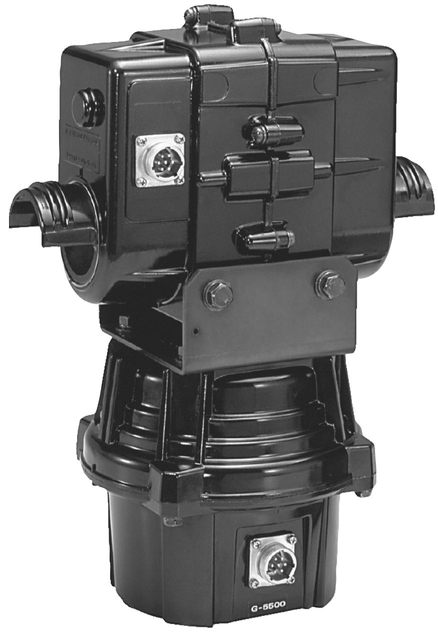


Figure 27 — The Yaesu G5500 azimuth/elevation rotator (left) and its control unit (right).

Parabolic antennas can be made from commercial or military surplus, including satellite TV dishes that you can "repurpose" in the finest amateur radio tradition. You will also find ham dealers selling so-called *barbecue* dishes that were originally designed for the Multichannel Multipoint Distribution Service, or "wireless cable TV" (see **Figure 25**). MMDS antennas come with built-in feed sources at the focal points, so all you have to do is connect the feed line and go. These are among the most popular dish antennas for amateur satellite enthusiasts.

4.4 Antenna Mounting

One beneficial characteristic of satellite antennas is that they can be installed close to the ground as long as the antenna can "see" as much of the unobstructed sky as possible. Signals to and from the satellite will already be traversing hundreds or thousands of free space. So, adding a few more feet of elevation to your ground station antenna won't perceptibly improve the strength of those signals. What such an arrangement *will* do, however, is needlessly increase the length of coax (and corresponding line losses) between your transceiver and your antenna.

If your antennas already have an unobstructed view of the sky from the ground, you usually won't need a tower or roof installation unless trees or buildings surround the antennas and block their upward view. Or, to put it another way, your antenna support only needs to be high enough to make sure the back end of the antenna array is far enough off the ground to prevent people from walking into it while it's pointing straight up.

What's more, and as we have already discussed, satellite antennas (particularly those of the circularly polarized variety) along with their associated rotators (discussed below) tend to create a more complex antenna arrangement than that used for ordinary HF or VHF/UHF terrestrial operation. So, mounting them close to the ground makes performing any needed adjustments or repairs a whole lot simpler.

4.5 Antenna Rotators

If you plan to use directional antennas and don't wish to manipulate them by hand, you will need to install an *antenna rotator* (**Figure 26**). Making the correct decision as to how much capacity the rotator must have is very important to ensure trouble-free operation.

Rotator manufacturers generally provide antenna surface area ratings to help you choose a suitable model. The maximum antenna area is linked to the rotator's torque capability. Some rotator manufacturers provide additional information to help you select the right size of rotator for the antennas you plan to use. Hy-Gain provides an *Effective Moment* value. Yaesu calls theirs a *K-Factor*. Both of these ratings are torque values in foot-pounds. You can compute the Effective Moment of your antenna by multiplying the antenna turning radius by its weight. So long as the effective moment rating of the rotator is greater than or equal to the antenna value, the rotator can be expected to provide a useful service life.

There are several rotator grades available to amateurs. The lightest-duty rotator is the type typically used to turn TV antennas. These rotators will handle smaller satellite antennas such as crossed Yagis. The problem with TV rotators is that they lack braking or holding capability. High winds can turn the rotator motor via the gear train in a reverse fashion, requiring realignment. Broken gears sometimes result.

The next grade up from the TV class of rotator usually includes a braking arrangement, whereby the antenna is held in place when power is not applied to the rotator. Generally speaking, the brake prevents antenna misalignment or gear damage on windy days. If adequate precautions are taken, this type of rotator is capable of holding and turning a stack of satellite antennas, including a parabolic dish which, by its nature, presents considerable wind loading. Keep in mind that as rotators increase in power, they become more expensive.

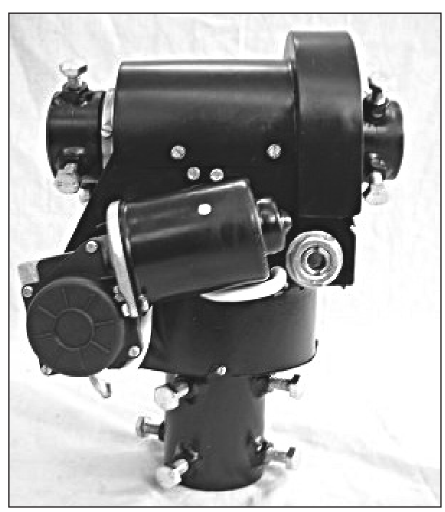


Figure 28 — An az/el rotator made by Alfa Radio.

AZIMUTH/ELEVATION ROTATOR

Perhaps the ultimate in operating convenience is the *azimuth/elevation (az/el) rotator*. This rotator is capable of moving your antennas horizontally (azimuth) and vertically (elevation) at the same time. There are well-designed models available from Yaesu (**Figure 27**) and Alfa Radio (**Figure 28**). You can operate these rotators manually, or connect them to your computer for automated tracking. The downside is that az/el rotators tend to be expensive, typically on the order of $600 or more at this writing.

If your budget can stand the strain, az/el rotators are clearly worth the investment. On the other hand, if cost is an issue, consider using a standard rotator instead. While a traditional rotator can only move your antennas in the azimuth plane (horizontally), you can strike a compromise by installing the antennas at a permanent 45° tilt (**Figure 29**). This configuration will allow you to work the vast majority of satellites with reasonable success. You won't be able to follow the satellite when it is overhead or near the horizon, but you'll enjoy the lion's share of every pass.

Regardless of which type you choose, proper installation of the antenna rotator can provide many years of dependable service. Sloppy installation can cause problems such as a burned out motor, slippage, binding and even breakage of the rotator's internal gear and shaft castings or outer housing. Most rotators are capable of accepting mast sizes of different diameters, and suitable precautions must be taken to shim an undersized mast to ensure dead-center rotation.

If you decide to install your rotator on a tower, it is desirable to mount the rotator inside and below the top of the tower as far as possible. A long mast (10 feet or so) absorbs the torsion developed by the antenna during high winds, as well as during starting and stopping. Another benefit is mitigating the effect of any misalignment among the rotator, mast and the top of the tower.

A tube at the top of the tower (a *sleeve bearing*) through which the mast protrudes almost completely eliminates any lateral forces on the rotator casing. All the rotator must do is support the downward weight of the antenna system and turn the array. Some installations use a *thrust bearing* mounted to the tower to support the weight of the antenna and mast.

Don't forget to provide a loop of coax to allow your antenna to rotate properly and allow water to drip off. Also, make sure you position the rotator loop so that it doesn't snag on anything.

COMPUTER CONTROL

As mentioned earlier, you can connect your rotator to your station computer and allow your satellite-tracking software to aim your antennas automatically (assuming your software supports rotator control). There used to be a number of commercial rotator/computer interface devices available for sale, but availability has dwindled over the years and those that remain tend to be expensive. An interface such as the Yaesu GS-232 (**Figure 30**) costs about $600 at the time of this writing. If you combine it with a Yaesu azimuth/elevation rotator, you will have invested $1300 total. Less expensive alternatives are now found as kits or homebrew devices. A good example is the G6LVB tracker interface at **www.g6lvb.com/Articles/LVBTracker/**. If you're willing to build it yourself, you can probably put together an LVB unit for less than $50. Do an internet search and you'll no doubt uncover other homebrew interfaces.

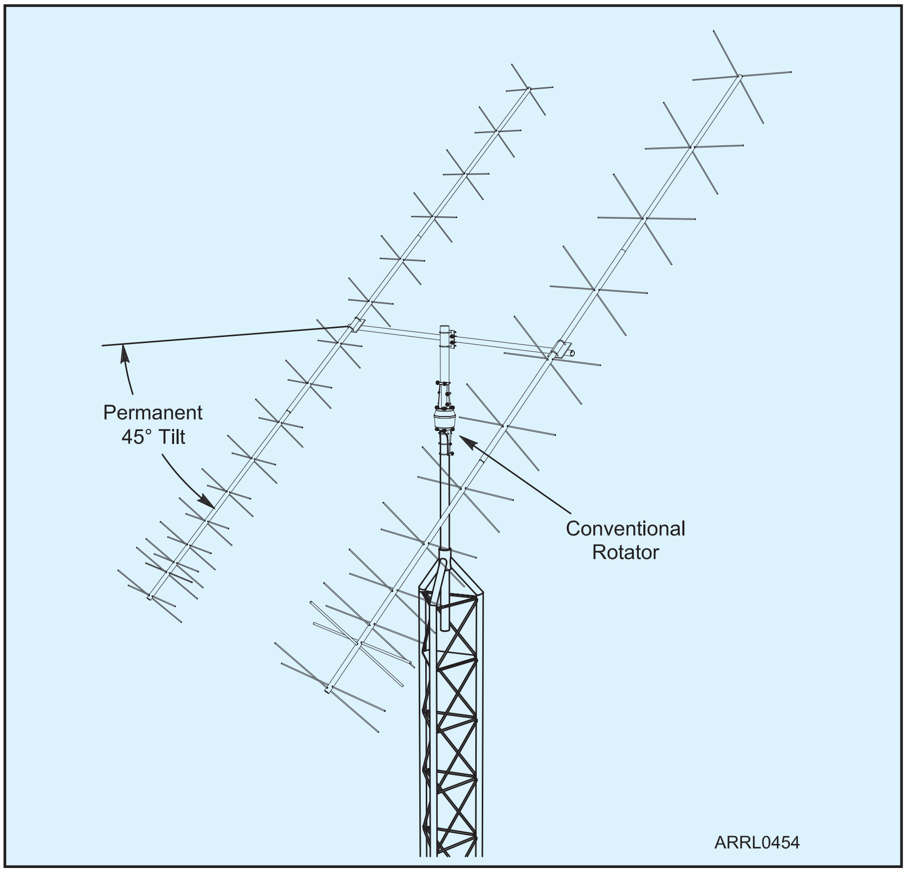


Figure 29 — The alternative to using an expensive azimuth/elevation antenna rotator is to simply install your antennas at a 45° tilt and use a conventional rotator to move them from side to side (azimuth only). This configuration will allow access during most satellite passes.

Figure 30 — The Yaesu GS-232 allows your computer and satellite tracking software to automatically control the movements of compatible azimuth/elevation antenna rotators.

5 Satellite Ground Station Equipment

5.1 Receive and Transmit Converters

Signals from satellites can be exquisitely weak, which means they need as much amplification as possible to be readable. Unfortunately, there are a number of factors that may conspire to weaken your radio's ability to render a decent received signal….

• *You're using omnidirectional antennas.* As discussed earlier, omni antennas lack much of the signal-capturing gain of directional antennas.

• *The feed line between the antennas and the radio is long and/or contains "lossy" coax.* Remember that even with the best coax, the longer the feed line the more signal you'll lose, especially at higher frequencies.

• *You're trying to communicate with a high-orbiting satellite at apogee.* When a signal travels up to 50,000 km to reach your station, even the gain of a directional antenna may not be sufficient.

PREAMPLIFIERS

The way to ensure that you have a useable received signal is to install a *receive preamplifier* (**Figure 31**) at the antenna. This is a high-gain, low-noise amplifier with a frequency response tailored for one band only.

When shopping for a receive preamplifier, you want the most amount of gain for the least amount of noise. Every preamplifier adds some noise to the system, but you want the least additional noise possible. A well-designed UHF preamplifier, for example, may have gain on the order of 15 to 25 dB and a *noise figure* (NF) of 0.5 to 2 dB (less is better).

If your antennas are outdoors, look for preamplifiers that are "mast mountable." These preamplifiers are housed in weatherproof enclosures.

You will need to devise a means to supply dc power to the remote preamplifier. This can be as simple as routing a two-conductor power cable to the device. Alternatively, preamplifiers can be powered by dc sent up the feed line itself. Some transceivers have the ability to insert 12 V dc on the feed line for this purpose. If not, you can use a *dc power inserter* to inject power at the station and/or recover it nearer the antenna (see **Figure 32**). Some preamplifier designs include feed line power capability, so all you need is an inserter at the "station end."

If your preamplifier is going to be installed in a feed line that will also be carrying RF power from the radio, you'll need a model that includes an internal relay to temporarily switch it out of the circuit to avoid damage to the preamplifier when you're transmitting. Some preamplifiers include this relay and nothing more; it is up to you to provide the means to energize the relay before you transmit. This is accomplished through a device known as a *TR sequencer*. A sequencer works with your transceiver to automatically switch the preamplifier out of the feed line before the radio can begin sending RF power (see **Figure 33**). A less complicated alternative is

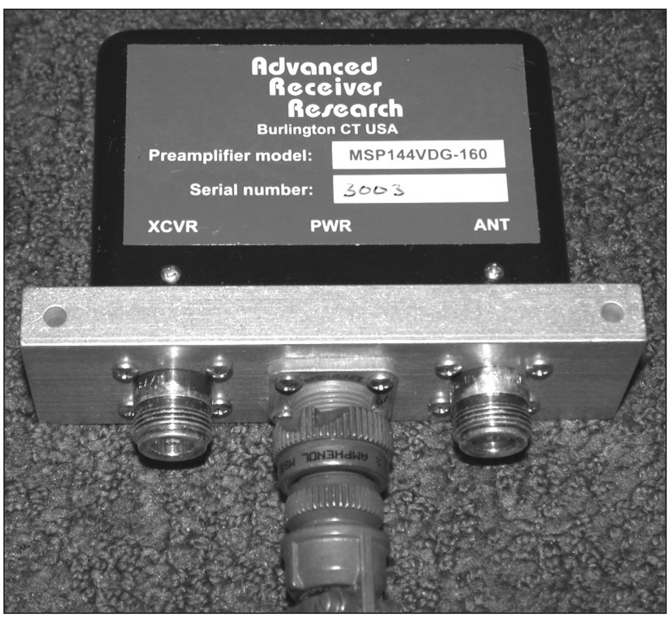


Figure 31 — This receive preamplifier by Advanced Receiver Research gives signals a substantial boost before they travel down the coaxial cable to your radio.

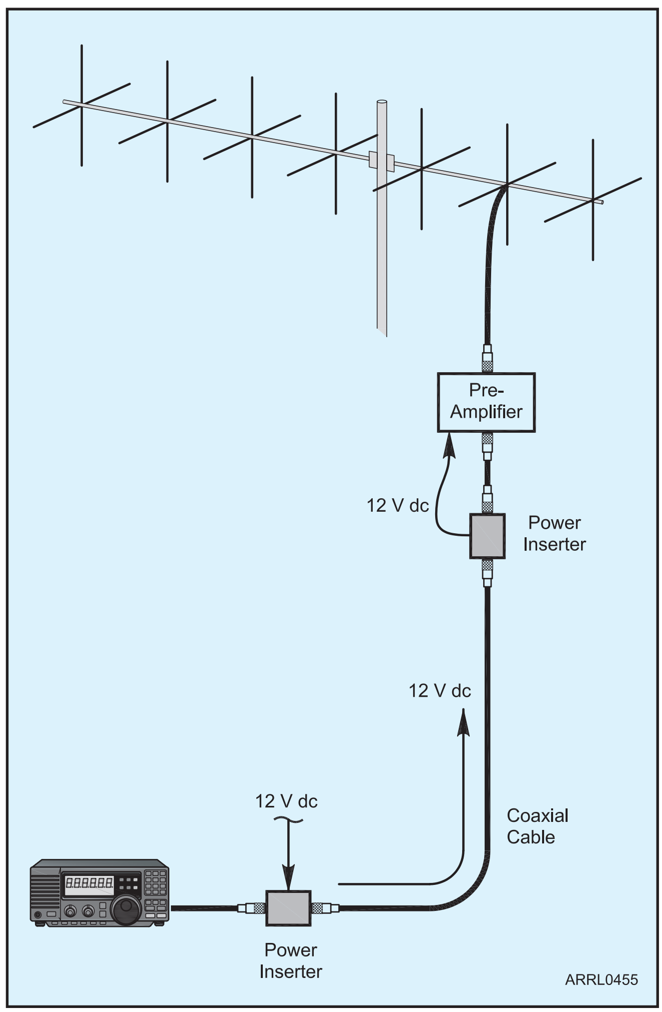


Figure 32 — A dc power inserter acts just as its name implies — it inserts a dc voltage to the coaxial cable at the station. The inserter is designed to block dc power from going "backward" to the radio. Instead, the power flows through the coax to the antenna where another inserter picks it off and supplies it to the device (a preamplifier, in this case). Both inserters pass RF with negligible loss.

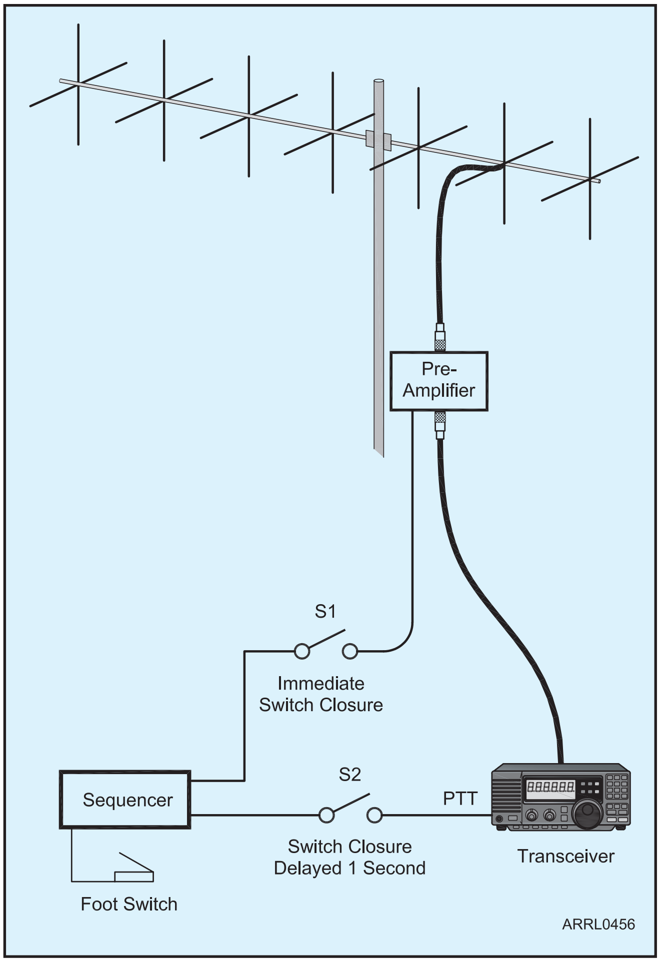


Figure 33 — In this simplified example, the sequencer is triggered when the operator presses the foot switch. It immediately closes switch S1, which activates a "bypass" relay in the receive preamplifier at the antenna, effectively removing it from the feed line circuit. One second later, the sequencer closes switch S2, which is connected to the transceiver PTT (Push To Talk) line, keying the radio and applying RF power.

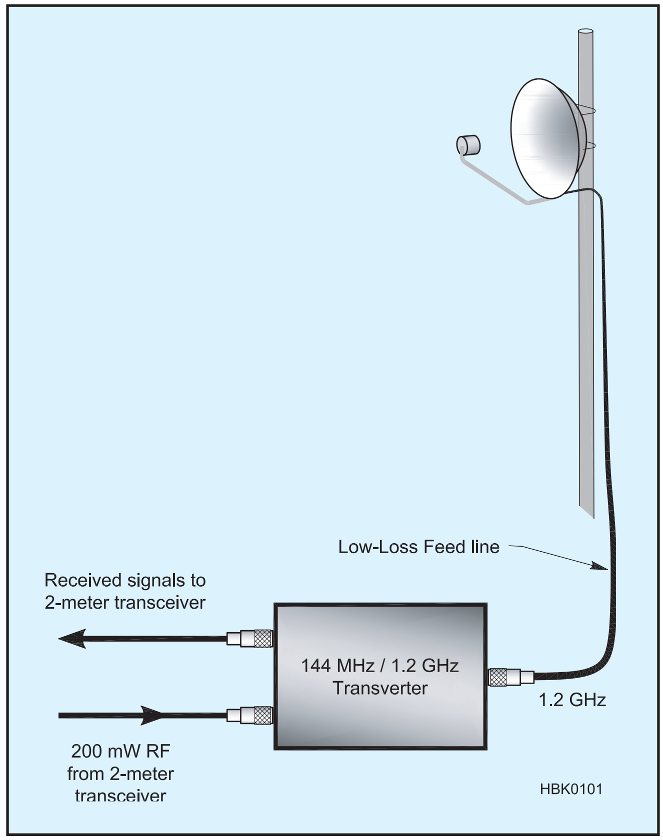


Figure 34 — In this example, the transverter is taking 1.2 GHz received signals and converting them to 2 meters. When it's time to transmit, the transverter takes RF at 2 meters and converts it to 1.2 GHz.

to purchase a preamplifier with *RF-sensed switching*. This design incorporates a sensor that detects the presence of RF from the radio and instantly switches the preamplifier out of harm's way. Note that RF-switched preamplifiers are rated according to the power they can safely handle. If you're transmitting 150 W, you'll need an RF-switched preamplifier rated for 150 W or more.

TRANSVERTERS

Transverters convert received and transmitted signals from one band to another. You can use a transverter to generate, say, a 1.2 GHz uplink signal when powered by RF energy from a 2 meter transceiver. The same transverter can convert 1.2 GHz downlink signals to 2 meters as well (**Figure 34**).

Transmit/receive switching in most transverters is accomplished through the use of an internal switch that is keyed through a sequencer. Some models provide automatic RF-sensed switching.

When working with transverters, one issue is supplying a safe level of RF power to the input. If your transceiver pumps out 50 W of power at 2 meters, for example, this is way too much RF for most transverters to handle. Unless the transverter has a built-in RF power attenuator, it is designed to deal with RF power levels on the order of *milliwatts* (typically 200 to 300 mW). If you are lucky enough to own a transceiver that features a transmit transverter port, you can obtain your milliwatt power levels there. If not, you'll need to add an attenuator at the transverter input to reduce the RF output of your radio to safe levels.

DOWNCONVERTERS

As the name implies, a *downconverter*, also known as a *receive converter*, converts one band of frequencies "down" to another. For example, a 2-to-10-meter downconverter would convert signals in a range from 144 to 146 MHz to 28 to 30 MHz.

In the days before HF/VHF/UHF transceivers, a downconverter was a popular means of receiving VHF and UHF signals by converting them to 10 meters (usually) for reception on an HF receiver. Today downconverters are used more often as a way to receive microwave signals, for example converting a range of frequencies at 2.4 GHz to 2 meters. A microwave downconverter works best when

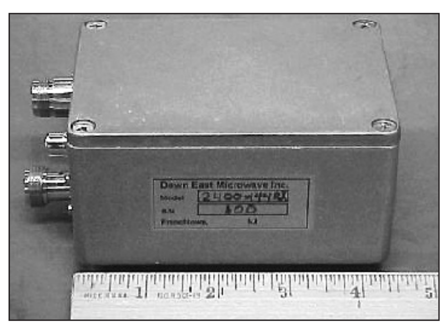


Figure 35 — This downconverter by Downeast Microwave converts signals at 2.4 GHz to 2 meters. With its weatherproof enclosure, it is designed to be installed at the antenna.

installed right at the antenna so that the microwave energy is immediately converted to a lower frequency before excessive feed line loss can occur. See **Figure 35**.

Like receive preamplifiers, downconverters are rated by their gain and NF (the lower the NF, the better). When it comes to installing a downconverter, all the same receive preamplifier issues apply. If the downconverter is installed outdoors it must be in a weatherproof enclosure. You must also supply dc power and be able to switch the downconverter out of the line if you are sending RF power to the same antenna.

Figure 36 — The ICOM ID-5100A FM transceiver can receive and transmit on 2 m and 70 cm independently. This dual-band FM radio is well-suited for FM repeater satellites as a base or mobile station.

5.2 Transceivers

There are many amateur transceivers that cover the VHF and UHF bands. Some popular radios offer all the HF bands as well. Some of these transceivers offer satellite-specific features, while others are oriented toward terrestrial operation.

WORKING WITH FM REPEATER AND DIGITAL SATELLITES

Almost any dual-band (2 meter/70 centimeter) FM transceiver will be adequate for operating FM repeater satellites such as OSCAR 27, and for digital operating with the International Space Station or LEO orbiting birds as well (**Figure 36**). Getting started with a dual-band FM radio and a repeater satellite is a worthwhile option.

Most modern dual-band rigs offer a "high power" output setting around 50 W. That's more than enough power to put a solid signal into a satellite with a directional antenna. It is also sufficient for omnidirectional antennas, including mobile antennas. (Yes, you can make contacts through FM repeater satellites while you drive!)

If you are considering digital operation, make sure to choose an FM transceiver that offers a data port. This will make it much easier to connect an external radio modem, such as a packet radio terminal node controller (TNC). There are even a few radios with TNCs already built in (**Figure 37**). Also, make sure the transceiver is rated to handle 1200 and 9600 baud data signals. Nearly all FM transceivers can work with 1200 baud, but not all can do 9600 baud.

You can use dual-band handheld transceivers to work the FM birds, but their RF output is so low (5 W or less) that you will definitely need to couple them to directional antennas to be heard consistently among the competing signals (**Figure 38**). What's more, at this writing, most of the newer handhelds will *not* allow so-called true (or "full") duplex operation. We will discuss what full-duplex means and why it is desirable for satellite work in a moment.

WORKING WITH LINEAR TRANSPONDER (SSB/CW) SATELLITES

FM signals tend to be wide and, by design, FM receivers are forgiving of frequency changes. That fortunate characteristic makes it easy to compensate for Doppler frequency shifting as an FM repeater satellite zips overhead.

SSB and CW signals are much narrower, however, and when you're working through a linear transponder satellite your signal is sharing the passband with several others. Not only do you need to adjust your receive (downlink) frequency almost continuously to keep the SSB voice or CW sounding "normal," you also have to stay on frequency to avoid drifting into someone else's conversation. The most effective way to do this is to listen to your own signal coming through the satellite in real time while you are transmitting on the uplink. This type of operation is known as *full duplex*.

Figure 37 — The Kenwood TM-D710 is a dual-band FM transceiver with a built-in packet radio Terminal Node Controller (TNC) for digital communication.

You will find many multimode (SSB, CW, FM) transceivers that boast a feature labeled "cross-band split" or even "cross-band duplex." Be careful, though. What you require is a radio that can transmit and receive on different bands *simultaneously*. Few amateur transceivers can manage such a trick!

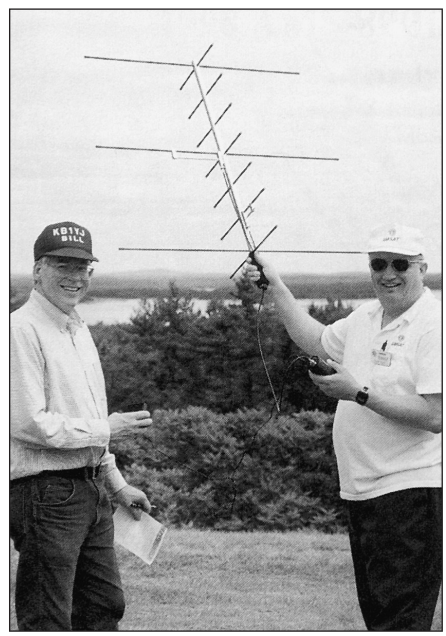


Figure 38 — The hand-held Arrow gain antenna is popular for FM repeater satellite operations. This is a dual band version for 2 meters and 70 centimeters. [AMSAT photo]

Figure 39 — The ICOM IC-9700 is an all-mode 2m/70cm/23cm transceiver capable of full-duplex operation.

Figure 40 — The Kenwood TS-2000 offers full HF coverage along with VHF/UHF full-duplex satellite capability.

Figure 41 — The Yaesu FT-736 is a legendary satellite transceiver. Although no longer manufactured, the ’736 is still available on the used market.

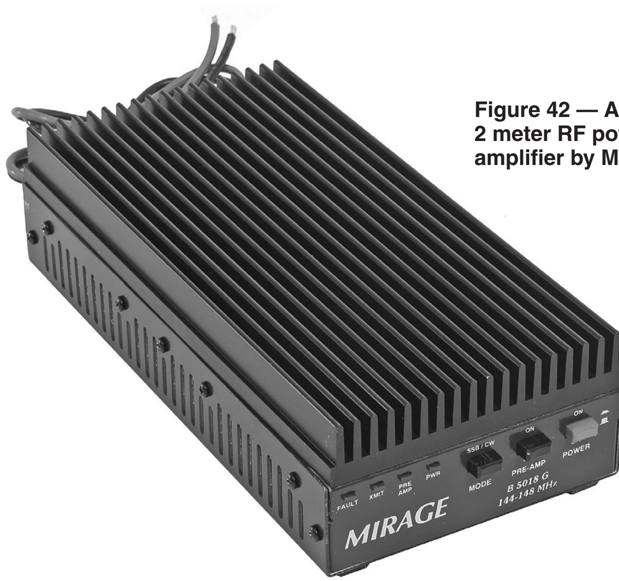


Figure 42 — A 160 W 2 meter RF power amplifier by Mirage.

As of March 2022, the only all-mode amateur transceiver in production that supports full-duplex VHF/UHF operation is the Icom IC-9700 (see **Figure 39**). Its predecessor, the IC-9100, and the Kenwood TS-2000 (**Figure 40**) are widely available on the used market. Other excellent used transceivers include the FT-847, IC-820, and IC-910H. The classic FT-736 (**Figure 41**) is still a popular choice, as well. Pairs of QRP transceivers such as the FT-817 or FT-818 can be combined with a duplexer as an excellent portable station.

It is also possible to exploit computer control of their ordinary non-duplex multiband transceivers to compensate for Doppler shift. Some satellite-tracking programs can automatically change the frequency of your radio during a pass. They do this by mathematically calculating the frequency shift and tweaking your radio accordingly. This solution for frequency stability isn’t as accurate as listening to your own downlink signal in full duplex, but it can work.

Another option is to use one transceiver for the uplink and a separate receiver or transceiver for the downlink. Some amateurs have even pressed old shortwave receivers into service along with VHF or UHF downconverters. They transmit with a 2 meter or 70 centimeter SSB radio on the uplink while listening to their shortwave receiver/downconverter combo on the downlink.

If you are working a linear transponder satellite with an uplink at 1.2 GHz or higher, you’ll likely have to take the transverter approach to getting on the air, although there are some transceivers that offer optional 1.2 GHz modules. Fortunately, satellite builders are well aware that most hams own 2 meter and 70 centimeter transceivers and they design new birds accordingly. Even transponders with microwave downlinks are usually configured with uplinks on 2 meters or 70 centimeters. So, if you purchase a VHF/UHF transceiver all you need to add is a downconverter to receive the microwave downlink.

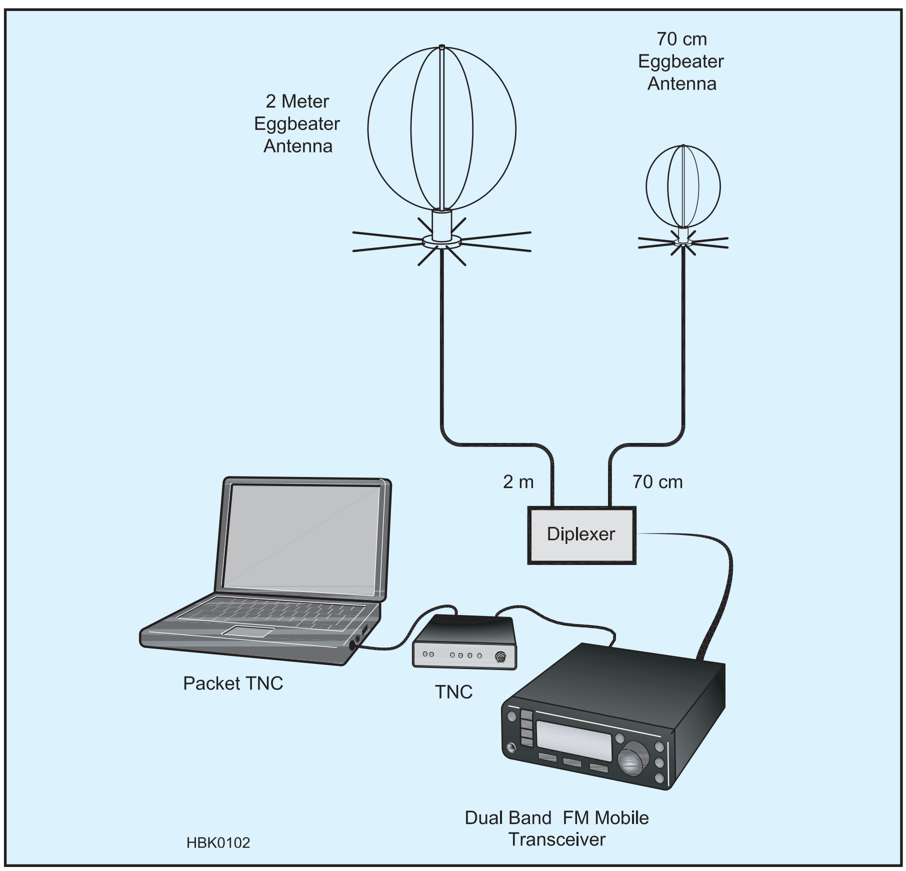


Figure 43 — A basic FM voice and data station for LEO satellites. At its core is a dual-band FM transceiver rated for 30 to 50 W output at its “high power” setting. This example uses omnidirectional antennas and it presumes that the FM transceiver has only one antenna jack, which is why a diplexer is indicated.

5.3 VHF/UHF RF Power Amplifiers

If your chosen transceiver offers at least 50 W output on the uplink band, you won't need an RF power amplifier to bring your signal to a level that can be "heard" by a LEO satellite, especially if you are using directional antennas.

On the other hand, if you are using omni antennas, 100 or 150 W output may help considerably. And if your target is an HEO satellite orbiting at 50,000 km, 100 W or more, along with a directional antenna, is *mandatory*. If your transceiver lacks the necessary punch for the application, the solution is an external RF power amplifier.

How much power should you buy? In most cases, a 100 or 150 W amplifier is a good choice (**Figure 42**). As you shop for amplifiers, take care to note the input and output specifications. How much RF at the input is necessary to produce, say, 150 W at the output? Can your radio supply that much power?

Another consideration is your dc power supply. While a 25 A 13.8 V dc supply is perfectly adequate to run a 100 W transceiver, if you also decide to add a 100 or 150 W amplifier to your satellite station, the current demands will increase considerably. A separate power supply may be required to provide an *additional* 20 A (or more) to safely power the amplifier when both the transceiver *and* the amplifier are transmitting at the same time.

5.4 Typical Station Designs

There are so many station equipment options available, it may be helpful to outline a few typical station configurations.

Figure 43 illustrates a basic FM voice and data station for LEO satellites. At its core is a dual-band FM transceiver rated for 30 to 50 W output. The example uses omnidirectional antennas and it presumes that the FM transceiver has only one antenna jack, which is why a diplexer is indicated. Otherwise, you could run two separate coaxial feed lines back to the radio.

The performance of this station can be substantially enhanced by adding directional antennas or a dual-band Yagi but, of course, that will require an antenna rotator (human or mechanical!).

In **Figure 44** we've stepped up to a multiband, multimode transceiver with full duplex capability and directional antennas. This station would be excellent for LEO satellites with linear SSB/CW transponders, as well as FM voice and data. By adding an RF power amplifier (assuming the output of the radio is less than 100 W), this station would be capable of working distant high-orbiting satellites as well.

Note that this illustration shows two separate antennas and feed lines. You could just as easily use a single dual-band Yagi antenna and one feed line. However, you may need a diplexer at the radio if it employs separate VHF and UHF antenna jacks.

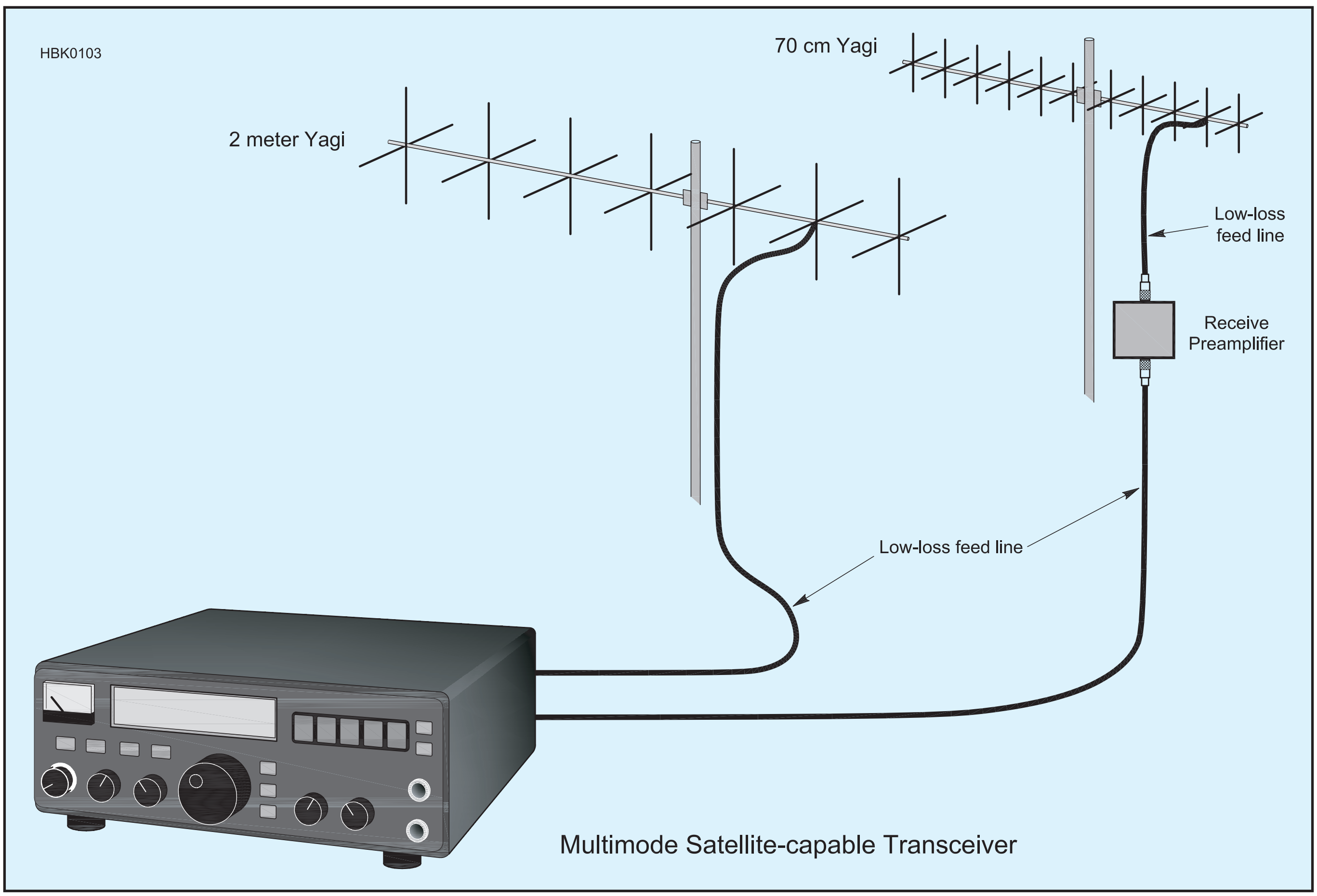


Figure 44 — This station would be adequate for LEO satellites with linear SSB/CW transponders such as OSCAR 52, as well as FM voice and data. This illustration shows two separate antennas and feed lines. You could just as easily use a single dual-band Yagi antenna and one feed line. However, you may need a diplexer at the radio if it employs separate VHF and UHF antenna jacks.

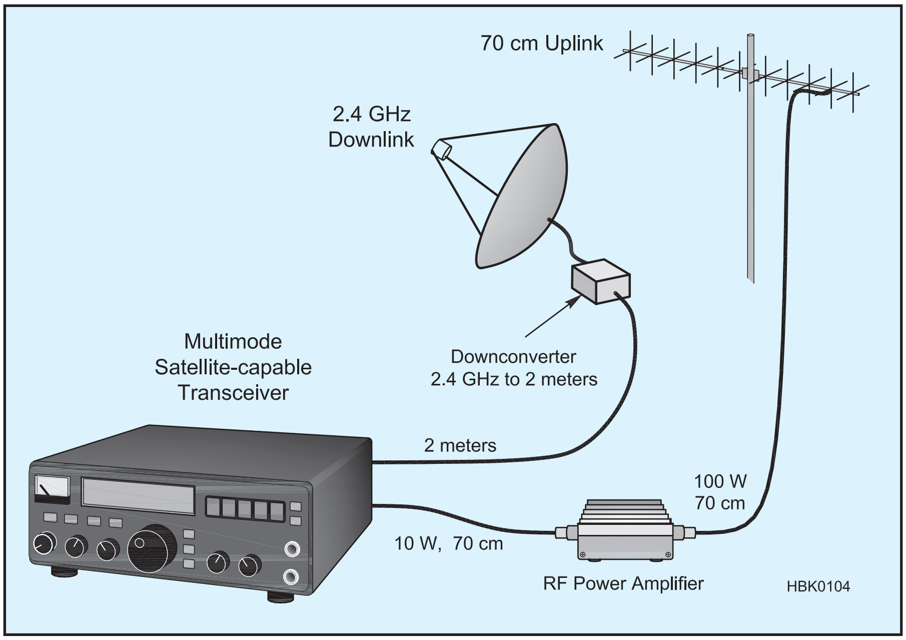


Figure 45 — This example illustrates a station designed to work a distant Phase III or IV satellite with a microwave downlink. It assumes that the uplink is at 70 cm and the downlink is at 2.4 GHz. Note the use of the downconverter to step the 2.4 GHz signal at the antenna down to 2 meters before it is fed to the radio.

Figure 45 addresses at least one method to work satellites with microwave downlinks. It assumes that the uplink is at 70 centimeters and the downlink is at 2.4 GHz. It also assumes that the satellite in question is a high-orbiting spacecraft (note the RF power amp on the uplink).

Note also the use of the downconverter to step the 2.4 GHz signal at the antenna to 2 meters before it is fed to the radio. You can actually use this same approach for any combination of bands and radios. For instance, let's say that you want to work the low-orbiting FM birds, but you have only a 2 meter FM transceiver for the uplink and a separate VHF FM police scanner receiver for the downlink. You could use a downconverter for the 70 centimeter downlink, stepping the signal down to 2 meters for reception with the scanner (**Figure 46**).

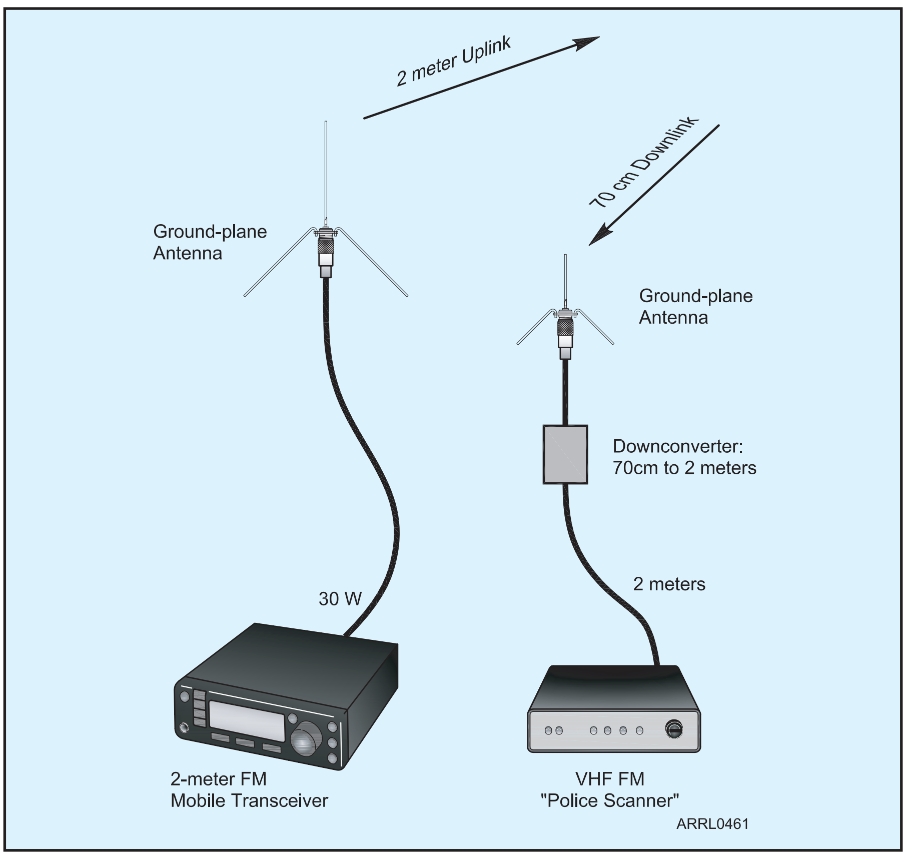


Figure 46 — Let's say that you want to work the low-orbiting FM birds, but you only have a 2 meter FM transceiver for the uplink and only a VHF FM "police scanner" receiver for the 70 cm downlink. You could use a downconverter for the 70 cm downlink, stepping the signal down to 2 meters for reception with the scanner.

6 Satellite Antenna Projects

6.1 An EZ-Lindenblad Antenna for 2 Meters

This easy-to-build antenna project by Anthony Monteiro, AA2TX, works well for satellite or terrestrial communication. It is circularly polarized yet has an omnidirectional radiation pattern (no rotator needed to track satellites). With most of its gain at low elevation angles, it is ideal for accessing LEO amateur satellites. It is good for portable operation or general-purpose use at home stations because its circular polarization is compatible with the linearly polarized antennas used for FM/repeater and SSB or CW operation.

This type of antenna was devised by Nils Lindenblad of the Radio Corporation of America (RCA) around 1940. His idea was to employ four dipoles spaced equally around a λ/3 diameter circle with each dipole canted 30° from the horizontal. The dipoles are all fed in phase and are fed equal power. The spacing and tilt angles of the dipoles create the desired antenna pattern when the signals are all combined. After WWII, George Brown and Oakley Woodward, also of RCA, were tasked with finding ways to reduce fading on ground-to-air radio links at airports and built on Lindenblad's design.

While the Brown and Woodward design is clever and worked well, it would be difficult for the home builder to duplicate because of the need for the four-way, in-phase, power splitting function. Since amateurs generally want to use 50 Ω coaxial cable feed line, we have to somehow provide an impedance match from the 50 Ω unbalanced coax to the four 75 Ω balanced dipole loads. Previous designs have used combinations of folded dipoles, open-wire lines, twin-lead feeds, balun transformers and special impedance matching cables to try to get a good match to 50 Ω. These in turn increase the complexity and difficulty of the construction.

THE EZ-LINDENBLAD

The key concept of the EZ-Lindenblad is to eliminate anything electrically or mechanically difficult. This leads to the idea of just feeding the four dipoles with coax cable and soldering the cables to a connector with no impedance matching devices at all. This would certainly be *easy* but we also want the antenna to work! Without the extra impedance matching devices, how is it possible to get a good match to 50 Ω?

If we could get each of the four coax feed cables to look like 200 Ω at the connector, then the four in parallel would provide a perfect match to 50 Ω. We could do this if we used ¼ λ sections of 122 Ω coax to convert each 75 Ω dipole load to 200 Ω. Unfortunately, there is no such coax that is readily available.

But we can accomplish the same thing with ordinary 75 Ω, RG-59 coax if we run the cable with an intentional impedance mismatch. By forcing the standing wave ratio (SWR) on the cable to be equal to 200/75, or about 2.7:1, we can make each cable look exactly like 200 Ω at the connector as long as we make them the right length. It is easy to make the SWR equal 2.7:1 by just making the dipoles a little too short for resonance. An *EZNEC* (**www.eznec.com**) antenna model can be used to determine the exact dipole dimensions.

The conversion from the balanced dipole load to unbalanced coax cable can be accomplished by threading each cable through a ferrite sleeve making a choke balun. The only remaining issue is the required length of the feed cables. With a Smith chart or software, we can easily determine the required length of 75 Ω coax to provide a 200 Ω load. An *EZNEC* antenna model was used to simulate cutting the dipole lengths until the SWR on the line reached 2.7:1. The model showed that the dipole load impedance would then be 49 –*j*55 Ω. Plotting that value and the desired 200 Ω impedance at the connector on the chart and drawing a constant 2.7:1 SWR curve between the two impedance points, the length of the line needed is 0.374 λ. (For more information about this process, see **www.arrl.org/smith-chart**.)

The EZ-Lindenblad was designed for a center frequency of 145.9 MHz to optimize its performance in the satellite sub band. At 145.9 MHz, a wavelength is about 81 inches and since the coax used has a velocity factor of 0.78, we need to make the feed cables 81 × 0.374 × 0.78 = 23.6 inches long.

It's imperative that stranded RG-59A foam PE dielectric coax be used. The solid-dielectric cable has a velocity factor of 66% and will not work. The author used part # RG59A-100 from **www.l-com.com**. This is a 100 ft roll; for one antenna you could buy L-Com part # CCF59-12, a 12 foot jumper, and cut it to the required length. Belden 9259 is another suitable cable.

CONSTRUCTION

This antenna was designed to be rugged and reliable yet easy to build using only hand tools with all of the parts readily available as well (see **Table 5**). Although not critical, the construction will be easier if the specified 17 gauge aluminum tubing is used since the inner wall of the tubes will be just slightly smaller than the outer wall of the PVC insert Ts used to connect them. If heavier gauge tubing is used, it will be necessary to file down the PVC insert Ts to make them fit inside the aluminum tubes.

Start by making a mounting bracket to mount the N-connector and the cross booms. Cut a ⅝ inch hole in one side of the short piece of angle stock and rivet or screw it to the bottom of the long piece of angle stock. The completed bracket with the connector and cables attached can be seen in **Figure 47**.

Next, cut the aluminum tubing to make the cross booms and dipole rods as shown in **Figure 48**. Drill holes for the sheet metal screws at each end of the cross booms but do not insert the screws yet. Attach the cross booms to the long section of angle stock with rivets or screws. One cross boom will mount

Table 5
Required Materials
Quantity one, unless noted.

- Aluminum tubing, 17 gauge, 6 ft length of ¾ in OD, quantity 3. Available from Texas Towers, **www.texastowers.com**.
- Aluminum angle stock, 8 in length of 2 × 2 × 1⁄16 in
- Aluminum angle stock, 2 in length of 2 × 2 × 1⁄16 in for mounting connector.
- Screws, #8 × ½ in aluminum sheet metal, quantity 12.
- Screws, #8 × ½ in aluminum sheet metal or 3⁄16 in aluminum rivets, quantity 12.
- PVC insert T-connector, ½ × ½ × ½ in grey for irrigation polyethylene tubing. LASCO Fittings, Inc. Part# 1401-005 or equivalent. Available from most plumbing supply and major hardware stores, quantity 4.
- Plastic end caps (optional), black ¾ in, quantity 8.
- N-connector for RG-8 cable, single-hole, chassis-mount, female.
- Cable ferrite, Fair-Rite part #2643540002, quantity 4 (Mouser Electronics #623-2643540002).
- RG-59A polyethylene foam coax with stranded center conductor (Belden 9259 or equiv; *must* be foam PE dielectric with 78% velocity factor, not solid dielectric), 10 ft length.
- Copper braid, 4 in long piece.
- Ring terminal, uninsulated 22-18 gauge for 8-10 stud, quantity 4.
- Ring terminal, uninsulated 12-10 gauge for 8-10 stud, quantity 4.
- Heat shrink tubing for ¼ in cable, wire ties, electrical tape, as needed.
- Ox-Gard OX-100 grease for aluminum electrical connections.

just above the other as can be seen in Figure 47. The cross booms should be perpendicular to the mounting bracket so that they will be horizontal when the antenna is mounted to its mast. Make sure that the centers of the cross booms are aligned with each other so that the ends of the cross booms are all 11.5 inches from the center cross.

Make the dipoles by inserting a PVC insert T into two dipole rods. It should be possible to gently tap in the rods with a hammer but it may be necessary to file down the insert T a little if the fit is too tight. Applying a little PVC cement to the insert T will soften the plastic and make it easier to insert into the aluminum tubing if the fit is too tight. The overall dipole length dimension is critical so take care to get this correct as shown in **Figure 49**.

Drill holes for screws in each dipole rod but do not insert the screws yet. The screws will be used to make the electrical connections to the dipoles at the center. The screw holes should be about $\frac{3}{8}$ inches from the end of the tubing.

The dipole assemblies are attached by gently tapping the PVC insert-T into the end of each cross-boom with a hammer. The dimensions are shown in Figure 48.

Next, temporarily attach the mounting bracket to a support so that each of the cross booms is perfectly horizontal. Measure this with a protractor. Now, using the protractor, rotate the dipole assemblies to a 30° angle with the right-hand side of the nearest dipole tilting up when you are looking toward the center of the antenna. Drill a small hole through the existing cross-boom holes into the PVC insert-Ts and then use the sheet metal screws to fasten the dipole assemblies into place. For a nice finishing touch, the dipole ends can be fitted with $\frac{3}{4}$ inch black plastic end caps.

Next, make the four feed cables by cutting and stripping the RG-59A as shown in **Figure 50**. On the dipole connection side, unwrap the braid and form a wire lead. Apply the smaller ring terminal to the center conductor and use the larger ring terminal for the braid.

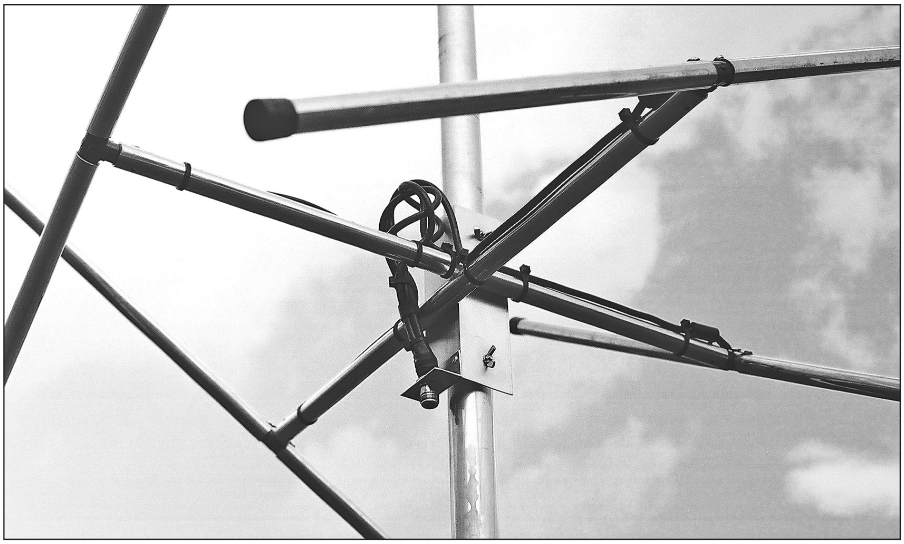


Figure 47 — View of cross booms mounted to mast.

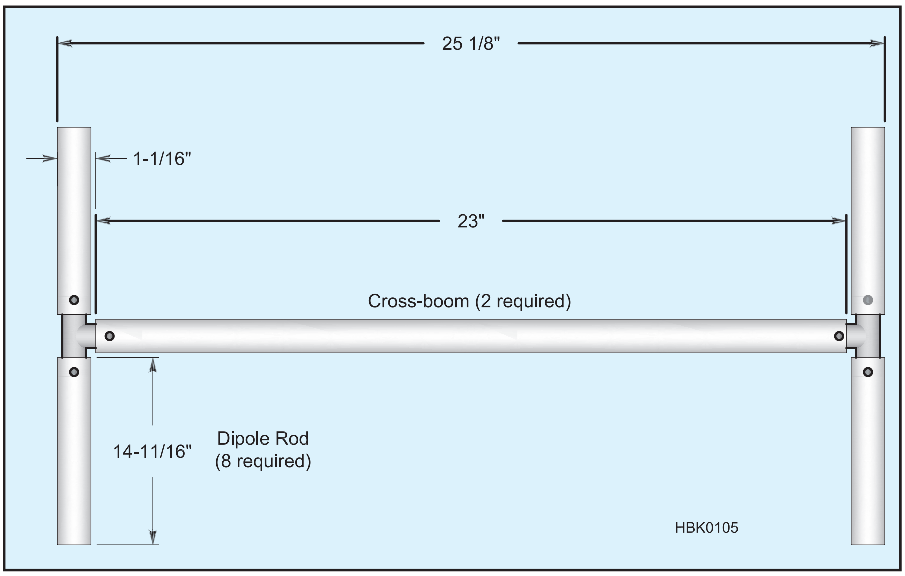


Figure 48 — Dimensions of the dipoles and cross booms. The antenna requires two cross booms, with a dipole at each end of each cross boom (four dipoles total).

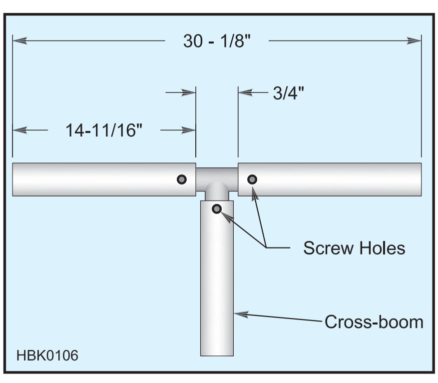


Figure 49 — Dipole assembly dimensions.

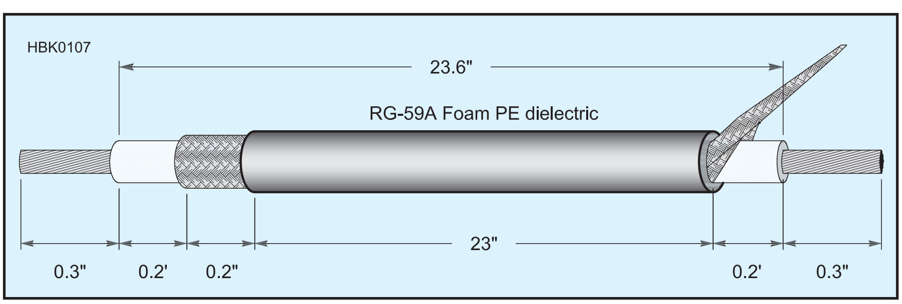


Figure 50 — Feed cables stripping dimensions.

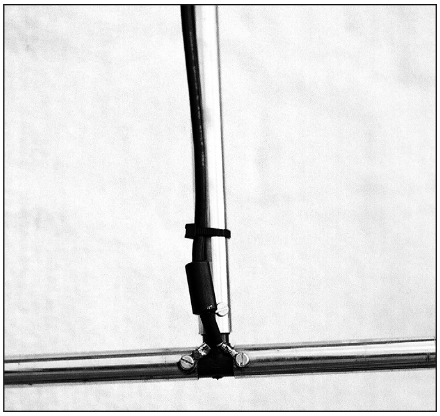


Figure 51 — Close-up of dipole electrical connections.

Figure 52 — The EZ-Lindenblad as a portable or Field Day antenna. A 70 cm antenna is on the top.

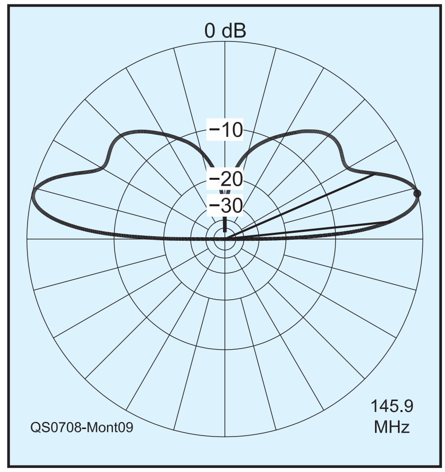


Figure 53 — *EZNEC* elevation radiation pattern of Lindenblad antenna.

At the other end of the cable, do not unwrap the braid but strip off the outer insulation. Slip a 1 inch piece of shrink wrap over the coax and apply to the dipole side. Next slip a cable ferrite over the cable and push all the way to the dipole end as far as it will go (ie, up to the heat-shrink tubing.) The fit will be snug and you may need to put a little grease on the cable jacket to get it started.

Prepare each dipole for its feed cable by first cleaning the area around the screw holes with steel wool and then applying Oxy-Gard or other corrosion resistant electrical grease. The coax center conductor goes to the up side of the dipole and the braid goes to the down side. To make a connection, put a screw through the ring terminal and gently screw into the dipole tubing. Do not overtighten the screws or you will strip the tubing. **Figure 51** shows the completed connections.

Apply Oxy-Gard around the hole for the N connector. Take the 4 inch piece of braid and put the end of it through the hole for the N connector. This provides the ground connection. Secure the N connector in the mounting hole to clamp the braid. Use a wire tie or tape to hold the four feed cables together at the connector ends. Make sure to align the cables so that all the ground braids are together and the center conductors all extend out the same amount. Do not twist the center conductors together. Carefully push the four cable center conductors into the center terminal of the N connector and solder them in place. Wrap the exposed center conductors of the cables and the connector with electrical tape.

Take the piece of braid that is clamped to the N connector and wrap it around the four exposed ground braids of the coax cables. Solder them all together. This will take a fair amount of heat but be careful not to melt the insulation. After this cools, apply electrical tape over all the exposed braid and fix with wire ties. Secure the cables to the cross booms with wire ties.

The mounting bracket provides a way to attach the antenna to a mast using whatever clamping mechanism is convenient (eg, U-bolts). The author's antenna was intended for portable operation and the bracket was drilled to accept two #8 machine screws. These screws pass through a portable mast and the antenna is secured with wing nuts for easy setup. The completed portable antenna is shown in **Figure 52**. The little antenna at the top is for 70 centimeters.

PERFORMANCE

The antenna impedance match to 50 Ω was tested using an MFJ-259B SWR meter, which was checked against an external frequency counter and precision 50 Ω load. The antenna provides an excellent match over the entire 2 meter band. This antenna was designed to safely handle any of the currently available VHF transceivers and tested by applying a 200 W signal key down for 9 minutes, then checking the ferrites and cables for temperature rise.

The antenna radiation pattern predicted by the *EZNEC* model is shown in **Figure 53**. This is the elevation plot with the antenna mounted at 6 ft above ground although it can be mounted higher if desired for better coverage to the horizon. As shown in the plot, the pattern favors the lower elevation angles. The –3 dB points are at 5° and 25° with the maximum gain of 4.8 dBic (dB with respect to an isotropic circularly polarized antenna) at around 13°. Most of the satellite pass elevations will be in this range and it is also the elevation at which the satellite provides the best chance for DX contacts. The antenna radiation is right-hand circularly polarized, which will work with virtually any LEO satellite that uses the 2 meter band.

The EZ-Lindenblad antenna has been used for SSB, FM and packet operation on a number of amateur satellites. A portable setup performed well on Field Day, an excellent test of any antenna as it is probably the busiest weekend of the year on the satellites.

6.2 The W3KH Quadrifilar Helix

If your existing VHF omnidirectional antenna coverage is "just okay," this twisted antenna project by Eugene F. Ruperto, W3KH, is probably just what you need! The ever-changing position of LEO satellites presents a problem for the Earth station equipped with a fixed receiving antenna: signal fading caused by the orientation of the propagated wavefront. This antenna provides a solution to the problem and can be used with weather satellites, or any of the polar-orbiting amateur satellites.

Several magazines have published articles on the construction of the quadrifilar helix antenna (QHA) originally developed by Dr. Kilgus.[1] A particularly good reference is *Reflections* by Walt Maxwell, W2DU, who had considerable experience evaluating and testing this antenna while employed as an engineer for RCA.[2]

Part of the problem of replicating the antenna lies in its geometry. The QHA is difficult to describe and photograph. Some of the artist's

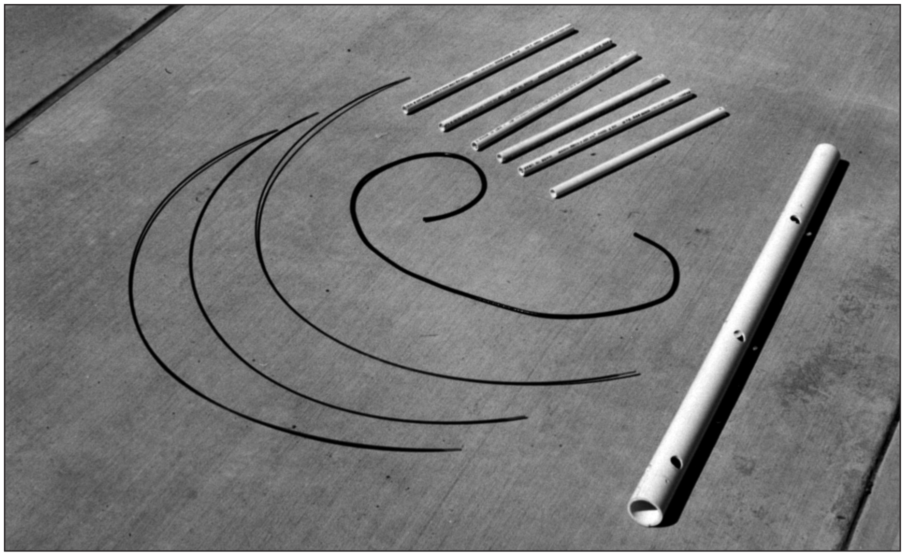


Figure 54 — The quadrifilar helix antenna (QHA) pieces, ready for assembly.

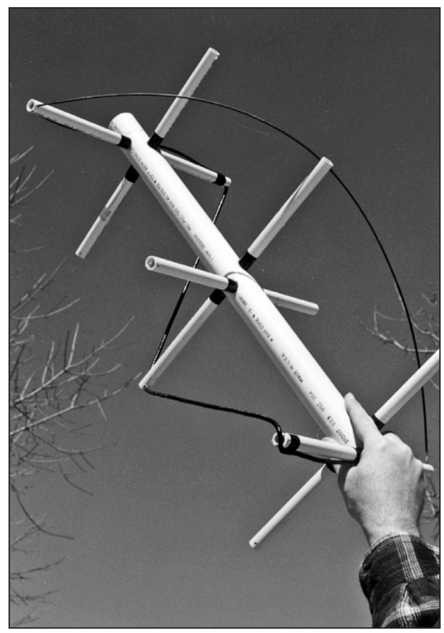


Figure 55 — The antenna with two of the four legs (filars) of one loop attached.

renditions leave more questions than answers, and some connections between elements as shown conflicted with previously published data. However, those who have successfully constructed the antenna say it is *the* single-antenna answer to satellite reception for the low-Earth-orbiting satellites.

DESIGN CONSIDERATIONS

Experts imply that sophisticated equipment is necessary to adjust and test the antenna, but the author found it possible to construct successful QHAs by following a cookbook approach using scaled figures from a proven design. The data used as the design basis for the antenna described here were published in an article describing the design of a pair of circularly polarized S-band communication-satellite antennas for the Air Force and designed to be spacecraft mounted.[3] Using this antenna as a model, the author constructed QHAs for the weather-satellite frequencies and the polar-orbiting 2 meter and 70 centimeter amateur satellites with excellent results and without the need for adjustments and tuning. By following some prescribed universal calculations, a reproducible and satisfactory antenna can be built using simple tools.

UHF and microwave antennas require a high degree of constructional precision because of the antenna's small size. For instance, the antenna used for the Air Force at 2.2 GHz has a diameter of 0.92 inch and a length of 1.39 inches! On the other hand, a QHA for 137.5 MHz is 22.4 inches long and almost 15 inches in diameter; for 2 meters, the antenna is not much smaller. Antennas of this size are not difficult to duplicate.

ELECTRICAL CHARACTERISTICS

A half-turn ½ λ QHA has a theoretical gain of 5 dBi and a 3-dB beamwidth of about 115°, with a characteristic impedance of 40 Ω. The antenna consists basically of a four-element, half-turn helical antenna, with each pair of elements described as a *bifilar,* both of which are fed in phase quadrature. Several feed methods can be employed, all of which appear complicated except the infinite-balun design, which uses a length of coax as one of the four elements.

To produce the necessary 90° phase difference between the bifilar elements, either of two methods can be used. One is to use the same size bifilars, which essentially consist of two twisted loops with their vertical axes centered and aligned, and the loops rotated so that they're 90° to each other (like an egg-beater), and using a quadrature hybrid feed. Such an antenna requires *two* feed lines, one for each of the filar pairs.

The second and more practical method is the self-phasing system, which uses *different-size loops:* a larger loop designed to resonate *below* the design frequency (providing an inductive reactance component) and a smaller loop to resonate higher than the design frequency (introducing a capacitive-reactance component), causing the current to lead in the smaller loop and lag in the larger loop. The element lengths are 0.560 λ for the larger loop, and 0.508 λ for the smaller loop. According to the range tests performed by Maxwell, to achieve *optimum* circular polarization, the wire used in the construction of the bifilar elements should be 0.0088 λ in diameter.

Maxwell indicates that in the quadrifilar mode, the fields from the individual bifilar helices combine in optimum phase to obtain unidirectional end-fire gain. The currents in the two bifilars must be in quadrature phase. This 90° relationship is obtained by making their respective terminal impedances $R + jX$ and $R - jX$ where $X = R$, so that the currents in the respective helices are –45° and +45°. The critical parameter in this relationship is the terminal reactance, X, where the distributed inductance of the helical element is the primary determining factor. This assures the ±45° current relationship necessary to obtain true circular polarization in the combined fields and to obtain maximum forward radiation and minimum back lobe. Failure to achieve the optimum element diameter of 0.0088 λ results in a form of elliptical, rather than true circular polarization, and the performance may be a few tenths of a decibel below optimum, according to Maxwell's calculations. Using #10 wire translates roughly to an element diameter of 0.0012 λ at 137.5 MHz — not ideal, but good enough.

To get a grasp of the QHA's topography, visualize the antenna as consisting of two concentric cylinders over which the helices are wound (see **Figure 54** through **Figure 58**). In two-dimensional space, the cylinders can be represented by two nested rectangles depicting the height and width of the cylinders. The width of the larger cylinder (or rectangle) can be represented by 0.173 λ and the width of the smaller cylinder represented

[1] C. C. Kilgus, "Resonant Quadrafilar Helix;" *IEEE Transactions on Antennas and Propagation*, Vol AP-17, May 1969, pp. 349-351.
[2] M. W. Maxwell, W2DU, *Reflections III* (CQ Communications, 2010, **cq-amateur-radio.com**)
[3] R. Brickner Jr and H. Rickert, "An S-Band Resonant Quadrifilar Antenna for Satellite Communication," RCA Corp, AstroElectronics Div.

Figure 56 — This view shows the QHA with all four legs in place. The ends of the PVC cross arms that hold the coaxial leg are notched; the wire elements pass through holes drilled in the ends of their supporting cross arms.

Figure 57 — Another view of the QHA.

by 0.156 λ. The length of the larger cylinder or rectangle can be represented by 0.260 λ, and the length of the smaller rectangle or cylinder can be represented by 0.238 λ. Using these figures, you should be able to scale the QHA to virtually any frequency. **Table 6** shows some representative antenna sizes for various frequencies, along with the universal parameters needed to arrive at these figures.

PHYSICAL CONSTRUCTION

Figure 59 shows the construction details. A 25-inch-long piece of schedule 40, 2-inch-diameter PVC pipe is used for the vertical member. The cross arms that support the helices are six pieces of ½-inch-diameter PVC tubing: three the width of the large rectangle or cylinder, and three the width of the smaller cylinder. Two cross arms are needed for the top and bottom of each cylinder. The cross arms are oriented perpendicularly to the vertical member and parallel to each other. A third cross arm is placed midway between the two

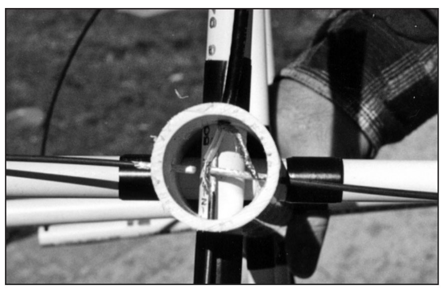


Figure 58 — An end-on view of the top of the QHA prior to soldering the loops and installing the PVC cap.

at a 90° angle. This process is repeated for the smaller cylindrical dimensions using the three smaller cross arms with the top and bottom pieces oriented 90° to the large pieces.

Using ⅝ inch-diameter holes in the 2-inch pipe ensures a reasonably snug fit for the ½-inch-diameter cross pieces. Each cross arm is drilled (or notched) at its ends to accept the lengths of wire and coax used for the elements. Then the cross arms are centered and cemented in place with PVC cement. For the 137 and 146 MHz antennas, use #10 AWG copper clad antenna wire for three of the helices and a length of RG-8 for the balun, which is also the fourth helix. (Do not consider the velocity factor of the coax leg for length calculation.) For the UHF antennas, use #10 AWG soft-drawn copper wire and RG-58 coax. Copper clad wire is difficult to work with, but holds its shape well. Smaller antennas can be built without the cross arms because the wire is sufficiently self-supporting.

To minimize confusion regarding the connections and to indicate the individual legs of the helices, label each loop or cylinder as B (for big) and S (for small); T and B indicate top and bottom. Each loop can be further split using leg designators as B1T and B1B, B2T and B2B, S1T and S1B and S2T and S2B, with B2 being the length of coax and the other three legs as wires. For right-hand circular polarization (RHCP) wind the helices *counterclockwise* as viewed from the top. This is contrary to conventional axial mode helix construction. (For LHCP, the turns rotate *clockwise* as viewed from the top.) See **Figure 60** for the proper connections for the top view. When the antenna is completed, the view shows that there are two connections

Table 6
Quadrifilar Helix Antenna Dimensions

		Small Loop			Big Loop		
Freq (MHz)	*Wavelength (λ) (inches)*	*Leg Size (0.508 λ)*	*Diameter (0.156 λ)*	*Length (0.238 λ)*	*Leg Size (0.560 λ)*	*Diameter (0.173 λ)*	*Length (0.261 λ)*
137.5	85.9	43.64	13.4	20.44	48.10	14.86	22.33
146	80.9	41.09	12.6	19.25	45.30	14.0	21.03
436	27.09	13.76	4.22	6.44	15.17	4.68	7.04

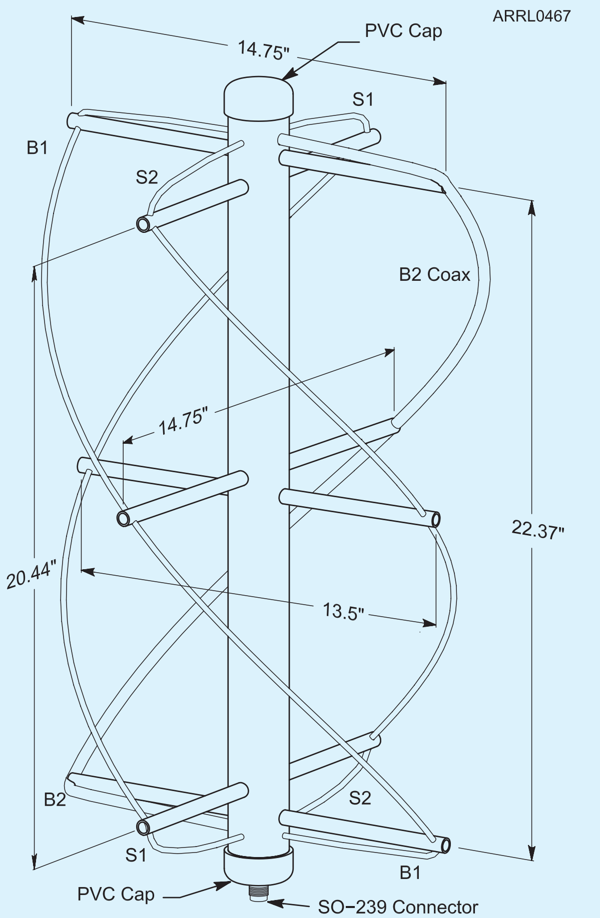


Figure 59 — Drawing of the QHA identifying the individual legs; see text for an explanation.

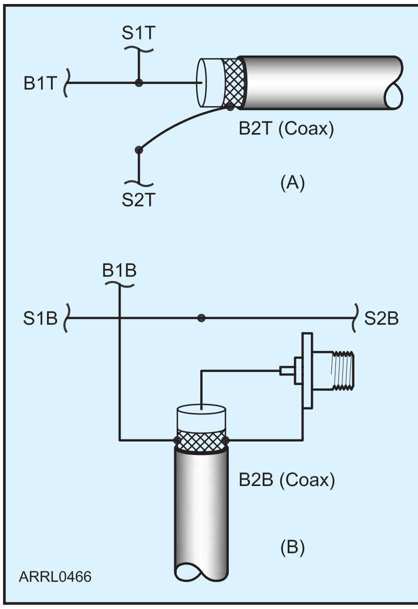


Figure 60 — At A, element connections at the top of the antenna. B shows the connections at the bottom of the antenna. The identifiers are those shown in Figure 59 and explained in the text.

made to the center conductor of the coax (B2) top. These are B1T and S1T, for a total of three wires on one connection. S2T connects to B2T braid. The bottom of the antenna has S1B and S2B soldered together to complete the smaller loop. B1B and the braid of B2B are soldered together. Attach an SO-239 connector to the bottom by soldering the center conductor of B2B to the center of the connector and the braid of B2B to the connector's shell. The bottom now has two connections to the braid: one to leg B1B, the other to the shell of the connector. There's only one connection to the center conductor of B2B that goes to the SO-239 center pin.

Total price for all new materials-including the price of a suitable connector-should be in the neighborhood of $10 or less.

RESULTS

With a 70-foot section of RG-9 between the receiver and antenna, which is mounted about 12 feet above ground, and a preamp in the station the author receives fade-free passes from the weather satellites. Although the design indicates a 3-dB beamwidth of 140°, an overhead pass provides useful data down to 10° above the horizon. The 70 centimeter antenna works fine for PACSATs, although Doppler effect makes manual tracking difficult. The weather-satellite antenna prototype worked better than expected and a number of copies built by others required no significant changes.

Thanks to Chris Van Lint, and Tom Loebl, WA1VTA, for supplying technical data to complete this project, and to the late Walt Maxwell, W2DU, for his review and technical evaluation and for sharing his technical expertise with the amateur satellite community.

7 Satellite References and Bibliography

Books

Smith, G., WA4SXM, et al., *Getting Started with Amateur Satellites* (AMSAT, 2020). Available from AMSAT-NA at **www.amsat.org/shop/**.

Articles

Alvarez-Cienfuegos, P., EB4DKA and Montana, J., EA4CYQ, "A Better Way to Work Low Earth Orbit FM Satellites," *QST*, Feb. 2009, pp. 41 – 43.

Antoniazzi, P., IW2ACD, and Arecco, M., IK2WAQ, "Low-Profile Helix Feed for Phase 3E Satellites: System Simulation and Measurements," *QEX*, May/Jun. 2006, pp. 34 – 39.

Cebik, L., W4RNL, "Circularly Polarized Aimed Satellite Antenna," Antenna Options, *QEX*, Sep./Oct. 2007, pp. 51 – 56.

Smith, L., W5KQJ, "An Affordable Az-El Positioner for Small Antennas," *QST*, Jun. 2003, pp. 28 – 34.

Spencer, M., WA8SME, "A Satellite Tracker Interface," *QST*, Sep. 2005, pp. 64 – 67.

8 Earth-Moon-Earth (EME) Communication

EME communication, also known as *moonbounce*, has become a popular form of amateur space communication. The EME concept is simple: the Moon is used as a passive reflector for two-way communication between two locations on Earth (see **Figure 61**). With a total path length of about half a million miles, EME may be considered the ultimate DX. Very large path losses suggest big antennas, high power and the best low noise receivers; however, the adoption of modern coding and modulation techniques can significantly reduce these requirements from their 20th-century levels. Even so, communication over the EME path presents unusual station design challenges and offers special satisfaction to those who can meet them.

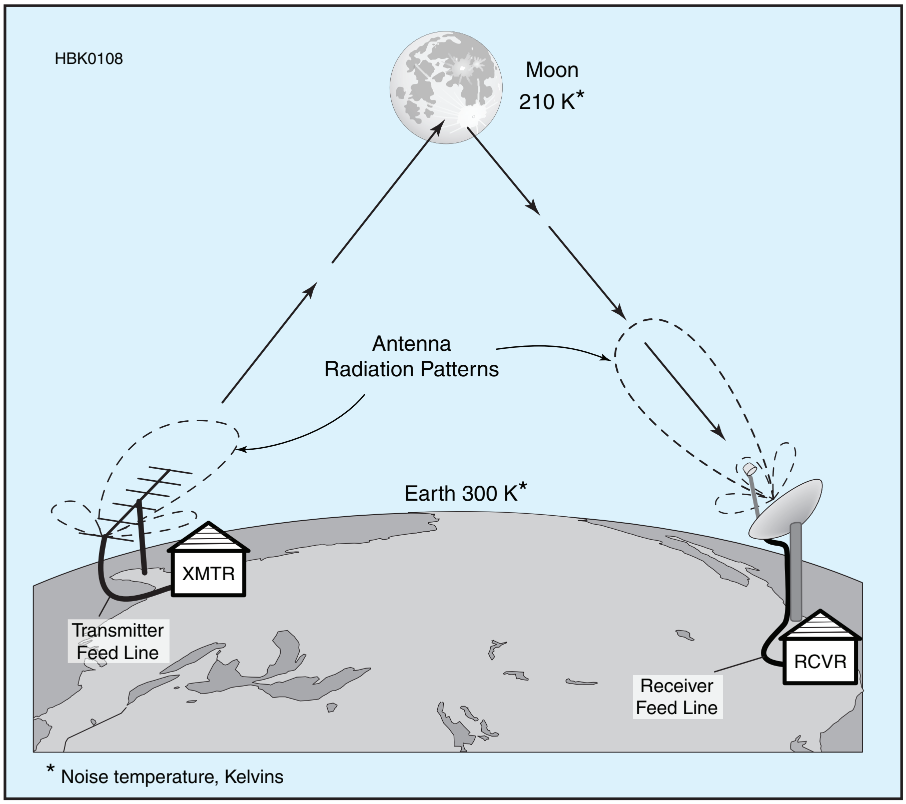


Figure 61 — Schematic representation of major system components for a (one-way) EME path. This illustration also shows some of the factors contributing to system noise temperature, which is discussed later in the chapter.

8.1 Background

EME is a natural and passive propagation phenomenon, and EME QSOs count toward WAC, WAS, DXCC, WAZ, and VUCC awards. EME opens up the bands at VHF and above to a new frontier of worldwide DX.

Professional demonstrations of EME capability were accomplished shortly after WW II. Amateurs were not far behind, with successful reception of EME echoes in 1953 and pioneering two-way contacts made on the 1296, 144, and 432 MHz bands in the 1960s. Increased EME activity and advances to other bands came in the 1970s, aided by the availability of reliable low-noise semiconductor devices and significant improvements in the design of Yagi arrays and feed antennas for parabolic dishes. These trends accelerated further in the 1980s with the advent of low-noise GaAsFET and HEMT preamplifiers and computer-aided antenna designs, and again after 2000 with the introduction of digital techniques. See the sidebar, "Amateur EME Milestones."

EME QSOs have been made on all amateur bands from 28 MHz to 47 GHz. Many operators have made WAC, WAS and even DXCC on one or more of the VHF and UHF bands. EME is now within the grasp of most serious VHF, UHF, and microwave operators.

Amateur EME Milestones

1953	W3GKP and W4AO detect lunar echoes on 144 MHz
1960	First amateur 2-way EME contact: W6HB works W1FZJ, 1296 MHz
1964	W6DNG works OH1NL, 144 MHz
1964	KH6UK works W1BU, 432 MHz
1970	WB6NMT works W7CNK, 222 MHz
1970	W4HHK works W3GKP, 2.3GHz
1972	W5WAX and K5WVX work WA5HNK and W5SXD, 50 MHz
1987	W7CNK and KA5JPD work WA5TNY and KD5RO, 3.4 GHz
1987	W7CNK and KA5JPD work WA5TNY and KD5RO, 5.7 GHz
1988	K5JL works WA5ETV, 902 MHz
1988	WA5VJB and KF5N work WA7CJO and KY7B, 10 GHz
2001	W5LUA works VE4MA, 24 GHz
2005	AD6FP, W5LUA and VE4MA work RW3BP, 47 GHz
2005	RU1AA works SM2CEW, 28 MHz
2009	GDØTEP works ZS6WAB, 70 MHz

9 EME Propagation

9.1 Path Loss

Path loss in free space is caused by nothing more than the spherical expansion of a radio wave as it propagates away from an antenna. An EME signal is attenuated as $1/d^2$ (inverse distance squared) over the quarter-million mile path to the Moon, and again as $1/d^2$ on the return trip, for a net $1/d^4$ path loss. Radio waves incident on the surface of the Moon are often said to be "reflected," although in fact they are partly absorbed and partly scattered by the irregular lunar surface. A full expression giving the EME path loss as a ratio of received power to transmitted power, assuming isotropic antennas at each end of the path, is

$$\ell = \frac{\eta r^2 \lambda^2}{64 \pi^2 d^4} \qquad (1)$$

where

r is the radius of the Moon
λ is the wavelength
d is the distance to the Moon
η is the lunar reflection coefficient.

In this section we use the convention of lower-case letters to denote dimensionless ratios, and the corresponding upper-case letters to give equivalent values in dB. Thus, the EME path loss in dB is given for isotropic antennas by the expression

$$L = 10 \log \ \ell = 10 \ \log\left(\frac{\eta r^2 \lambda^2}{64 \pi^2 d^4}\right) \qquad (2)$$

Inserting values $r = 1.738 \times 10^6$ m, $d = 3.844 \times 10^8$ m and $\eta = 0.065$ gives the average path losses quoted in **Table 7** for the principal amateur EME bands. The need to overcome these very large attenuations is of course the main reason why EME is so challenging. The Moon's orbit is an ellipse, and its distance d varies by ±6.8% over each month. Because of the inverse-fourth-power law in Equations (1) and (2), this change results in path-loss variations of ±1.1 dB at the extremes of lunar distance, independent of frequency. The reflection of radio waves is of course not affected by the optical phases of the Moon.

The dependence of path loss on l^2 suggests that EME should be nearly 20 dB more difficult at 1296 MHz than at 144 MHz. This conclusion is misleading, however, because of the assumption of isotropic antennas. If one uses transmitting and receiving antennas of gain g_t and g_r, expressed as ratios, the expected power p_r received as a lunar echo may be written as the product

$$p_r = p_t g_t g_r \ell \qquad (3)$$

Table 7
Two-Way EME Path Loss with Isotropic Antennas

Frequency (MHz)	*Average Path Loss (dB)*
50	–242.9
144	–252.1
222	–255.8
432	–261.6
902	–268.0
1296	–271.2
2304	–276.2
3456	–279.7
5760	–284.1
10368	–289.2
24048	–293.5

where p_t is the transmitted power. The standard expression for an antenna's power gain is

$$g = 4\pi A/\ell^2$$

where A is the effective aperture or collecting area. Gain in dBi (dB over an isotropic antenna) may therefore be written as

$$G = 10\log (4\pi A/\ell^2)$$

With P_r and P_t expressed in dB relative to some reference power, for example 1 W, we have

$$P_r = P_t + G_t + L + G_r \qquad (4)$$

Thus, assuming a fixed size of antenna, such as a parabolic dish or Yagi array of effective frontal area A, the frequency dependence is reversed: for a given transmitted power, lunar echoes would be 20 dB stronger for every decade increase in frequency, rather than 20 dB weaker. Most practical situations fall somewhere between these two extremes of frequency dependence.

For reasons explained in detail below, amateur EME communication is feasible with roughly comparable degrees of difficulty over nearly two decades of frequency, from 144 MHz to 10 GHz. Not surprisingly, some very different techniques must be mastered in order to do successful EME at the lower and upper extremes of this wide frequency range — so the final choice of band(s) for EME is often determined by the interests, skills and resources of an individual operator.

9.2 Echo Delay and Time Spread

Radio waves propagate at speed c, the speed of light, very nearly equal to 3×10^8 m/s. Propagation time to the Moon and back is therefore 2d/c or about 2.4 s at perigee, 2.7 s at apogee and 2.56 s on average. The Moon is nearly spherical, and its radius corresponds to r/c = 5.8 ms of wave travel time. The trailing parts of an echo, reflected from irregular surface features near the edge of the lunar disk, are delayed from the leading edge by as much as twice this value. In practice, most of the Moon's surface appears relatively smooth at the radio wavelengths used for amateur EME. Lunar reflections are therefore quasi-specular, like those from a shiny ball bearing, and the power useful for communication is mostly reflected from a small region near the center of the disk. At VHF and UHF frequencies, the effective *time spread* of an echo amounts to no more than 0.1 ms.

Reflection from a smooth surface preserves linear polarization and reverses the sense of circular polarization. At shorter wavelengths the lunar surface appears increasingly rough, so reflections at 10 GHz and above contain a significant diffuse component as well as a quasi-specular component. The diffuse component is depolarized, and significant portions of it arise from regions farther out toward the lunar rim. The median time spread can then be as much as several milliseconds. In all practical cases, however, time spreading is small enough that it does not cause significant smearing of CW keying or intersymbol interference in the slowly keyed modulations commonly used for digital EME.

Time spreading does have one very significant effect. Signal components reflected from different parts of the lunar surface travel different distances and arrive at Earth with random phase relationships. As the relative geometry of the transmitting station, receiving station and reflecting lunar surface changes, signal components may sometimes add and sometimes cancel, creating large amplitude fluctuations. Often referred to as *libration fading*, these amplitude variations will be well correlated over a *coherence bandwidth* of a few kHz, the inverse of the time spread.

9.3 Doppler Shift and Frequency Spread

EME signals are also affected by Doppler shifts caused by the relative motions of Earth and Moon. Received frequencies may be higher or lower than those transmitted; the shift is proportional to frequency and to the rate of change of total path length from transmitter to receiver. The velocities in question are usually dominated by the Earth's rotation, which at the equator amounts to about 460 m/s. For the self-echo or "radar" path, frequency shift will be maximum and positive at moonrise, falling through zero as the Moon crosses the local meridian (north-south line) and a maximum negative value at moonset. The magnitude of shifts depends on station latitude, the declination of the Moon and other geometrical factors. For two stations at different geographic locations the mutual Doppler shift is the sum of the individual (one-way) shifts. Maximum values are around 440 Hz at 144 MHz, 4 kHz at 1296 MHz and 30 kHz at 10 GHz. (See the article by Al Katz, K2UYH, "Devilish Doppler" in the online supplemental material for more information on Doppler shift and its effect on EME communications.)

Just as different reflection points on the lunar surface produce different time delays, they also produce different Doppler shifts. The Moon's rotation and orbital motion are synchronized so that approximately the same face is always toward Earth. The orbit is eccentric, so the orbital speed varies; since the rotation rate does not vary, an observer on Earth sees an apparent slow "rocking" of the Moon, back and forth.

Further aspect changes are caused by the 5.1° inclination between the orbital planes of Earth and Moon. The resulting total line-of-sight velocity differences are around 0.2 m/s, causing a *frequency spread* of order 0.2 Hz at 144 MHz. Like all Doppler effects, these shifts scale with frequency. However, measured values of frequency spread increase slightly more rapidly than frequency to the first power because a larger portion of the lunar surface contributes significantly to echo power at higher frequencies. Linear scaling would suggest frequency spread around 15 Hz at 10 GHz, but measurements show it to be several times larger.

From a communication engineering point of view, libration fading is just another example of the so-called *Rayleigh fading* observed on any radio channel that involves multiple signal paths — such as ionospheric skywave, tropospheric scatter and terrain multipath channels with reflections from buildings, trees or mountains. Interference effects that cause signal fading depend on frequency spread as well as time spread. Signal amplitudes remain nearly constant over a *coherence time* given by the inverse of frequency spread. In general, fading rates are highest (shortest coherence times) when the Moon is close to the local meridian and lowest near moonrise and moonset. They also depend on the Moon's location in its elliptical orbit.

Typical coherence times are several seconds at 144 MHz, a few tenths of a second at 1296 MHz and 20 ms at 10 GHz. At 144 MHz, intensity peaks lasting a few seconds can aid copy of several successive CW characters, but at 432 MHz the timescale of peaks and dropouts is closer to that of single characters. At 1296 MHz the fading rates are often such that CW characters are severely chopped up, with dashes seemingly converted to several dits; while the extremely rapid fading at 10 GHz can give signals an almost "auroral" tone. Skilled operators must learn to deal with such effects as best they can. As described further below, modern digital techniques can use message synchronization as well as error-correcting codes and other diversity techniques to substantially improve the reliability of copy on marginal, rapidly fading EME signals.

9.4 Atmospheric and Ionospheric Effects

Propagation losses in the Earth's troposphere are negligible at VHF and UHF, although rain attenuation can be an important factor above 5 GHz. Tropospheric ducting of the sort that produces enhanced terrestrial propagation can bend signals so that the optimum beam heading for EME is directed away from the Moon's center. Even under normal conditions, enough refraction occurs to allow radio echoes when the Moon is slightly below the visible horizon. In practice, these problems are usually overshadowed by other complications of doing EME at very low elevations, such as blockage from nearby trees or buildings, increased noise from the warm Earth in the antenna's main beam and man-made interference.

The Earth's ionosphere causes several propagation effects that can be important to EME. These phenomena depend on slant distance through the ionospheric layer, which increases at low elevations. At elevation 10°, attenuation through the daytime ionosphere is generally less than 0.5 dB at 144 MHz, and nighttime values are at least 10 times lower. These numbers scale inversely as frequency squared, so ionospheric absorption is mostly negligible for EME purposes. Exceptions can occur at 50 MHz, and under disturbed ionospheric conditions at higher frequencies. Ionospheric refraction can also be important at 50 MHz, at very low elevations. Ionospheric scintillations (analogous to the "twinkling" of stars in the Earth's atmosphere) can exhibit significant effects at VHF and UHF, primarily on EME paths penetrating the nighttime geomagnetic equatorial zone or the auroral regions. Again, disturbed ionospheric conditions magnify the effects. The multipath time spread is very small, less than a microsecond, while frequency spread and fading rate can be in the fractional hertz to several hertz range. These scintillations can increase the fading rates produced by Earth rotation and lunar librations.

Much more important is the effect of Faraday rotation in the ionosphere. A linearly polarized wave will see its plane of polarization rotate in proportion to the local free-electron density, the line-of-sight component of the Earth's magnetic field and the square of wavelength. The effect is therefore greatest during the daytime, for stations well away from the equator, and at low frequencies. A mismatch $\Delta\theta$ between an incoming wave's polarization angle and that of the receiving antenna will attenuate received signal power by an amount $\cos^2\Delta\theta$. As shown in **Figure 62**, polarization losses increase rapidly when the misalignment exceeds 45°.

Because of the ℓ^2 dependence, Faraday rotation is generally important for EME operation only at 432 MHz and below. The effect is cumulative for an outgoing signal and its returning echo, so a station transmitting and receiving with the same linearly polarized antenna will see its own echoes disappear whenever the total Faraday rotation is close to an odd integral multiple of 90°. Faraday rotation in the daytime ionosphere can amount to as much as a full turn at 432 MHz and many turns at 144 MHz. At 432 MHz the rotation may be essentially constant over several hours; on lower bands significant changes can occur in 30 minutes or less. Variations are especially noticeable near sunrise or sunset at one end of the path, where ionization levels are changing rapidly.

The Earth's spherical shape determines the orientation in space of a wave emitted or received by an antenna with horizontal (or other locally referenced) polarization angle. As discussed in detail below, when combined with Faraday rotation this effect can cause users of fixed-linear-polarization antennas to experience apparent one-way propagation.

A polarized radio signal reflected from the Moon's rough surface is partially scattered into other polarization states, and a disturbed

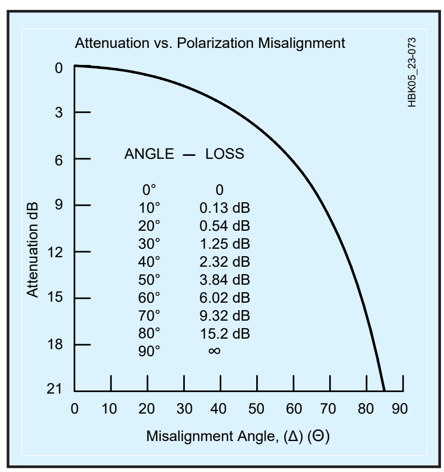


Figure 62 — Attenuation caused by misalignment of a linearly polarized signal with the polarization angle of a receiving antenna. The attenuation increases rapidly for alignment errors greater than 45°.

ionosphere can sometimes generate a mixture of polarization angles. As a consequence, fading caused by 90° polarization misalignments will not always produce deep nulls. Measurements show that at UHF and below, the cross-polarized scattered signal is usually 15 dB or more below the principal polarization. On the other hand, at 10 GHz and higher, where the lunar surface is much rougher in terms of wavelength, cross-polarized diffuse echoes may be only a few dB below the principal reflected polarization. These comments apply to both linear and circular polarization.

10 Fundamental Limits

10.1 Background Noise

EME signals are always weak, so considerations of signal-to-noise ratio are paramount. (Noise is also discussed in the **RF Techniques** chapter.) A received signal necessarily competes with noise generated in the receiver as well as that picked up by the antenna, including contributions from the warm Earth, the atmosphere, the lunar surface, the diffuse galactic and cosmic background and possibly the sun and other sources. (Refer to Figure 61, and think of adding a warm atmosphere just above the Earth, the sun somewhere beyond the Moon, and galactic and extragalactic noise sources at even greater distances, filling the whole sky.) If P_n is the total noise power collected from all such noise sources expressed in dBW, we can write the expected signal-to-noise ratio of the EME link as

$$SNR = P_r - P_n = P_t + G_t + L + G_r - P_n \quad (5)$$

Since isotropic path loss L is essentially fixed by choice of a frequency band (Table 7), optimizing the signal-to-noise ratio generally involves trade-offs designed to maximize P_r and minimize P_n — subject, of course, to such practical considerations as cost, size, maintainability and licensing constraints.

It is convenient to express P_n (in dBW) in terms of an equivalent system noise temperature T_s in kelvins (K), the receiver bandwidth B in Hz and Boltzmann's constant k = 1.38 × 10^{-23} J K^{-1}:

$$P_n = 10 \log (kT_sB) \quad (6)$$

The system noise temperature may in turn be written as

$$T_s = T_r + T_a \quad (7)$$

Here T_r is receiver noise temperature, related to the commonly quoted noise figure (NF) in dB by

$$T_r = 290 (10^{0.1NF} - 1) \quad (8)$$

Antenna temperature T_a includes contributions from all noise sources in the field of view, weighted by the antenna pattern. The lunar surface has a temperature around 210 K; since most antennas used for amateur EME have beamwidths greater than the

Table 8
Typical Contributions to System Noise Temperature

Freq (MHz)	*CMB (K)*	*Atm (K)*	*Moon (K)*	*Gal (K)*	*Side (K)*	*T_a (K)*	*T_r (K)*	*T_s (K)*
50	3	0	0	2400	1100	3500	50	3500
144	3	0	0	160	100	260	50	310
222	3	0	0	50	50	100	50	150
432	3	0	0	9	33	45	40	85
902	3	0	1	1	30	35	35	70
1296	3	0	2	0	30	35	35	70
2304	3	0	4	0	30	37	40	77
3456	3	1	5	0	30	40	50	90
5760	3	3	13	0	30	50	60	110
10368	3	10	42	0	30	85	75	160
24048	3	70	170	0	36	260	100	360

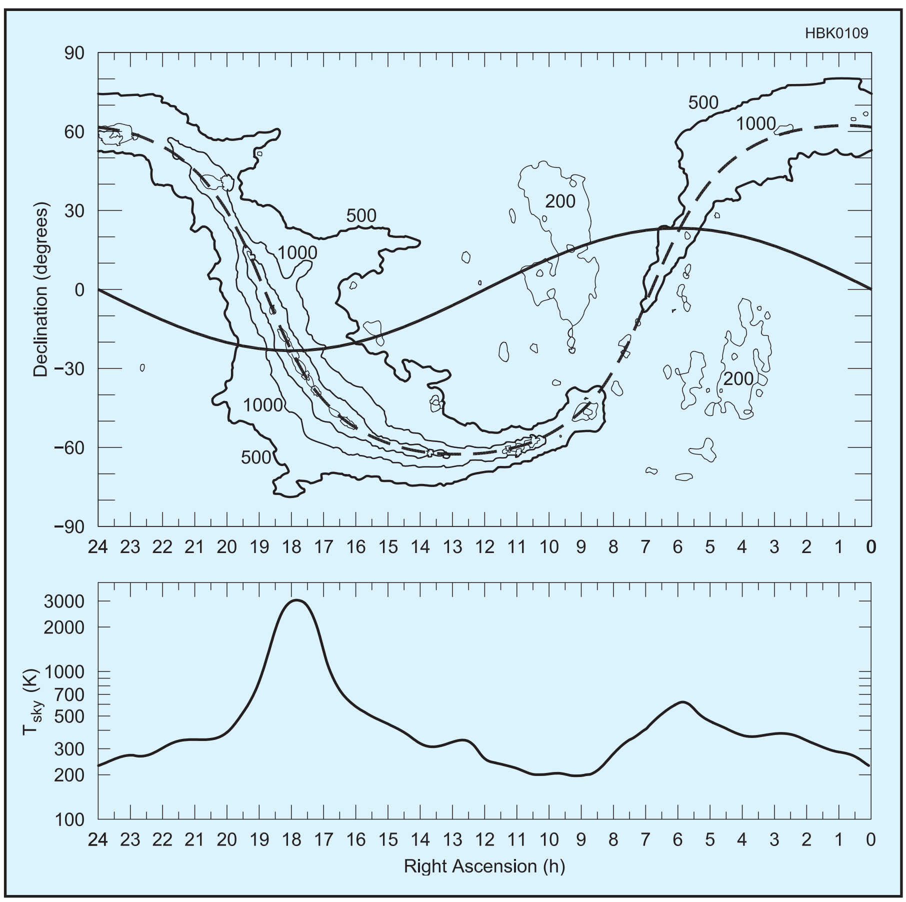


Figure 63 — *Top:* All-sky contour map of sky background temperature at 144 MHz. The dashed curve indicates the plane of our galaxy, the Milky Way; the solid sinusoidal curve is the plane of the ecliptic. The Sun follows a path along the ecliptic in one year; the Moon moves approximately along the ecliptic (± 5°) each month. Map contours are at noise temperatures 200, 500, 1000, 2000 and 5000 K. *Bottom:* One-dimensional plot of sky background temperature at 144 MHz along the ecliptic, smoothed to an effective beamwidth 15°.

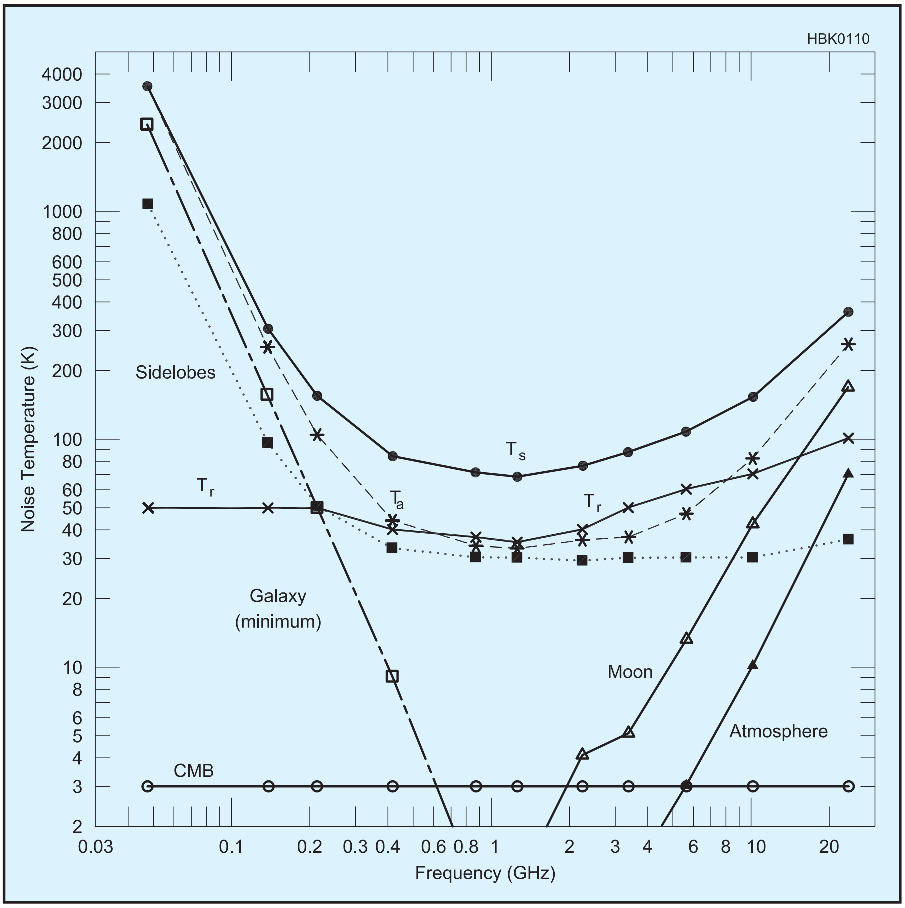


Figure 64 — Typical contributions to system noise temperature T_s as function of frequency. See text for definitions and descriptions of the various sources of noise.

Moon's angular size, as well as sidelobes, the Moon's effect will be diluted and noise from other sources will also be received. Sidelobes are important, even if many dB down from the main beam, because their total solid angle is large and therefore they are capable of collecting significant unwanted noise power.

At VHF the most important noise source is diffuse background radiation from our Galaxy, the Milky Way. An all-sky map of noise temperature at 144 MHz is presented in the top panel of **Figure 63**. This noise is strongest along the plane of the Galaxy and toward the galactic center. Galactic noise scales as frequency to the –2.6 power, so at 50 MHz the temperatures in Figure 63 should be multiplied by about 15, and at 432 divided by 17. At 1296 MHz and above galactic noise is negligible in most directions. During each month the Moon follows a right-to-left path lying close to the ecliptic, the smooth solid curve plotted in Figure 63. Sky background temperature behind the Moon therefore varies approximately as shown in the lower panel of Figure 63, regardless of geographical location on Earth. For about five days each month, when the Moon is near right ascension 18 hours and declination –28°, VHF sky background temperatures near the Moon are as much as 10 times their average value, and conditions for EME on the VHF bands are poor.

By definition the Sun also appears to an observer on Earth to move along the ecliptic, and during the day solar noise can add significantly to P_n if the Moon is close to the sun or the antenna has pronounced sidelobes. At frequencies greater than about 5 GHz the Earth's atmosphere also contributes significantly. An ultimate noise floor of 3 K, independent of frequency, is set by cosmic background radiation that fills all space. A practical summary of significant contributions to system noise temperature for the amateur bands 50 MHz through 24 GHz is presented in **Table 8** and **Figure 64** and **Figure 65**, discussed in the next section.

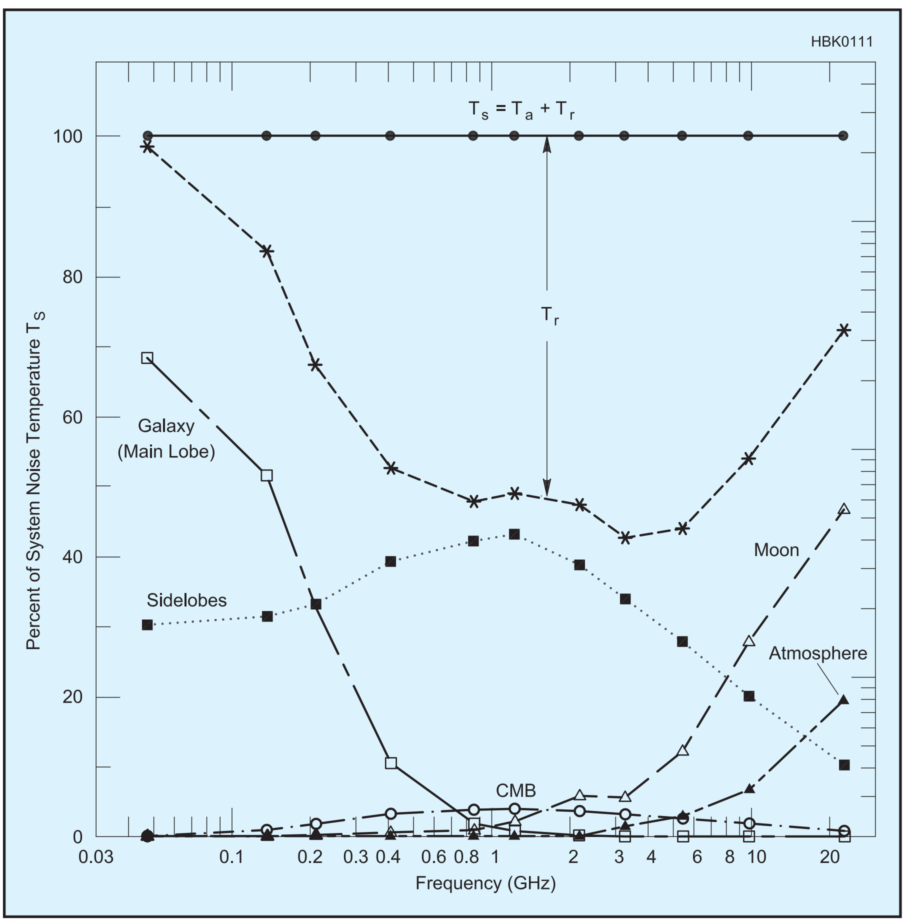


Figure 65 — Percentage contributions to system noise temperature as a function of frequency.

10.2 Antenna and Power Requirements

The basic circumstances described so far ensure that frequencies from 100 MHz to 10 GHz are the optimum choices for EME and space communication. Over this region and a bit beyond, a wide variety of propagation effects and equipment requirements provide a fascinating array of challenges and opportunities for the EME enthusiast. The enormous path-loss variability encountered in terrestrial HF and VHF propagation does not occur in EME work, and some of the remaining, smaller variations — for example, those arising from changing lunar distance and different sky background temperatures — are predictable. We can therefore estimate with some confidence the minimum antenna sizes and transmitter powers required for EME communication on each amateur band.

The necessary information for this task is summarized in Table 8 and Figures 64 and 65. Columns 2 through 6 of the table give typical contributions to system noise temperature from the cosmic microwave background (CMB), the Earth's atmosphere, the warm surface of the Moon, galactic noise entering through the main antenna beam and sky and ground noise from an antenna's side and rear lobes. Antenna temperature T_a is a combination of all these contributions, appropriately weighted by antenna pattern; the system noise temperature T_s is then the sum of T_a and receiver noise temperature T_r, referred to the antenna terminals. Numbers in Table 8 are based on the fundamentals described in the previous section and on hypothetical antennas and receivers that conform to good amateur practice in the year 2009; they have been rounded to two significant figures. It is possible to do slightly better than these numbers — for example, by building antennas with lower sidelobe response or preamplifiers with still lower noise figure — but it's not easy!

The topmost curve in Figure 64 illustrates clearly why the frequency range from 100 MHz to 10 GHz is optimum for EME communication. Figure 65 shows that further reductions of T_s must come from lower T_r or better suppression of antenna sidelobes. There is nothing you can do about noise from the CMB, atmosphere, Moon or Galaxy entering your main beam! For comparison, the very best professional receiving equipment achieves system noise temperatures around 20 K in the 1-2 GHz region — only a few dB better than current amateur practice. These systems generally use cryogenic receivers and very large dish antennas that can provide better suppression of sidelobes.

Having established reasonable target figures for system noise temperature, we can now proceed to estimate minimum antenna and power requirements for an EME-capable station on each amateur band. Rearrangement of Equations (5) and (6) yields the following relation for transmitter power P_t in dBW:

$$P_t = SNR - G_t - G_r - L + 10 \log (kT_sB) \quad (9)$$

Values for L and T_s can be taken for each amateur band from Tables 7 and 8. For illustrative purposes let's assume SNR = 3 dB and B = 50 Hz, values appropriate for a good human operator copying a marginal CW signal. (The 50 Hz effective bandwidth may be established by an actual hardware or software filter, or more commonly by the operator's "ear-and-brain" filter used toget her with a broader filter in the transceiver.) For antennas we shall assume bays of four long Yagis for the 50 through 432 MHz bands, parabolic dishes of diameter 3 m on 1296 and 2304 MHz and 2 m dishes on the higher bands. Representative gains and half-power beamwidths for such antennas are listed in columns 3 and 4 of **Table 9**. Column 5 then gives the necessary transmitter power in watts, rounded to two significant figures.

A station with these baseline capabilities should be self sufficient in terms of its ability to overcome EME path losses — and thus able to hear its own EME echoes and make CW contacts with other similarly equipped EME stations. Note that the quoted minimum values of transmitter power do not allow for feed line losses; moreover, a CW signal with SNR = 3 dB in 50 Hz bandwidth hardly represents "armchair copy." At the highest frequencies, issues of oscillator stability and Doppler spreading might make the assumed 50 Hz bandwidth unrealistically narrow, thus requiring somewhat more power or a larger antenna. On the other hand, lower power and smaller antennas can be sufficient for working stations with greater capabilities than those in the table.

Other factors can reduce the minimum power or antenna gains required for successful EME, at least some of the time. One possibility, especially effective at 50 and 144 MHz at low moon elevations, is to take advantage of reflections from reasonably smooth ground (or better still, water) in front of your antenna. Often referred to as *ground gain*, these reflections can add as much as 6 dB to an antenna's effective gain at elevations where the reflections are in phase with the direct signal. Another possibility is to use more efficient coding and modulation schemes than provided by Morse coded CW.

Table 9
Typical Antenna and Power Requirements for CW EME

Freq (MHz)	*Ant Type*[1]	*Gain (dBi)*	*HPBW (deg)*	*TxPwr (W)*
50	4×12 m	19.7	18.8	1200
144	4×6 m	21.0	15.4	500
432	4×6 m	25.0	10.5	250
1296	3 m	29.5	5.5	160
2304	3 m	34.5	3.1	60
3456	2 m	34.8	3.0	120
5760	2 m	39.2	1.8	60
10368	2 m	44.3	1.0	25

[1]Example antennas for 50, 144 and 432 MHz are Yagi arrays with stated lengths; those for 1296 MHz and higher are parabolic dishes of specified diameter.

10.3 Coding and Modulation

International Morse code with on-off keying (OOK) is an excellent general purpose communication mode. It is easy to implement and performs well in weak-signal conditions. EME operating procedures for CW usually include multiple repetitions so that essential parts of a bare-minimum QSO can be assembled from fragments copied on signal peaks. However, modern communication theory points the way toward modulation schemes significantly more efficient than OOK, codes better than Morse, and error-control methods more effective than simple repetition. Amateur experiments with these ideas have led to the current popularity of digital EME on the VHF, UHF, and microwave bands. In general, an efficient digital mode designed for basic communication with weak signals will compress user messages into a compact form and then add redundancy in the form of a mathematically defined error-correcting code (ECC). Such codes can ensure that full messages are recoverable with high confidence, even when significant portions of a transmission are lost or corrupted.

A number of distinct sources may contribute to the improved performance of such a mode over CW. Multitone FSK (MFSK) is a more efficient modulation than OOK, in part because each received symbol is roughly the equivalent of a full character, rather than a single dot or dash. For equivalent messages, MFSK can therefore be keyed much more slowly than CW and detected in a much smaller bandwidth. Morse code is self-synchronizing at the character level (if a signal is strong enough for letters to be recognized), but a Morse transmission contains no useful information for synchronizing a whole message. This fact makes it difficult to piece together copied fragments of a CW message being sent repeatedly. As discussed later in the Operating Procedures section, K1JT's software package *WSJT-X* includes several MFSK modes for low SNR communications on HF and VHF/UHF/microwaves. More information is available in the **Digital Protocols and Modes** chapter and at **physics.princeton.edu/pulsar/k1jt/wsjt.html**. Also see the sidebar later in this chapter, "Comput-

Figure 66 — The 12-element Yagi used by DL1VPL to complete DXCC on 144 MHz.

Figure 67 — TF/DL3OCH used a rural road sign to help him give contacts with Iceland to a number of EME operators on 1296 MHz. Bodo has activated many DXCC entities on 1296 MHz EME by using JT65, a single long Yagi and a 100 W solid state amplifier.

Figure 68 — The portable EME-capable 10 GHz station of VK7MO, set up at roadside in the Australian outback.

ing and Internet Resources for EME."

In contrast, a synchronized digital transmission with ECC can encode the complete message into a new data format designed to enhance the probability that successful decoding will produce the message's full information content, with everything in its proper place. For the limited purpose of exchanging call signs, signal reports and modest amounts of additional information, digital EME contacts can be made at signal levels some 10 dB below those required for CW, while at the same time improving reliability and maintaining comparable or better rates of information throughput. Depending on your skill as a CW operator, the digital advantage may be even larger.

Thus, digital EME contacts are possible between similar stations with about 10 dB less power than specified in Table 9, or with 5 dB smaller antenna gains at both transmitter and receiver. Examples of antennas for three small but very effective EME stations are shown in **Figures 66** to **68**. Figure 66 shows the single 12-element Yagi used by Thomas, DL1VPL, to complete his DXCC on 144 MHz. Figure 67 shows the highly portable EME setup of Bodo, DL3OCH. With a single long Yagi (59 elements, 5 m boom, 21.8 dBi gain), a 100 W solid state power amplifier (SSPA) and the JT65C digital mode, this equipment has helped him to provide dozens of new DXCC credits on 1296 MHz from countries with little or no regular EME activity. Figure 68 shows the 10 GHz portable station of Rex, VK7MO. It includes a 10 GHz transverter, a 50 W SSPA, and a 2.5-foot (75 cm) dish mounted on a collapsible tripod. Rex has made hundreds of EME contacts with this equipment using the JT4 and QRA64 digital modes.

11 Building an EME Station

11.1 Antennas

The antenna is arguably the most important element in determining an EME station's capability. It is not accidental that the baseline station requirements outlined in Table 9 use Yagi arrays on the VHF bands and parabolic dishes at 1296 MHz and above: one of these two antenna types is almost always the best choice for EME. The gain of a modern, well designed Yagi of length ℓ can be approximated by the equation

$$G = 8.1 \log(\ell / \lambda) + 11.4 \text{ dBi} \qquad (10)$$

and stacks of Yagis can yield close to 3 dB (minus phasing line losses) for each doubling of the number of Yagis in the stack.

For comparison, the gain of a parabolic dish of diameter d with a typical feed arrangement yielding 55% efficiency is

$$G = 20 \log(d/\lambda) + 7.3 \text{ dB} \qquad (11)$$

The gains of some nominal antennas of each type are illustrated graphically in **Figure 69**, which helps to show why Yagis are nearly always the best choice for EME on the VHF bands. They are light, easy to build and have relatively low wind resistance. Stacks of four Yagis are small enough that they can be mounted on towers for sky coverage free of nearby obstructions. Larger arrays of 8, 16 or even more Yagis are possible, although the complexity and losses in phasing lines and power dividers then become important considerations, especially at higher fre-

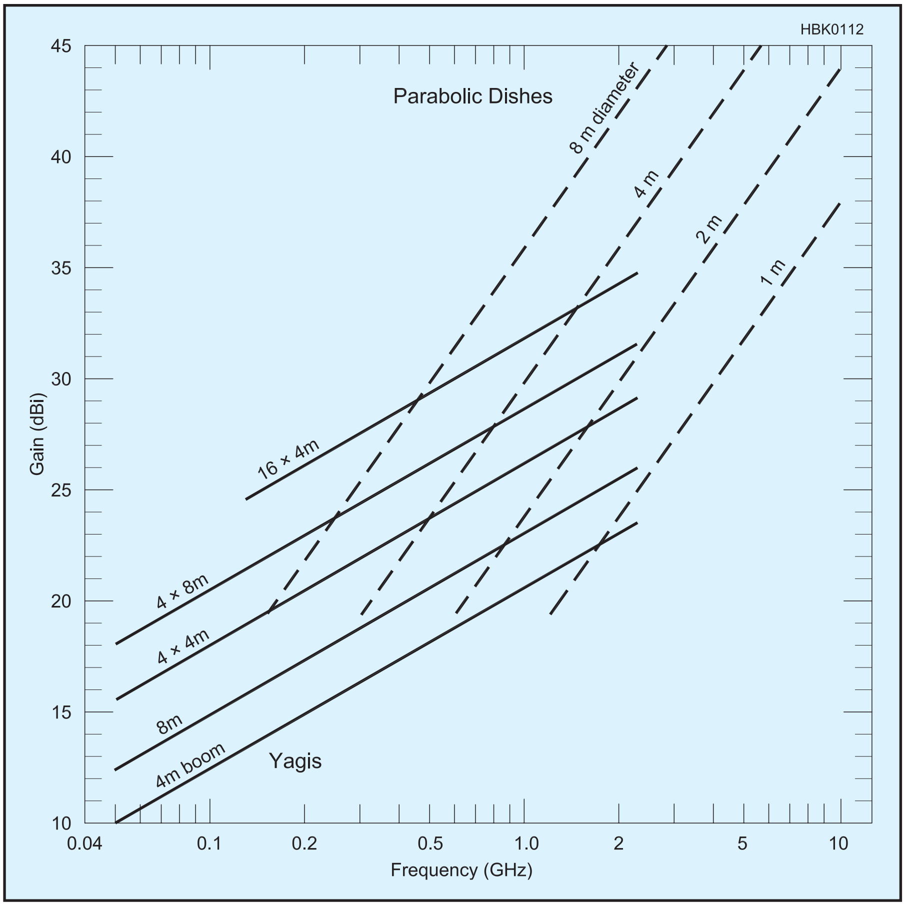


Figure 69 — Representative gains of practical Yagi antennas, arrays of Yagis and parabolic dishes as a function of frequency. Yagi arrays make the most cost-effective and convenient antennas for EME on the VHF bands, while parabolic dishes are generally the best choice above 1 GHz.

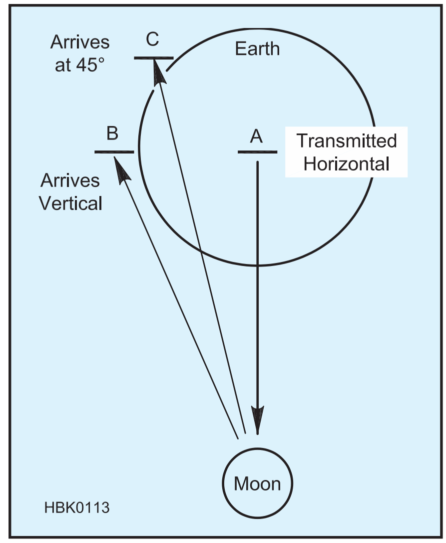


Figure 70 — The spherical Earth creates spatial polarization offsets for well-separated stations with horizon-oriented linear polarization. Here, a signal transmitted horizontally at A arrived with vertical polarization at B and midway between horizontal and vertical at C. When combined with Faraday rotation, offsets close to 45° can lead to apparent one-way propagation. See text for details.

quencies. Long Yagis are narrowband antennas, usable on just a single band.

We usually think of the linear polarization of a transmitted signal as being "horizontal" or "vertical." Of course, on the spherical Earth these concepts have meaning only locally. As seen from the Moon, widely separated horizontal antennas may have very different orientations (see **Figure 70**). Therefore, in the absence of Faraday rotation an EME signal transmitted with horizontal polarization by station A will have its linear polarization misaligned at stations B and C by angles known as the *spatial polarization offset*. In Figure 70 the signal from A arrives with vertical polarization at B and at 45° to the horizon at C. Suppose C is trying to work A and $q_s = 45°$ is the spatial polarization offset from A to C. The return signal from C to A will be offset in the opposite direction, that is, by an amount $-q_s = -45°$. The Faraday rotation angle θ_F, on the other hand, has the same sign for transmission in both directions. Thus the net polarization shift from A to C is $\theta_F + q_s$, while that from C to A is $\theta_F - q_s$. If θ_F is close to any of the values ±45°, ±135°, ±225°, …, then one of the net polarization shifts is nearly 90° while the other is close to 0°. The result for stations with fixed linear polarization will be apparent one-way propagation: for example, A can copy C, but C cannot copy A.

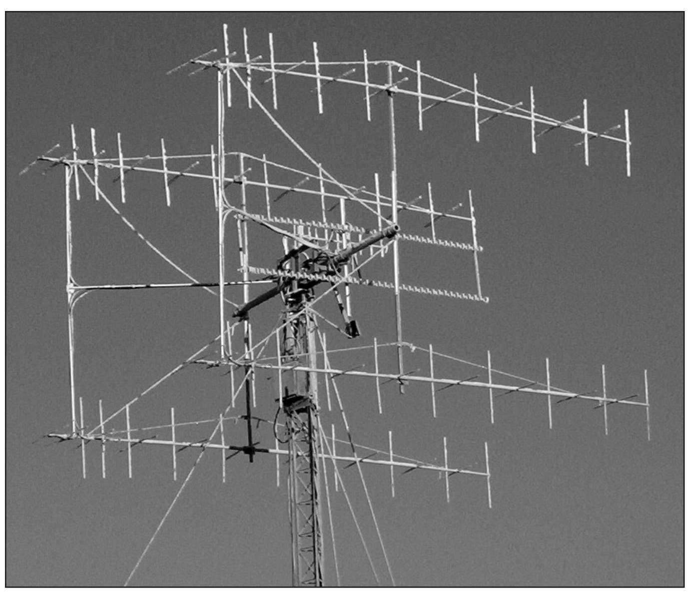


Figure 71 — Array of four 10-element, dual-polarization 144 MHz Yagis at KL7UW. Alaskan frost makes the horizontal and vertical elements stand out clearly. A pair of loop Yagis for 1296 MHz can be seen inside the 2 meter array.

Obviously no two-way contact can be made under these conditions, so the operators must wait for more favorable circumstances or else

Figure 72 — Dual-polarization EME array at W2PU. At the left, shows the four 15-element, rear-mounted Yagis. Boom length is 3.5 m, and stacking distance is 1.2 m in each direction. The right photo is a close-up showing some details around the driven loops.

implement some form of polarization control or polarization diversity. One cost-effective solution is to mount two full sets of Yagi elements at right angles on the same boom. Arrays of such cross-polarized or "Xpol" Yagis make especially attractive EME antennas on the VHF and lower UHF bands because they offer a flexible solution to the linear-polarization misalignment problem. As an example, **Figure 71** shows the 4 × 10 element, dual-polarization EME array at KL7UW. This antenna has accounted for many hundreds of EME contacts with the state of Alaska on 2 meters.

At 1296 MHz and above, gains of 30 dBi and more can be achieved with parabolic dishes of modest size. As a result, these antennas are almost always the best choice on these bands. Their structure does not depend on any radio frequency resonances, so in many ways dishes are less critical to build than Yagis. Element lengths in high-gain Yagis must be accurate to better than 0.005 λ, while the reflecting surface of a dish need be accurate only to about 0.1 λ. Mesh surfaces are attractive at frequencies up to at least 5 GHz, because of their light weight and lower wind resistance. Openings in the mesh can be as large as 0.05 λ without allowing much ground noise to feed through the surface. A parabolic antenna has a single feed point, so there are no losses in phasing lines or power splitters. You can use a dish on several bands by swapping feeds, and with suitable feed designs you can produce either linear or circular polarization, including dual polarizations. A very attractive and convenient option is to transmit in one sense of circular polarization and receive in the opposite sense. Transmitting in right-hand circular (RHC) and receiving in LHC has become the standard for EME on bands from 1296 MHz up to 5.7 GHz. Linear polarization is still used most commonly for EME at 10 and 24 GHz.

As made clear in Figure 69, the 432 MHz band lies in a transition region where both Yagis and parabolic dishes have attractive features. Either four long Yagis or a 6 m dish can produce enough gain (about 25 dBi) to let you work many other EME stations on this band. Many linear-polarization systems are already in use — for good reason, since most amateur use of this band is for terrestrial communication — so converting everyone to circular polarization is impractical. Therefore, schemes have been devised to physically rotate dish feeds and even whole Yagi arrays to cope with the resulting polarization alignment problems. Another scheme is to use a dual-polarization dish feed or dual-polarization Yagis, as described above and increasingly used on 144 MHz. This approach has not gained wide popularity on 432 MHz, mainly because at this wavelength it is hard to find room for the feedlines and matching system at the antenna feed points. One successful implementation is shown in **Figure 72**.

ANTENNA PATTERN

A clean pattern with good suppression of side and rear lobes is important for all EME antennas — especially at 432 MHz and above, where excessive noise pickup through sidelobes can significantly increase T_s. For Yagi arrays you should use modern, computer-optimized designs that maximize G/T_s, the ratio of forward gain to system noise temperature. Be sure to pay attention to maintaining a clean pattern when stacking multiple antennas. First sidelobes within 10-15° of the main beam may not be a major problem, because their solid angle is small and they will look

Figure 73 — This 3 meter TVRO dish with aluminum frame and mesh surface was outfitted for 1296 MHz EME as a joint effort by VA7MM and VE7CNF. The dual-circular polarization feed is a VE4MA/W2IMU design.

mostly at cold sky when EME conditions are favorable. Side and rear lobes farther from the main beam should be suppressed as much as possible, however. Remember that even close-in sidelobes will degrade your receiving performance at low elevations.

For parabolic dishes, G/T_s is optimized by using a feed with somewhat larger taper in illumination at the edge of the dish than would yield the highest forward gain. Best forward gain is generally obtained with edge taper around −10 dB, while best G/T_s occurs around −15 dB. Edge taper of −12 dB is usually a good compromise. Some good reproducible designs for dish feeds are described in references at the end of this section.

Figure 74 — Mounting arrangement, counterweights and az/el control system for the VA7MM 3 meter dish.

ANTENNA MOUNTS

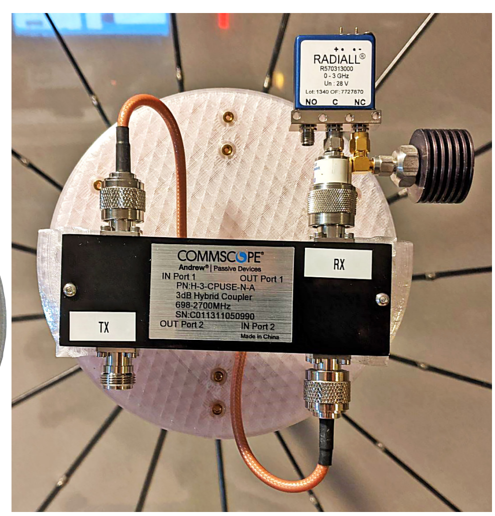
EME antennas have high gain and narrow main beams that must be properly aimed at the Moon in two coordinates. Although polar mounts (one axis parallel to the Earth's axis) have sometimes been used, by far the most popular mounting scheme today is the elevation-over-azimuth or *az/el* mount. Readily available computer software (see the sidebar, "Computer and Internet Resources for EME") can provide azimuth and elevation coordinates for the Moon, and a small computer can also control antenna positioning motors to automate the whole pointing system.

For mechanical reasons it is desirable to place the antenna's center of gravity close to the intersection of the vertical (azimuth) and horizontal (elevation) axes. On the other hand, the mounting structure must not interfere with critical active regions of the antenna. Stacked Yagis are generally mounted so that metallic supporting members are perpendicular to the radiating elements or located at midpoints where the effective apertures of separate Yagis meet. Feed lines and conducting support members must not lie in the active planes containing Yagi elements, unless they run wholly along the boom. For dual-polarization Yagis, feed lines should be routed toward the rear of each Yagi and any mid-boom support members must be non-conducting. For EME there is nothing magical about using horizontal and vertical for the two orthogonal polarizations, and there are some advantages to mounting cross-Yagis with elements in the "×" rather than "+" orientation.

Parabolic dishes are usually mounted from behind, with counterweights extending rearward to relieve torque imbalance on the elevation axis. Screw-jack actuators designed for positioning 1980s-style TVRO dishes can be readily adapted for elevation control. Standard heavy-duty antenna rotators can be used for azimuth positioning of dishes up to about 3 m in size. Larger dishes may require heavier, one-of-a-kind designs for pointing control. **Figures 73** through **75** show examples of parabolic dishes in the 2 – 3 m range that are outfitted for EME.

(A)

(B)



(C)

Figure 75 — NT6V operates a lightweight (12 lb) portable folding dish in his front yard during the ARRL EME Contest in 2021 (A). The dish and circular polarization feed was designed and built by W2HRO and www.Sub-Lunar.com. The dish is mounted on a dual axis slew drive positioner and a surveyor tripod. The 1296 MHz patch feed (B) is 3D printed with PETG plastic and lined with 1 mil copper. A quadrature hybrid (C) is used to create RHCP for transmit and LHCP for received.

Computer and Internet Resources for EME

Software for finding and tracking the Moon:

MoonSked, by GM4JJJ, **www.gm4jjj.co.uk/MoonSked/moonsked.htm** (Not currently maintained)
EME System, by F1EHN, **www.f1ehn.org**
EME Planner, by VK3UM, **www.vk5dj.com/doug.html**
GJTracker, by W7GJ, **www.bigskyspaces.com/w7gj/tracker.htm**
Sun & Moon calculator, **www.satellite-calculations.com/Satellite/suncalc.htm**
Sun and Moon Rise and Set times **www.timeanddate.com/moon/**
Sun & Moon App, **sun-moon-app.com**
WSJT-X, by K1JT, **physics.princeton.edu/pulsar/k1jt/wsjtx.html**

Software for EME performance calculations:

EMECalc, by VK3UM, www.**vk5dj.com/doug.html**

Digital EME:

WSJT, WSJT-X, MAP65: **physics.princeton.edu/pulsar/K1JT/**
LiveCQ: **www.livecq.eu/**

Topical email reflectors:

Moon-Net: **www.nlsa.com/nets/moon-net-help.html**
Moon: **www.moonbounce.info/mailman/listinfo/moon**

Beginner information:

EA6VQ: **www.dxmaps.com/jt65bintro.html**
W7GJ (EME on 50 MHz): **www.bigskyspaces.com/w7gj/**
W8TN: **w8tn.blogspot.com/2017/03/w8tns-2-m-eme-project.html**
DL7APV: **dl7apv.de/start/start.htm**
K4MSG: **history.k4lrg.org/Projects/K4MSG_EME/**

Technical references:

SM5BSZ: **www.sm5bsz.com/linuxdsp/linrad.htm**
W1GHZ: **www.w1ghz.org/antbook/contents.htm**
GM3SEK**: www.ifwtech.co.uk/g3sek/eme/pol1.htm** and **www.ifwtech.co.uk/g3sek/stacking/stacking2.htm**
Dubus: **www.marsport.org.uk/dubus/eme.htm**

Chatrooms and Loggers:

NØUK: **www.chris.org/cgi-bin/jt65emeA**
ON4KST: **www.on4kst.com/chat/**
HB9Q: **www.hb9q.ch/hb9q**

Monthly Newsletters:

144 MHz, by DF2ZC: **www.df2zc.de/newsletter**
432 and Above, by K2UYH: **www.nitehawk.com/rasmit/em70cm.html**

Solar Flux data:

Archival: **www.ngdc.noaa.gov/stp/solar/solarradio.html**
Current: **www.swpc.noaa.gov/ftpdir/lists/radio/45day_rad.txt**

EME Contests

ARRL: **contests.arrl.org/eme/**
(A.R.I.) Italian: **www.ari.it/english-area/eme.html**
S.R.R. (Russian): **eme.srr.ru/rules/**

11.2 Feed Lines, Preamplifiers, and TR Switching

Any feed line between the antenna and receiver introduces attenuation and noise, so it is preferable that the *low noise preamplifier* (LNA) be mounted very close to the antenna terminals. At ambient temperature, every 0.1 dB of loss in front of the LNA from feed line, relays, and connectors adds directly to system noise figure and at least 7 K to the effective T_r, and therefore to T_s. On bands where T_a is much lower than ambient, even 0.1 dB of attenuation can result in 0.5 dB loss of receiver sensitivity.

LNA gain should be sufficient to overcome feed line losses and dominate the noise contributed by subsequent stages by at least 15 – 20 dB. Current practices usually employ one or, especially at 432 MHz and above, two low-noise GaAsFET or HEMT transistors in the preamplifier, with only a simple noise impedance matching circuit between the first active device and the antenna. Only if severe out-of-band interference is present should a narrow filter be placed ahead of the first LNA because the added loss will degrade system noise figure.

Bandpass filtering is often desirable between LNA stages and may be used without significant impact on system noise temperature. The feed horn of a dish antenna can have a valuable high-pass effect that attenuates signals at lower frequencies.

The same antenna is generally used for both transmitting and receiving, so the LNA must be out of the line and protected when transmitting. **Figure 76A** illustrates a switching arrangement that uses two separate feed lines: a low-loss line to carry transmitter power and a relatively inexpensive feed line from LNA to the receiver. A high-power relay, K1, at the antenna handles T-R switching; a second relay, K2, may be used to protect the LNA in case the isolation at K1's receive port is inadequate.

Additional relays are required in order to make the best use of a dual-linear-polarization system. A dual-channel receiver can form a linear combination of signals in the two channels to match the polarization of a desired signal exactly, whatever its arrival angle. Figure 76B shows an arrangement that lets you select either horizontal or vertical polarization for transmitting (via relay K5) and use both polarizations simultaneously for receiving.

Figure 77A shows another option. This arrangement maintains both polarizations for receiving, but connects the two antennas together through ¼-wave sections of 75-Ω coax when transmitting to create circular polarization to overcome fading due to Faraday rotation. The ¼-wave sections transform the antenna impedances to 100 Ω, and when connected in parallel, back to 50 Ω. This arrangement assumes that the H and V antennas have a ¼-wave delay either in the feed lines or in the mechanical construction of the array. The switching system shown in Figure 77B, built by DK5YA, uses relays with sufficient isolation to eliminate the need for switching the LNA inputs to resistors as shown in the previous example.

With circular polarization on a dish feed, you may not need a high-power T-R relay at all. Figure76C shows a typical arrangement with transmitter connected to one port of a feed horn providing both senses of circular polarization, and the LNA to the other port. Since the isolation between ports may be only 20 or 30 dB, a low-power relay protects the LNA during transmit periods.

In all these schemes, suitable sequencing should be used to assure that the LNA is disconnected before transmission can begin. Many amateurs find it best to use the energized position of T-R relays on receive. When the station is not in use, preamplifiers will then be disconnected from the antenna.

11.3 Transmitters and Power Amplifiers

FREQUENCY STABILITY

Weak signals are best detected in a bandwidth no wider than the signal itself. As a consequence, EME systems must use stable oscillators. For best results with CW your frequency drift over a minute or so should be no more than 10 Hz at the operating frequency; with digital modes the ideal target may be several times smaller. Most modern transceivers are stable enough at VHF, but some only marginally so at UHF. The crystal oscillators used in transverters may need temperature compensation for adequate stability; better still, they can be phase-locked to an external high-stability reference oscillator.

Many successful EME QSOs have been made on the microwave bands using 5 – 10 W transmitter power and parabolic dishes smaller than 2 m (up to 5.7 GHz) and even 1 m (at 10 and 24 GHz). These are significantly smaller systems than the baseline examples listed in Table 9. Such contacts generally depend on having stabilized local oscillators. Especially for digital EME, where detection bandwidths less than 10 Hz are used, unstable oscillators lead directly to loss of sensitivity.

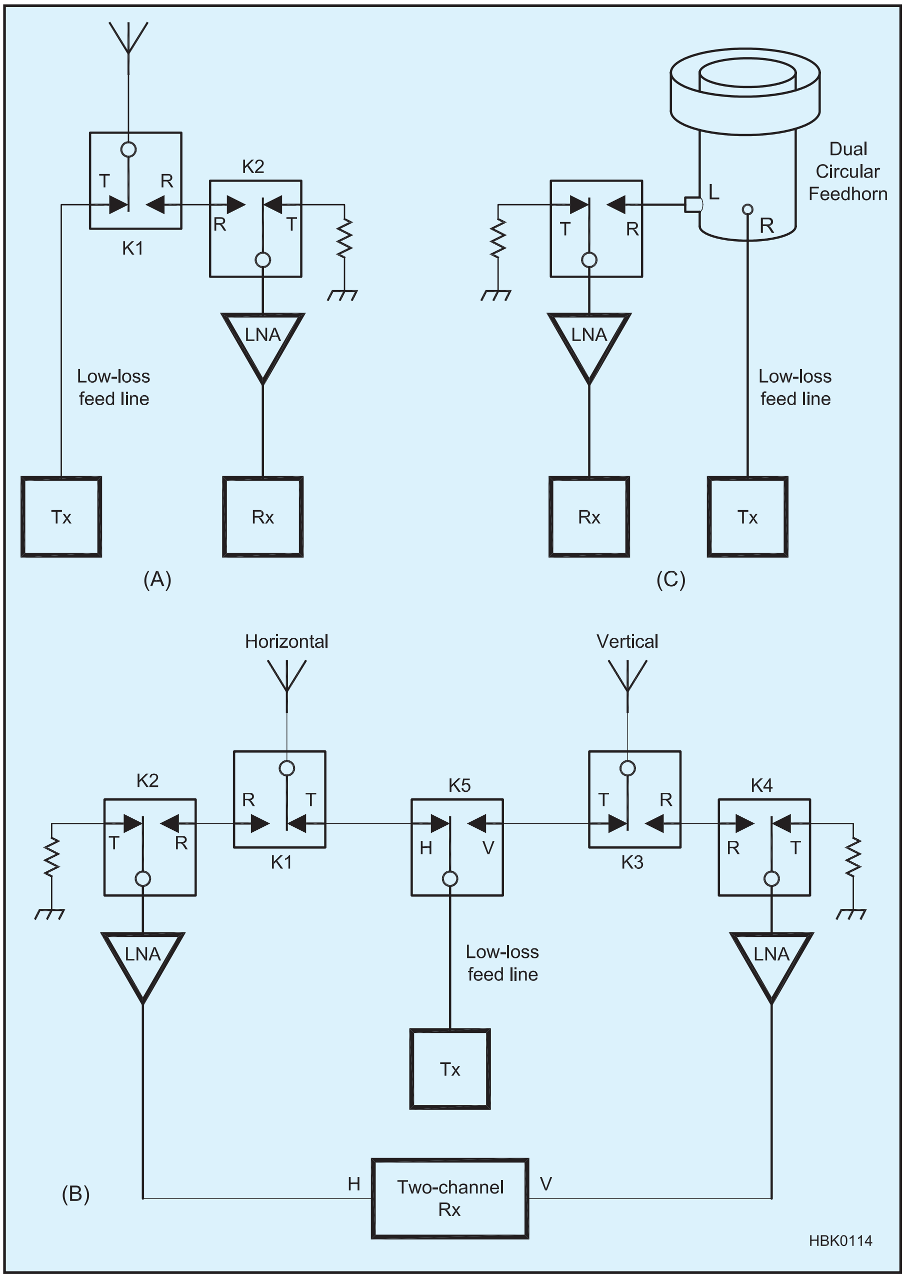


Figure 76 — Recommended "front ends" for EME systems include low-noise preamplifiers (LNAs) mounted at the antenna and use separate feed lines for transmitting and receiving. Relay K2 shown in (A) may be omitted if K1 provides adequate isolation of the LNA while transmitting. An arrangement like that in (B) is recommended for a dual-polarization antenna such as an array of cross-Yagis. Transmitter power is sent to one polarization or the other but received signals in both polarizations are amplified and sent on to a dual-channel receiver. Part (C) shows a suitable arrangement for circular polarization implemented with a two-port, dual-circular-polarization feed horn. In this case, no high-power TR relay is required.

POWER OUTPUT

After frequency stability, the most important specification for an EME transmitter is power output. The maximum power practically achievable by amateurs ranges from 1500 W on the VHF and lower UHF bands down to the 100 W range at 10 GHz. Fortunately, the required power levels for EME (Table 9) are compatible with these numbers. At 432 MHz and below, triode or tetrode vacuum tubes with external-anode construction can provide ample gain and power output. Some popular tubes include the 4CX250, 8930, 8874, 3CX800, 8877, GU-74B, GS-23B and GS-35B. Amplifiers using one or a pair of these (or other similar tubes) can provide output powers ranging up to 1,000 or 1,500 W on the 50 to 432 MHz bands. VHF and UHF power amplifiers based on solid state power devices have also become viable and attractive alternatives. Many amateurs have built solid-state power amplifiers (SSPAs) using these techniques, and commercial designs are available. **Figure 78** shows a kilowatt amplifier for 2 meters made by W6PQL.

At frequencies above 1 GHz, transit-time limitations and physical structures prevent most high-power vacuum tubes from performing well. For many years planar triodes in the 2C39/7289/3CX100 family were the mainstays of amateur 1296 MHz power amplifiers. These still work well, but today they are increasingly being replaced by SSPAs. As prices come down and power levels increase, these units are becoming more popular with EME operators. Surplus SSPAs usable on the 902, 2304 and 3456 MHz bands have been attractive buys in recent years, providing output power up to several hundred watts at reasonable cost. Two, four or even more units are sometimes used together to achieve higher output. SSPAs with at least 50 W output can be built and are available for the 5.7 and 10 GHz bands.

RF SAFETY

One final point must be made in a discussion of high-power amplifiers. Anyone who has thought about how a microwave oven works should know why RF safety is an important issue. Dangerous levels of radio frequency radiation exist inside and at short

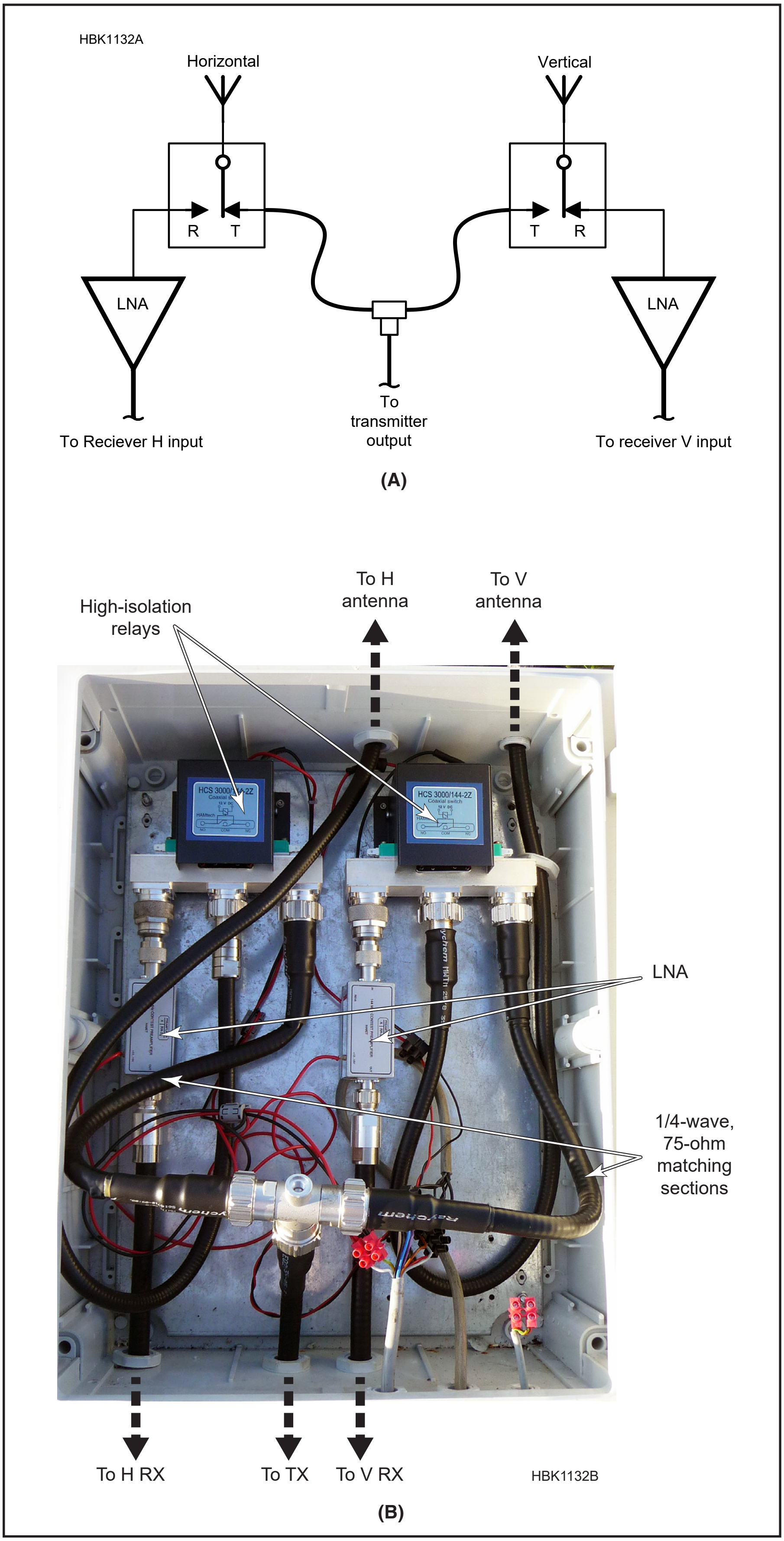
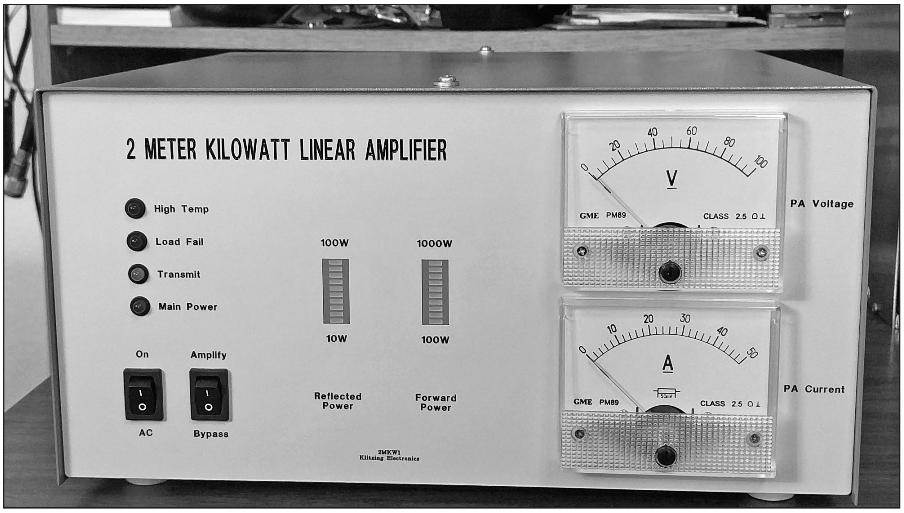
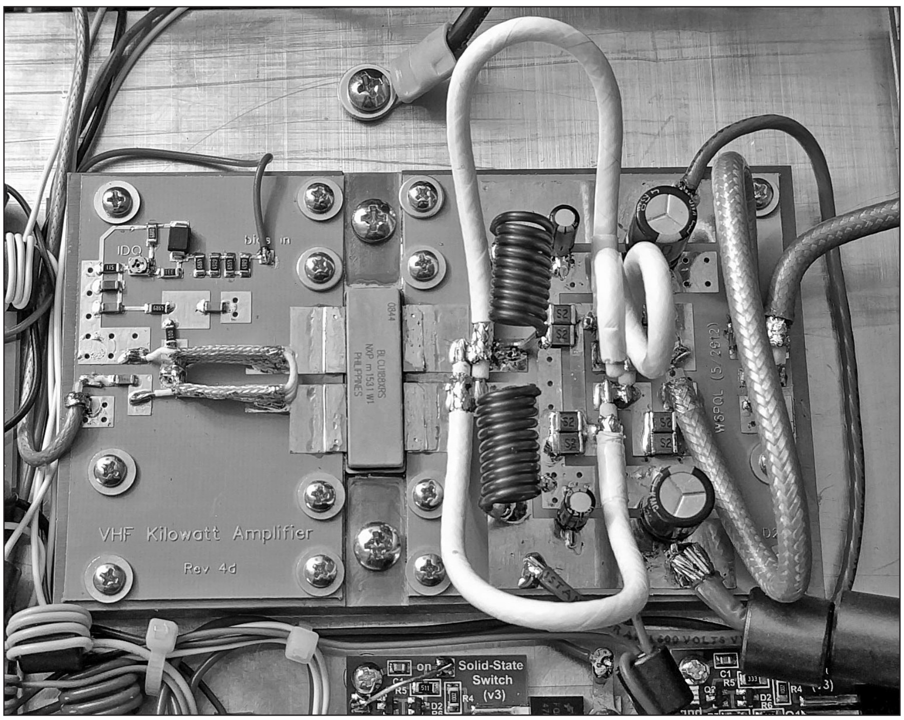


Figure 77 — A design to create circular polarization using ¼-wavelength lines (A) and constructed by DK5YA (B).

distances from power amplifiers and antennas. In normal operation, power density is highest in the immediate vicinity of small, low-gain antennas such as feeds for parabolic dishes. EME operators should be aware that ERP (effective radiated power) can be highly misleading as a guide to RF hazards. Somewhat counter-intuitively, a large, high-gain antenna helps to reduce local RF hazards by distributing RF power over a large physical area, thus reducing power density. Be sure to read the RF Safety section in the **Safe Practices** chapter and pay attention to the RF protection guidelines there.



(A)



(B)

Figure 78 — Solid-state power amplifier for 2 m built by W6PQL. (A) Outside cabinet view; (B) inside view showing the core of the amplifier.

12 Getting Started in EME

Perhaps you already have a weak-signal VHF or UHF station with somewhat lesser capabilities than those recommended in Tables 8 and 9 and would like to make a few EME contacts before possibly undertaking the task of assembling a "real" EME station. These aids may be all you need to make your first EME contacts, especially if you take advantage of the weak-signal capabilities of an efficient digital mode. You may want to try to make your first EME QSO on an audible mode such as CW or SSB. These modes take considerably more power and antenna gain than the digital modes and are not recommended for first-time EME operators.

On 144 and 432 MHz — probably the easiest EME bands on which to get started — you can visually point a single long-boom Yagi at the rising or setting Moon and copy some of the larger EME stations. With a transmitter of 100 watts or more, you should be able to work a few of them. Your daily newspaper probably lists the approximate times of moonrise and moonset in your vicinity; many simple web- or smartphone-based calculators can give you that information as well as the Moon's azimuth and elevation at any particular time (see the sidebar, Computer and Internet Resources for EME).

To optimize your chances of success, adapt your operating procedures to the prevailing standards that other EME operators will be using, as discussed below. For your first attempts you should plan to make prearranged schedules with some established stations.

12.1 Evaluating Your Station Capabilities

EME signals are very weak, and it is critical that your station be free from any noise sources or obstructions that block the Moon from view. You can start by listening in the weak-signal section of the band for distant beacon stations. You can use the *WSJT-X* software to test your location by observing the noise as you rotate your antenna. You may also be able to see the signals from distant beacons even if they are not audible. If you find noise sources in the directions when the Moon will be rising or setting you should fix those if possible.

At 144 MHz and higher, tree branches and foliage can attenuate signals significantly, so you should install your antenna where it is not blocked by trees. A flat foreground is very desirable because it will provide "ground gain" at certain takeoff angles and improve both your transmitting and receiving capability while the Moon is in those ground gain lobes. Most first-time EME operators do not have the luxury of antennas that can be tilted up to track the moon's path across the sky and are limited to operating at moonrise and moonset. However, it is necessary to track the moon's azimuth bearing as it rises or sets.

For 2-meter EME, you can test your receiving system by trying to detect the "GRAVES" radar located in France (grid locator JN27). This radar, operating on 143.050 MHz, transmits a continuous series of pulses about 1.6 seconds long, and with multiple kilowatts of power. The antenna pattern covers vertical takeoff angles from about 15 to 45 degrees of elevation and a wide range of azimuths, so if the Moon is in that range, the signal will reflect off the Moon and back to Earth. The actual mission of this radar is to track satellites and "space junk." However, amateurs have found it a useful resource for system testing — most 2-meter antennas still have sufficient gain to be effective at this frequency.

Single-Yagi stations with a few hundred watts of transmitter power can usually make EME QSOs with the larger stations, which have bigger antennas, full-power transmitters, and very sensitive receivers in quiet locations. Their station will be doing most of the work, but operators at these stations welcome newcomers and will patiently assist you. Perhaps the smallest station to make an EME QSO with amateur equipment at both ends was the QSO between MXØCNS and DL7APV in the 70 cm band. MXØCNS was using a dipole and 50 W transmitter power. DL7APV, on the other hand was running full power and an array of 128 11-element Yagis (yes, a 128-antenna array, see **Figure 79**).

Figure 79 — The 128-antenna 70 cm EME array of DL7APV. (Photo courtesy of Bernd Wilde, DL7APV.)

12.2 Getting Ready For a QSO

Once you have determined that your station is probably ready for an EME QSO, you need to take several steps.

First, you will need to download and install suitable software, such as *WSJT-X*. Then you need to connect your computer to your radio — either using the computer's audio inputs and outputs or via a USB connection of the radio supports it. Nearly all beginners use a digital mode to complete their first EME QSO. As this is being written in early 2022, the dominant modes are JT65 and Q65. Given the likely evolution of coding and modulation schemes to improve detection of weak signals, these modes may be replaced by newer modes at any time. Make sure your software is up to date. In addition to *WSJT-X* or similar software, you will need to set your computer's clock accurately. Several free programs are available for this — *Meinberg NTP* and *Dimension4* are the most popular.

Second, you should plan to operate on a day when conditions are optimum. Surprisingly, the Moon's orbit around the Earth is not exactly circular — the distance between Moon and Earth varies about ± 20% over a month, which changes the path loss by about ±2 dB. Furthermore, the Moon's orbit is inclined about 5 degrees relative to the orbit of the Earth around the Sun. The Earth is inclined about 23.5 degrees relative to the plane of its orbit. What that means is that moonrise occurs at a different azimuth and time every day. Sometimes the Moon rises in the daytime, sometimes in the evening. Obviously, if your antenna cannot "see" the moon, you won't have much success trying to bounce a signal off it. Similarly, the Moon must also be visible to a potential QSO partner.

Since the bigger EME stations have already worked most of the other bigger stations, they tend to operate during the best moon conditions to try to work smaller stations and avoid periods of poor conditions. For example, when the moon's position is in the same direction as the sun (a new moon), sun noise can cause problems for the bigger stations with large antennas and sensitive receivers. Similarly, at times of the month when the Moon is positioned toward the southern hemisphere, the period of moon visibility in the northern hemisphere is limited (and vice-versa).

EME conditions are summarized by the "Degradation" on a given day based on the Moon's orbit and position relative to the Sun, etc. The More Miles on VHF website (**mmmonvhf.de/eme.php**) shows the degradation for any selected date as shown in the screenshot in **Figure 80**.

Most EME QSOs are arranged either by advance schedule or in real-time on a "chat room." There are several chat rooms in use, and EME operators tend to gravitate to one for their band of interest. At present, the prevalent rooms for each band are:

50 MHz: **www.on4kst.com/index.php**
144 MHz: **www.chris.org/cgi-bin/jt65emeA**
432 MHz and up: **hb9q.ch/logger**

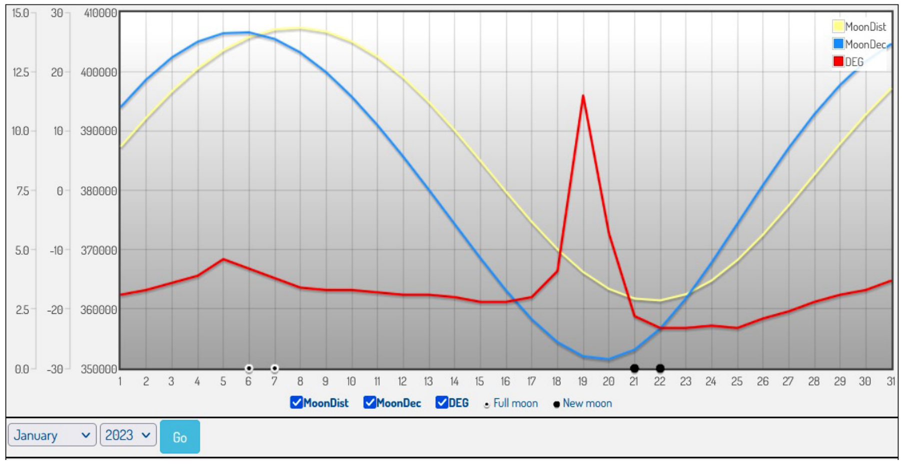
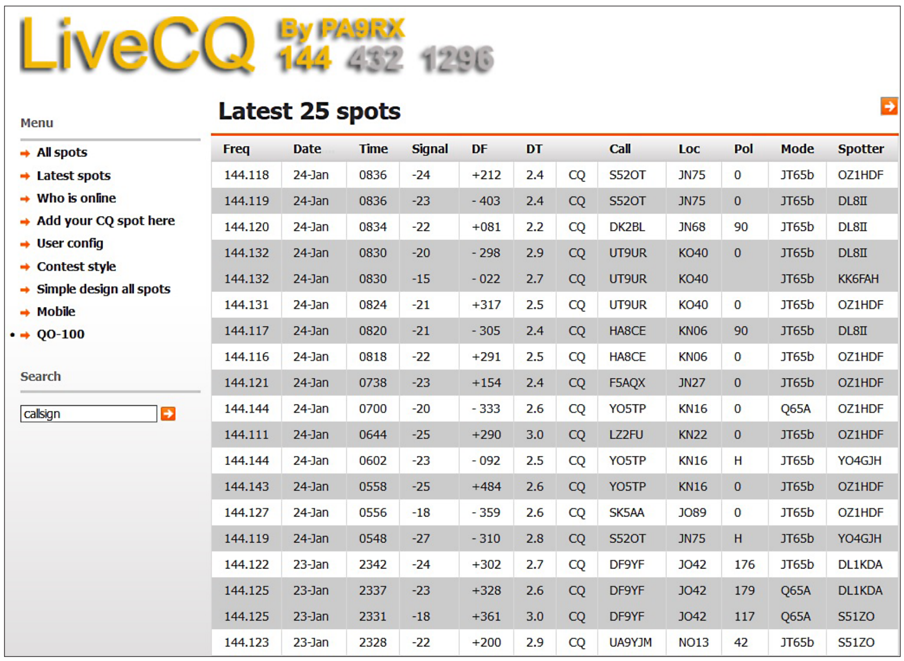


Figure 80 — Screenshot of the More Miles on VHF web page for lunar degradation.



Freq	Date	Time	Signal	DF	DT		Call	Loc	Pol	Mode	Spotter
144.118	24-Jan	0836	-24	+212	2.4	CQ	S52OT	JN75	0	JT65b	OZ1HDF
144.119	24-Jan	0836	-23	- 403	2.4	CQ	S52OT	JN75	0	JT65b	DL8II
144.120	24-Jan	0834	-22	+081	2.2	CQ	DK2BL	JN68	90	JT65b	DL8II
144.132	24-Jan	0830	-20	- 298	2.9	CQ	UT9UR	KO40	0	JT65b	DL8II
144.132	24-Jan	0830	-15	- 022	2.7	CQ	UT9UR	KO40		JT65b	KK6FAH
144.131	24-Jan	0824	-21	+317	2.5	CQ	UT9UR	KO40	0	JT65b	OZ1HDF
144.117	24-Jan	0820	-21	- 305	2.4	CQ	HA8CE	KN06	90	JT65b	DL8II
144.116	24-Jan	0818	-22	+291	2.5	CQ	HA8CE	KN06	0	JT65b	OZ1HDF
144.121	24-Jan	0738	-23	+154	2.4	CQ	F5AQX	JN27	0	JT65b	OZ1HDF
144.144	24-Jan	0700	-20	- 333	2.6	CQ	YO5TP	KN16	0	Q65A	OZ1HDF
144.111	24-Jan	0644	-25	+290	3.0	CQ	LZ2FU	KN22	0	JT65b	OZ1HDF
144.144	24-Jan	0602	-23	- 092	2.5	CQ	YO5TP	KN16	H	JT65b	YO4GJH
144.143	24-Jan	0558	-25	+484	2.6	CQ	YO5TP	KN16	0	JT65b	OZ1HDF
144.127	24-Jan	0556	-18	- 359	2.6	CQ	SK5AA	JO89	0	JT65b	OZ1HDF
144.119	24-Jan	0548	-27	- 310	2.8	CQ	S52OT	JN75	H	JT65b	YO4GJH
144.122	23-Jan	2342	-24	+302	2.7	CQ	DF9YF	JO42	176	JT65b	DL1KDA
144.125	23-Jan	2337	-23	+328	2.6	CQ	DF9YF	JO42	179	Q65A	DL1KDA
144.125	23-Jan	2331	-18	+361	3.0	CQ	DF9YF	JO42	117	Q65A	S51ZO
144.123	23-Jan	2328	-22	+200	2.9	CQ	UA9YJM	NO13	42	JT65b	S51ZO

Figure 81 —Screenshot of the LiveCQ.eu web page for EME operation.

12.3 Choosing a QSO Partner

Once you have determined that you are ready, you should try to copy one of the bigger stations. You can tune your receiver through the normal frequency ranges used for EME, which are, in MHz:

50.190 +/-
144.100 – 144.150
432.060 – 432.090
1296.050 – 1296.090

However, it is much more productive to tune where stations are known to be transmitting. The website **liveCQ.EU** (see **Figure 81**) shows the current activity on 144, 432, and 1296 MHz. The site is fed by receivers around the world and shows the signals being heard calling CQ on each band, including the call sign, operating mode, and polarization at the receiving site.

In this example there are several stations showing received signal/noise ratios better than –20 dB. Reaching out to one of them on a chat room and asking for a test is the first step. Let's say you choose UT9UR and he agrees to a test. You would set your radio to the frequency indicated (144.132 MHz), set the TX tone frequency for 1270 Hz, and set your software to transmit on the 2nd period (odd minutes) since UT9UR is transmitting on the 1st period (even minutes). Confirm that your software is set up for the mode he is using (in this case, JT65B). For EME, the "Sh" (Shorthand) box should be checked. This generates simple two-tone signals for the signal report messages that are more easily detectable and easily visible on the waterfall display.

If you are able to copy him, then you would call him with the TX1 message ("UT9UR W1AW FN31"). If he copies you, he will respond with the TX2 message ("W1AW UT9UR KO40 OOO"). "O" is the traditional EME signal report signifying that both call signs have been copied. In JT65B, it is repeated three times. If you are able to copy that transmission, your response would be "RO" ("I have received your O message, and am sending you O in return"). If that transmission is received, UT9UR will respond with "RRR" ("I have received your report"). At that point the QSO is complete, but many stations choose to add a transmission of "73" as a courtesy (see **Table 10**).

Once you begin a QSO attempt, you should not correspond on the chat room while the QSO is in progress. If the QSO is not progressing smoothly, you may ask the other station if you should continue. He may reply that he is not seeing your signal and suggest trying again another time. Or he may suggest continuing for some additional length of time. However, it is considered inappropriate to ask "Did you copy my RO?" Once the required QSO information has been exchanged, it is then appropriate to thank the other station on the chat room.

The procedure for making a QSO using the newer Q65 protocol is similar but with a few differences. First, both QSO partners should agree on the mode and transmission period. On 144 MHz, Q65A-60 (mode A, 60-second periods) is most often used. The TX tone is set for 1500 Hz. On the lower bands (50, 144, and 432 MHz), the "shorthand" messages are usually not used, and actual signal reports are used instead. Shorthand messages are often used on higher frequency bands; TX4 is replaced by a single tone at 1500Hz and TX5 is replaced by a single tone at 1750 Hz See **Table 11**).

12.4 If You Are Unsuccessful

Don't give up! EME is very challenging, and everything has to be just right to make a two-way QSO. Even when things are right, it is common for polarization issues (spatial and Faraday rotation) to prevent a QSO from completing quickly. Aside from those effects, which just require patience, there are several common problems encountered by first-time EME-ers.

First, if you are not *seeing* stations (their signal visible on a waterfall display) and they are not seeing you, it is either because your antenna is not pointed at the Moon, your antenna system needs improvement, or you have too much local noise. The first problem can be tested by visually checking that the antenna is pointed where you think it is.

If the antenna is aimed correctly, you need to carefully evaluate your entire antenna system. At VHF, parameters that can be ignored at HF become major sources of system shortcomings. Most common coaxial feed lines are very lossy in the VHF range, especially if they are long. For example, a 100-foot run of LMR-400 coaxial cable has loss of about 1.5 dB at 144 MHz. Replacing such a cable with ⅞-inch hardline such as LDF5-50A would reduce the loss to less than 0.5 dB. In EME work, 1 dB is a significant difference.

Most receivers are not quite sensitive enough for EME work without a *low-noise preamplifier* (LNA). If the feed line is short and has low enough loss, a preamp in the station can help. If the feed line is long and /or lossy, the LNA should be located at the antenna. Of course, that will require a relay at the antenna to switch between transmit and receive. You will also need a *sequencer* to make sure the preamplifier has been switched out of line before transmission begins. (Sequencers are discussed in the **Transceiver Design Topics** chapter's section on Transverters.)

If you are seeing signals on the waterfall display, but not decoding them, check the software settings. Confirm that you have the correct mode selected, and the "Decode after EME Delay" box checked. You can also be fooled by a trace that looks like a signal but is actually a spurious signal generated by something else in your local environment. You can tell the difference by observing whether the signal stops at about 10 seconds before the end of a minute. If the signal is continuous, it is not an EME signal. You will also need to confirm that the software is looking on the right tone frequency — usually clicking on the visible trace will shift the software to focus its decoding on that tone. You can also narrow the receive bandwidth to improve sensitivity.

If you are decoding stations but they are not seeing your signal trace or decoding you, you should verify that your transmitter is delivering power to the antenna on the right

Table 10
Message Sequence for JT65B EME Contact

Time		Message	Meaning
XXXX (Even minute)	TX6	CQ UT9UR KO40	UT9UR is calling CQ
XXXX+1 (Odd minute)	TX1	UT9UR W1AW FN31	W1AW is calling UT9UR
XXXX+2	TX2	W1AW UT9UR KO40 OOO	UT9UR answers W1AW with a report of **O** (repeated x3)
XXXX+3	TX3	RO	W1AW has **R**eceived UT9UR's report and is replying with a report of **O**
XXXX+4	TX4	RRR	UT9UR acknowledges **R**eceiving W1AW's report
XXXX+5	TX5	73	W1AW sends best regards

Table 11
QSO Sequence for Q65A-60 EME Contact

Time		Message	Meaning
XXXX (Even minute)	TX6	CQ UT9UR KO40	UT9UR is calling CQ
XXXX+1 (Odd minute)	TX1	UT9UR W1AW FN31	W1AW is calling UT9UR
XXXX+2	TX2	W1AW UT9UR -25	UT9UR answers W1AW and gives a report of –25dB
XXXX+3	TX3	R-20	W1AW has Received UT9UR's report and is replying with a report of –20dB
XXXX+4	TX4	RR73	UT9UR acknowledges receipt of W1AW's report
XXXX+5	TX5	73	W1AW sends best regards

frequency when you transmit. It is possible that your station simply does not have enough output power to bounce a signal off the Moon and back to Earth. The solution here is to either improve the antenna system (including replacing a lossy feed line), add more power, or try again with another QSO partner that may be in a quieter location or have a better receiving setup.

12.5 Getting Serious with EME

If you are successful in making one EME contact, perhaps you find it interesting enough to want to try for more. This will require upgrading your station to be able to work stations other than the "big guns." Incremental upgrades can be made over a period of time, depending on your time and budget constraints.

UPGRADING THE ANTENNA SYSTEM

The biggest improvement in EME station performance almost always comes from improving the antenna system. The ARRL *Antenna Book* includes numerous examples of highly effective EME antenna systems and advice on construction.

The first upgrade involves adding elevation control capability to the antenna so that it can be pointed at the Moon as it traverses the sky. This allows operation at times other than moonrise and moonset. For small arrays, rotators intended for amateur satellite use are sufficient. For larger arrays, several commercial elevation (or combination azimuth-elevation) rotators are available. Operators with good mechanical construction skills often build their own home-brew units using surplus components from TV satellite or solar array positioners.

The second upgrade is improving the antenna itself. There are many options here. One option is to simply replace the original Yagi with a longer one with more elements. This will provide more gain and narrower beamwidth, which reduces noise pickup. Another option is to add another Yagi identical to the original antenna and phase the two antennas. This also increases the gain and reduces the beamwidth but requires precisely matched phasing lines to connect the two antennas.

It is very common to use a 4-Yagi array, arranged in an H configuration, with the Yagis stacked both vertically and horizontally. This results in more gain and makes the beamwidth narrower in both vertical and horizontal planes, reducing noise pickup. Of course, the narrower beamwidth requires accurate positioning, and a positioning system capable of tracking the Moon automatically is helpful. Construction of such an array takes some planning but can yield excellent results.

Sometimes a station using an array of four horizontally polarized Yagis will be unable to complete an EME contact due to Faraday rotation and spatial polarization differences. The solution to this problem is to use antennas with both vertical and horizontal polarization (cross-polarized, or "XPOL"), and switch between them to find the optimum choice. It is often necessary to transmit on one polarization and receive on the other.

The tradeoff of longer single-polarization Yagis vs. shorter cross-polarized Yagis is that the longer Yagis (with higher gain) will be capable of working more (and smaller) stations, but due to polarization mismatches, those QSOs may take longer to complete. In contrast, using shorter Yagis with both polarizations will allow QSOs to complete faster, but will limit the number of stations that are workable.

Remember that the antenna system includes the antennas, phasing lines, connectors, relays, and feed lines. Each one of these often-overlooked elements should be carefully considered to make sure it is not limiting the station performance.

ADDING A PREAMPLIFIER

The best placement for a preamp/LNA is at the antenna end of the feed line. Any loss in the feed line before a preamp adds directly to the system noise figure and compromises the performance. The effect of feed line loss after a preamp is reduced by the gain of the preamp and usually becomes negligible. Typical LNAs for EME work have noise figures of less than 0.5 dB, and gain of 20 dB or more.

The sensitive front end of a VHF/UHF preamp can be damaged by leakage from the transmitter, so a relay is necessary to bypass the preamp during transmitting periods. This relay should have high enough isolation to prevent damage to the preamp or be arranged such that the preamp input is connected to a low-impedance source such as a 50-Ω dummy load when the transmitter is active. As mentioned earlier, a sequencer is required to ensure that the preamp is in a safe condition before transmission begins.

ADAPTIVE RECEIVING

If your antenna system includes both horizontal and vertical polarization, you can use two receivers to listen on both simultaneously. Software such as *MAP65* allows two receivers to be connected and will determine the incoming polarization of signals being received and avoid missing a signal due to receiving on the wrong polarization. This also allows the operator to choose the best polarization for transmission.

CIRCULAR POLARIZATION

If both polarizations are available, you can arrange the transmission path to utilize both by using circular polarization. This requires a 90-degree phase shift between horizontal and vertical elements, either through a coaxial delay line or by mechanically offsetting the H and V elements by ¼ wavelength. This has the advantage of constantly rotating the polarization of the transmitting signal which eliminates fading due to polarization effects but also reduces the effective power in each polarization by 3 dB.

IMPROVING THE EQUIPMENT

Finally, the equipment in the station can be improved. Some transceivers and transverter-based systems have too much drift for digital EME modes. Adding a GPS-locked reference oscillator can eliminate frequency drift. This improves receiver sensitivity and makes the transmitted signal easier for other stations to decode.

Higher transmitter power is an easy upgrade, using a commercial or home-brew amplifier. A sequencer then becomes even more critical to make sure the amplifier T/R relays are in the correct position before the transceiver begins to transmit.

Some EME operators have chosen to use dedicated optimized digital receivers rather than use the audio inputs and outputs built-in to their PCs. Such receivers usually connect to the PC via a USB port and can provide lower noise and fewer spurious tones in the receive spectrum, improving receiver performance.

USING ANALOG MODES FOR EME

As mentioned earlier, digital-mode EME is much easier than using legacy analog modes such as CW or SSB voice. The requirements for power, receiver sensitivity, and antenna gain are significantly higher than for digital EME. The QSO protocol is similar to that used for digital EME, with slight differences. The fading in EME signals usually requires that CW signals be copied by ear rather than by a code reader.

The more that's known about the likely structure, content and timing of a transmitted message, the easier it is to copy. EME signals are often near the threshold of readability, so it is highly desirable to standardize operating procedures and message structure, and to provide transmissions with enough redundancy to capitalize on signal peaks and bridge likely gaps in reception.

As with digital EME, you may wish to make your first EME QSOs with the aid of explicit schedules: that is, arrangements to attempt a contact with a particular station at a specified time and frequency. As with digital EME, QSO partners need to agree on the duration of timed transmissions as well as starting time, transmitter frequency, and an indication of which station will transmit first. For a minimal QSO, message information is often reduced to the bare essentials of call signs, signal reports, and acknowledgments. The signal report is sometimes reduced to a "yes or no" indication of whether both call signs have been successfully copied. Remember to allow for Doppler shift, especially at higher frequencies where the offset may exceed your receiver bandwidth.

Most moon-tracking software used for EME can display the expected frequency shift for your own echoes as well as that for a distant station. In a scheduled QSO attempt, keep your transceiver set to the schedule frequency and use its RIT control to search for the other station around their expected Doppler shift.

When looking for non-scheduled random contacts, especially at 432 MHz and above, set your RIT to the expected Doppler shift of your own echoes. If a station you copy does likewise, you will find each other's signals on the same frequency as your own echoes. Many operators also benefit from using a waterfall display, which can make signal acquisition much easier. The *WSJT-X* program, widely used for digital EME, can be configured to compensate for EME Doppler shifts automatically with most transceivers.

CW activity on the 144 MHz band, as well as EME activity on higher bands in any mode, tends to be concentrated in activity weekends scheduled once each month when the Moon is in a favorable location. After 144 MHz, the bands with most EME activity are 1296 and 432 MHz. On those bands random CW (and occasionally SSB) activity is mostly found between 5 and 30 kHz above the nominal sub-band boundary (for example, between 1296.005 and 1296.030).

Table 12
Typical Messages in a Minimal EME CW Contact

Period	*Message*
1	CQ CQ CQ DE W6XYZ W6XYZ …
2	W6XYZ DE K1ABC K1ABC …
3	K1ABC DE W6XYZ OOO OOO …
4	W6XYZ DE K1ABC RO RO RO …
5	K1ABC DE W6XYZ RRR RRR …
6	W6XYZ DE K1ABC TNX 73 …

CW EME QSO FORMAT

By convention, a minimal CW EME contact usually follows a format something like the sequence of messages in **Table 12**. If timed T-R sequences are being used, the essential information is repeated for the full duration of a sequence. The standard QSO procedures involve a number of different messages sent in sequence, and operators do not proceed to the next message until they have copied the essential information (call signs, signal reports, acknowledgements) in previous messages.

After call signs have been copied, a signal report is sent. Because CW dahs are easier to discern than dits, a default EME signal report (essentially meaning "I have copied both call signs") is the letter O. A station receiving call signs and O responds with RO, and a final acknowledgment of a valid contact is signified by sending RRR. On 432 MHz and above, the letter M is sometimes used as an alternative signal report meaning "both call signs copied with difficulty." Of course, when signals are adequate for reasonably good copy, normal RST signal reports can be used and other restrictions on message structure and timing relaxed.

In non-scheduled operation, it frequently happens (for example, in response to your CQ) that you can recognize and copy your own call more easily than the other station's call. The sequence YYY… (for "Your call") can be sent to ask a calling station to send their call only, repeating it many times. A contact is considered complete and valid when RRR has been received (after message number 5 in Table 10 has been received). However, at this point the other station does not know that their acknowledgment was copied, so it is normal to finish with something like message 6.

The conventional duration of transmit and receive periods is different on different bands and has evolved somewhat over time. On 50 and 144 MHz, stations usually transmit for one full minute and then receive for a full minute. On 432 MHz and above, schedules with 2.5-minute transmissions have been standard. The longer period gives stations with mechanically variable polarization adequate time to peak a received signal.

CW sending speed is generally around 12 to 15 WPM. Some operators find it helpful to use greater than normal spacing between complete letters. Keep in mind that characters sent too slowly may be chopped up by typical EME fading, while code sent too fast will be jumbled. When transmitting call sequences, send the other station's call once, followed by "DE" and your own call once or twice. Then pause and repeat the sequence. This cadence sets a rhythm so that the receiving operator can anticipate when the missing parts of a message can be expected to arrive. Send with proper spacing; the use of a programmable keyer or computer keyboard-to-Morse program is especially helpful and encouraged. A signal buried in the noise and accompanied by fading is hard enough to copy without the added complication of irregular sending.

13 Digital EME

Since 2003 most EME work has been done using the JT65 protocol as implemented in computer programs *WSJT*, *MAP65*, and most recently W*SJT-X* (see the sidebar, "Computer and Internet Resources for EME"). Like other popular digital modes, digital EME requires a personal computer with a sound card for audio input and output. The *WSJT-X* family of protocols use structured message formats, error-correcting code with redundancy, and relatively long T/R sequences. Signal peaks and dropouts due to multipath fading do not affect individual characters or words, but rather the probability of decoding the whole message.

Digital EME uses the *WSJT-X* "Slow Modes" of JT65 and Q65. (See the **Digital Protocols and Modes** chapter for detailed information and see **Tables 13** and **14**) The modulation in both is 65-tone frequency shift keying (65-FSK) with computer-generated audio tones modulating a single-sideband transmitter in USB mode. As expected from theory, results show that JT65 contacts can be made at signal levels more than 10 dB below those needed for CW. Q65 has been shown to be another 2 – 3 dB better than JT65. Another mode, known as QRA64, was promoted for a few years, but the signal structure did not include a sync tone that was visible on the waterfall display, so it never became popular.

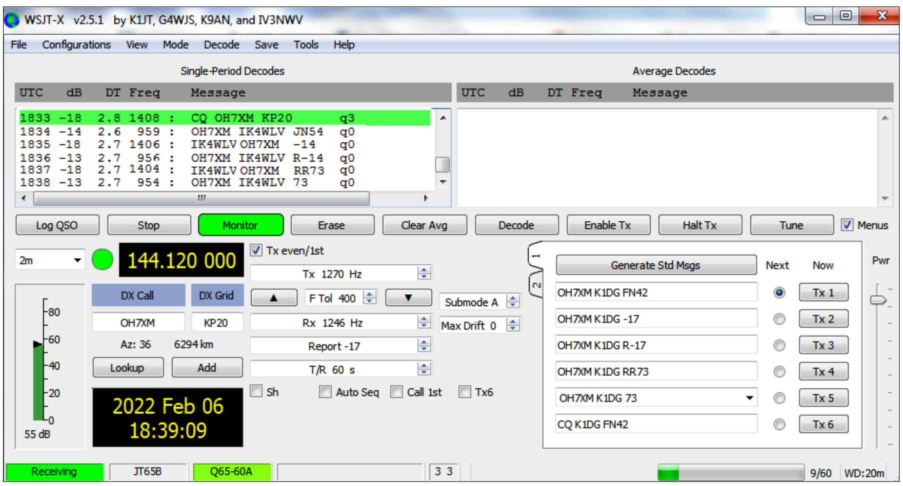


Figure 82 — Screenshot showing EME JT65B QSO between OH7XM and IK4WLV. At the top, OH7XM calls CQ, is answered by and responds to IK4WLV, and both stations exchange closing acknowledgements.

In JT65, it is standard practice on EME to use shorthand messages for RO, RRR, and 73. These messages are transmitting as pairs of alternating tones using time intervals of 16384/11025 = 1.486 seconds. The lower frequency is the same as that of the sync tone used in long messages, and the frequency separation is 110250/4096 = 26.92 Hz multiplied by n for JT65A, with n = 2, 3, and 4 used to convey the messages RO, RRR, and 73, respectively. In the Q65 modes, shorthand is usually not necessary and actual signal reports are used instead. **Figure 82** shows a typical EME QSO in JT65B.

Preferred modes for EME work on each band are:

- 50 MHz: Q65A-60
- 144 MHz: JT65B, Q65A-60
- 432 MHz: JT65B, Q65B-60
- 1296 MHz: Q65B-30, Q65C-60

The basic parameters of JT65 and Q65 for each of the T/R sequence length and minimum tone spacing submodes are summarized in the tables below. Threshold sensitivities (SNR in a 2500 Hz bandwidth yielding 50% probability of decode) were measured for each submode using simulations over the *additive white Gaussian noise* (AWGN) channel. As with other recently developed modes in *WSJT-X*, a feature called *a priori* (AP) decoding improves sensitivity in Q65 by several additional dB as information is accumulated during a standard minimal QSO.

Table 13 Basic Parameters of JT65 and Q65 Signals Used for Digital EME

Mode	*FEC Type**	*Keying Rate (baud)*	*Bandwidth (Hz)*	*Sync energy Duration, s*	*Transmission*	*SNR (dB)*	*SNR AP (dB)*
JT65A	RS	2.692	177.6	50%	46.8	–25	n/a
JT65B	RS	5.383	352.6	50%	46.8	–25	n/a
JT65C	RS	10.767	702.5	50%	46.8	–25	n/a
Q65-15A	QRA	6.667	433	26%	12.8	–22.2	–23.7
Q65-30A	QRA	3.333	217	26%	25.5	–24.8	–26.6
Q65-60A	QRA	1.667	108	26%	51.0	–27.6	–30.2
Q65-120A	QRA	0.750	49	26%	113.3	–30.8	–32.5
Q65-300A	QRA	0.289	19	26%	293.8	–33.8	–36.4

*(FEC) Forward Error Correction types: RS = Reed-Solomon; QRA = Q-ary Repeat Accumulate

Table 14 Expanded Key Parameters of Q65 sub-modes

T/R Period (s)	**Q65A**		**Q65B**		**Q65C**		**Q65D**		**Q65E**	
	Symbol spacing (Hz)	*Bandwidth (Hz)*	*Symbol spacing (Hz)*	*Bandwidth (Hz)*	*Symbol spacing (Hz)*	*Bandwidth (Hz)*	*Symbol spacing (Hz)*	*Bandwidth (Hz)*	*Symbol spacing (Hz)*	*Bandwidth (Hz)*
15	6.67	433	13.33	867	26.67	1733	N/A		N/A	
30	3.33	217	6.67	433	13.33	867	26.67	1733	N/A	
60	1.67	108	3.33	217	6.67	433	13.33	867	26.67	1733
120	0.75	49	1.50	98	3.00	195	6.00	390	12.00	780
300	0.29	19	0.58	38	1.16	75	2.31	150	4.63	301

14 EME References

Åsbrink, L., "Linrad Home Page" **www.sm5bsz.com/linuxdsp/linrad.htm**.

Åsbrink, L., SM5BSZ, "Linrad: New Possibilities for the Communications Experimenter," *QEX*, Part 1, Nov./Dec. 2002; Part 2, Jan./Feb. 2003; Part 3, May/Jun. 2003; Part 4, Sep./Oct. 2003.

Åsbrink, L., "Linrad with High Performance Hardware," *QEX*, Jan./Feb. 2004, pp. 20 – 31.

Åsbrink, L., SM5BSZ, "The '+' Configuration vs. the 'X' Configuration," **www.sm5bsz.com/polarity/simplesw.htm**.

Franco, M., N2UO, "Computer Optimized Dual Mode Circularly Polarized Feedhorn," in *Microwave Update 2008*, ARRL, 2008, and **ok1dfc.com/EME/technic/septum/N2UO%20opt.pdf**

Halliday, D., KD5RO (now K2DH), "Microwave EME Using a Ten-Foot TVRO Antenna," *The ARRL UHF/Microwave Projects Manual*, Vol 1, 1996.

Klitzing, J., W6PQL, **www.w6pql.com/1_kw_2m_ldmos_amplifier.htm**.

Kollner, G., DL4MEA, "Designing a Super-VE4MA feed horn for 23 cm and 13 cm," *Dubus,* 1/2007, p. 33.

Mataka, Y., JA4BLC, "Full Spectrum Receiver for 13 cm EME," *Dubus* 3/2005, p. 21.

Taylor, J., K1JT, "The JT65 Communications Protocol," *QEX*, Sep./Oct. 2005, pp. 3 – 12.

Taylor, J., K1JT, "MAP65 Version 2: A Panoramic, Polarization-Matching Receiver for JT65," in 15th International EME Conference, Cambridge, England, August 2012); also available at **physics.princeton.edu/pulsar/K1JT/K1JT_EME2012.pdf**.

Wade, P., W1GHZ, "VE4MA and Chaparral feeds with Septum Polarizers," **www.w1ghz.org/antbook/conf/VE4MA_Chaparral_septum_feeds.pdf**.

15 Glossary of Space Communications Terminology

AMSAT — A registered trademark of the Radio Amateur Satellite Corporation, a non-profit scientific/educational organization located in Washington, DC. It builds and operates Amateur Radio satellites and has sponsored the OSCAR program since the launch of OSCAR 5. (AMSAT, 712 H Street NE, Ste 1653 Washington DC, 20002. **info@amsat.org**)

Q65 — One of the modes in the WSJT family of digital modes.