Repeaters, Satellites, EME and Direction Finding

23

Repeaters

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In the late 1960s two events occurred that changed the way radio amateurs communicated. The first was the explosive advance in solid state components — transistors and integrated circuits. A number of new "designed for communications" integrated circuits became available, as well as improved high-power transistors for RF power amplifiers. Vacuum tube-based equipment, expensive to maintain and subject to vibration damage, was becoming obsolete.

At about the same time, in one of its periodic reviews of spectrum usage, the Federal Communications Commission (FCC) mandated that commercial users of the VHF spectrum reduce the deviation of truck, taxi, police, fire and all other commercial services from 15 kHz to 5 kHz. This meant that thousands of new narrowband FM radios were put into service and an equal number of wideband radios were no longer needed.

As the new radios arrived at the front door of the commercial users, the old radios that weren't modified went out the back door, and hams lined up to take advantage of the newly available "commercial surplus." Not since the end of World War II had so many radios been made available to the ham community at very low or at least acceptable prices. With a little tweaking, the transmitters and receivers were modified for ham use, and the great repeater boom was on.

WHAT IS A REPEATER?

Trucking companies and police departments learned long ago that they could get much better use from their mobile radios by using an automated relay station called a repeater. Not all radio dispatchers are located near the highest point in town or have access to a 300-ft tower. But a repeater, whose basic idea is shown in **Fig 23.1**, can be more readily located where the antenna system is as high as possible and can therefore cover a much greater area.

Types of Repeaters

The most popular and well-known type of amateur repeater is an FM voice system on the 29, 144, 222 or 440-MHz bands. Tens of thousands of hams use small 12-V powered radios in their vehicles for both casual ragchewing and staying in touch with what is going on during heavy traffic or commuting times. Others have low-power battery-operated hand-held units, known as "handi-talkies" or "HTs" for 144, 222 or 440 MHz. Some mobile and hand-held transceivers operate on two bands. But there are several other types of ham radio repeaters. **Table 23.1** describes them.

FM is the mode of choice, as it was in commercial service, since it provides a high degree of immunity to mobile noise pulses. Operations are *channelized* — all stations operate on the same transmit frequency and receive on the same receive frequency. In addition, since the repeater receives signals from mobile or fixed stations and retransmits these signals simultaneously, the transmit and receive frequencies are different, or *split*. Direct contact between two or more stations that listen and transmit on the same frequency is called operating *simplex*.

Individuals, clubs, amateur civil defense support groups and other organizations all sponsor repeaters. Anyone with a valid amateur license for the band can establish a repeater in conformance with the FCC rules. No one owns specific repeater frequencies, but nearly all repeaters are *coordinated* to minimize repeater-to-repeater interference. Frequency coordination and interference are discussed later in this chapter.

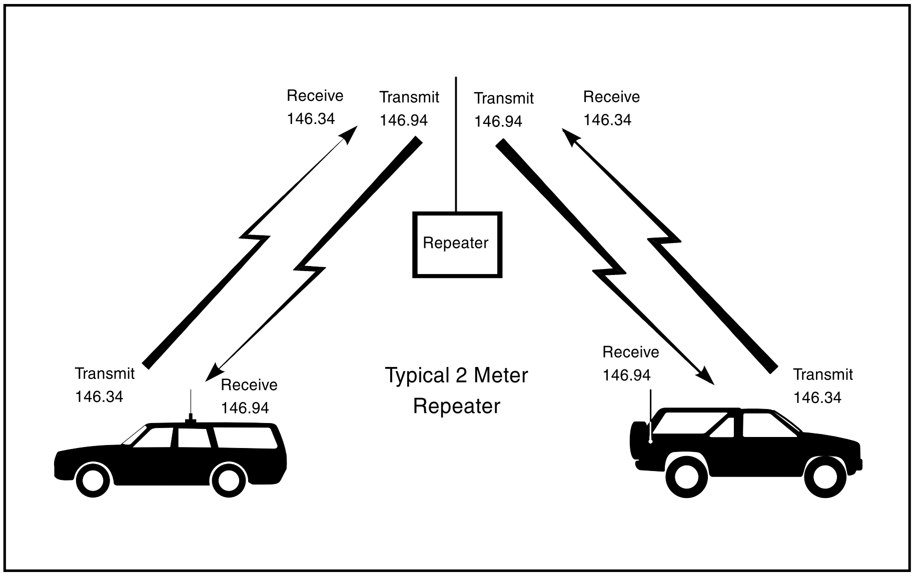


Fig 23.1 — Typical 2-m repeater, showing mobile-to-mobile communication through a repeater station. Usually located on a hill or tall building, the repeater amplifies and retransmits the received signal on a different frequency.

Table 23.1
Types of Repeaters

ATV — Amateur TV	Same coverage advantages as voice repeaters to hams using wideband TV in the VHF and UHF bands. Often consist of pairs of repeaters — one for the ATV and the other for the voice coordination.
AM and SSB	There is no reason to limit repeaters to FM. There are a number of other modulation-type repeaters, some experimental and some long-established.
Digipeaters	Digital repeaters used primarily for packet communications (see the **Modes** chapter). Can use a single channel (single port) or several channels (multi-port) on one or more VHF and UHF bands.
Multi-channel (wideband)	Amateur satellites are best-known examples. Wide bandwidth (perhaps 50 to 200 kHz) is selected to be received and transmitted so all signals in bandwidth are heard by the satellite (repeater) and retransmitted, usually on a different VHF or UHF band. Satellites are discussed elsewhere in this chapter. Although not permitted or practical for terrestrial use in the VHF or UHF spectrum, there is no reason wideband repeaters cannot be established in the microwave region where wide bandwidths are allowed. This would be known as frequency multiplexing.

Block Diagrams

Repeaters normally contain at least the sections shown in **Fig 23.2**. After this, the sky is the limit on imagination. As an example, a remote receiver site can be used to try to eliminate interference (**Fig 23.3**).

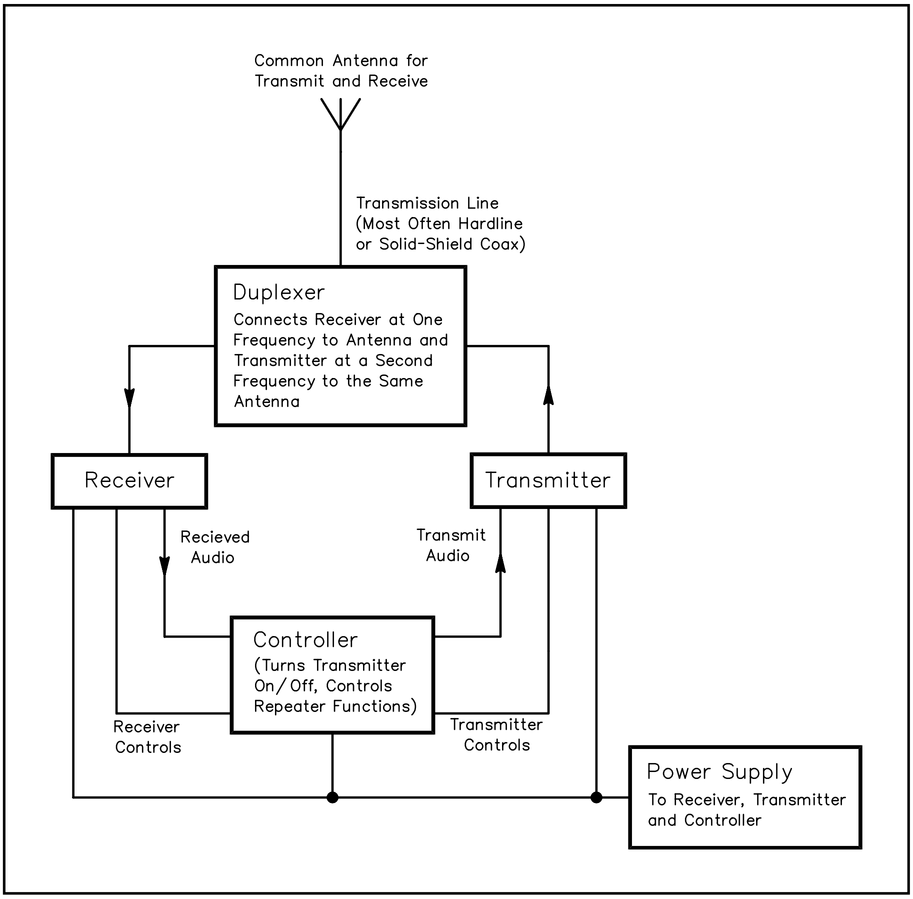


Fig 23.2 — The basic components of a repeater station. In the early days of repeaters, many were home-built. These days, most are commercial, and are far more complex than this diagram suggests.

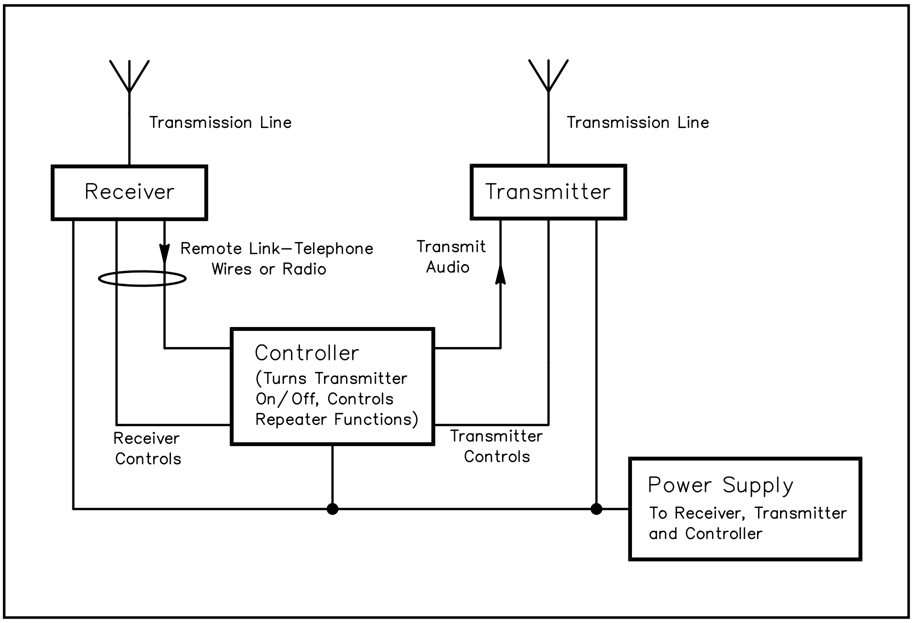


Fig 23.3 — Separating the transmitter from the receiver helps eliminate certain types of interference. The remote receiver can be located on a different building or hill, or consist of a second antenna at a different height on the tower.

The two sites can be linked either by telephone (“hard wire”) or a VHF or UHF link. Once you have one remote receiver site it is natural to consider a second site to better hear those “weak mobiles” on the other side of town (**Fig 23.4**). Some of the stations using the repeater are on 2 m while others are on 440? Just link the two repeaters! (**Fig 23.5**).

Want to help the local Civil Air Patrol (CAP)? Add a receiver for aircraft emergency transmitters (ELT). Tornadoes? It is now legal to add a weather channel receiver (**Fig 23.6**).

The list goes on and on. Perhaps that is why so many hams have put up repeaters.

Repeater Terminology

Here are some definitions of terms used in the world of Amateur Radio FM and repeaters:

access code — one or more numbers and/or symbols that are keyed into the repeater with a DTMF tone pad to activate a repeater function, such as an autopatch.

autopatch — a device that in-

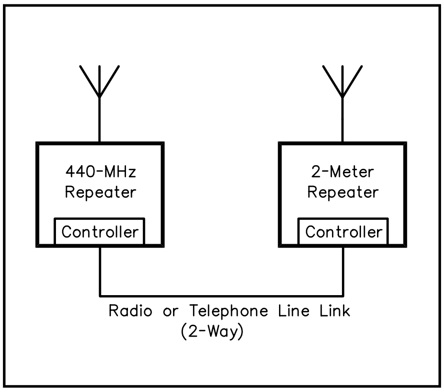


Fig 23.5 — Two repeaters using different bands can be linked for added convenience.

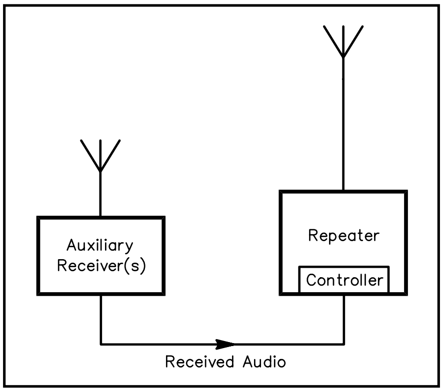


Fig 23.6 — For even greater flexibility, you can add an auxiliary receiver.

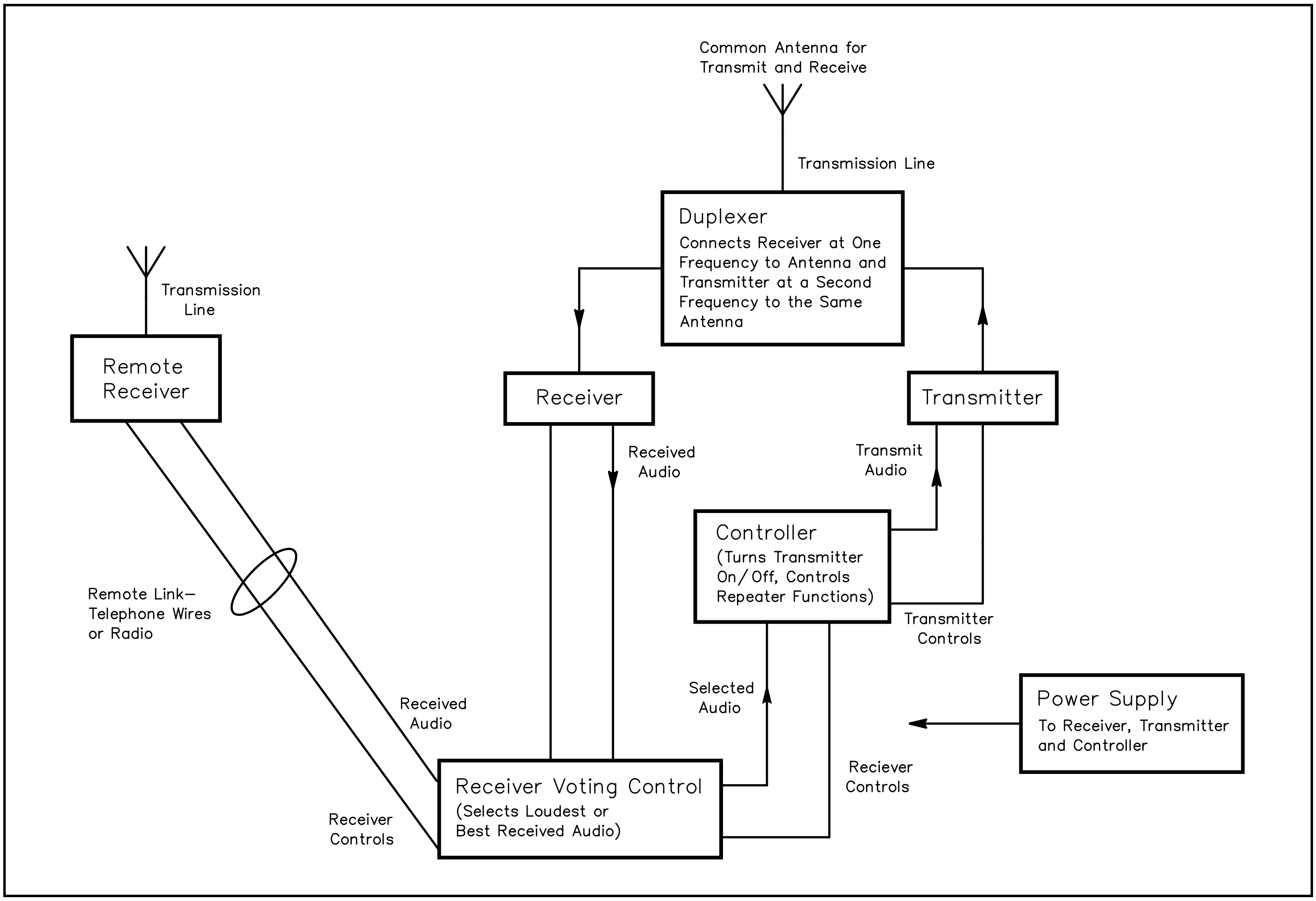


Fig 23.4 — A second remote receiver site can provide solid coverage on the other side of town.

terfaces a repeater to the telephone system to permit repeater users to make telephone calls. Often just called a “patch.”

break — the word used to interrupt a conversation on a repeater *only* to indicate that there is an emergency.

carrier-operated relay (COR) — a device that causes the repeater to transmit in response to a received signal.

channel — the pair of frequencies (input and output) used by a repeater.

closed repeater — a repeater whose access is limited to a select group (see ***open repeater***).

control operator — the Amateur Radio operator who is designated to “control” the operation of the repeater, as required by FCC regulations.

courtesy beep — an audible indication that a repeater user may go ahead and transmit.

coverage — the geographic area within which the repeater provides communications.

CTCSS — abbreviation for continuous tone-controlled squelch system, a series of subaudible tones that some repeaters use to restrict access. (see **closed repeater**)

digipeater — a packet radio (digital) repeater.

DTMF — abbreviation for dual-tone multifrequency, the series of tones generated from a keypad on a ham radio transceiver (or a regular telephone).

duplex or **full duplex** — a mode of communication in which a user transmits on one frequency and receives on another frequency simultaneously (see ***half duplex***).

duplexer — a device that allows the repeater transmitter and receiver to use the same antenna simultaneously.

frequency coordinator — an individual or group responsible for assigning frequencies to new repeaters without causing interference to existing repeaters.

full quieting — a received signal that contains no noise.

half duplex — a mode of communication in which a user transmits at one time and receives at another time.

hand-held — a small, lightweight portable transceiver small enough to be carried easily; also called HT (for Handie-Talkie, a Motorola trademark).

hang time — the short period following a transmission that allows others who want to access the repeater a chance to do so; a *courtesy beep* sounds when the repeater is ready to accept another transmission.

input frequency — the frequency of the repeater’s receiver (and your transceiver’s transmitter).

intermodulation distortion (IMD)— the unwanted mixing of two strong RF signals that causes a signal to be transmitted on an unintended frequency.

key up — to turn on a repeater by transmitting on its input frequency.

machine — a repeater system.

magnetic mount or **mag-mount** — an antenna with a magnetic base that permits quick installation and removal from a motor vehicle or other metal surface.

NiCd — a nickel-cadmium battery that may be recharged many times; often used to power portable transceivers. Pronounced “NYE-cad.”

open repeater — a repeater whose access is not limited.

output frequency — the frequency of the repeater’s transmitter (and your transceiver’s receiver).

over — a word used to indicate the end of a voice transmission.

Repeater Directory — an annual ARRL publication that lists repeaters in the US, Canada and other areas.

separation or **split** — the difference (in kHz) between a repeater’s transmitter and receiver frequencies. Repeaters that use unusual separations, such as 1 MHz on 2 m, are sometimes said to have “oddball splits.”

simplex — a mode of communication in which users transmit and receive on the same frequency.

time-out — to cause the repeater or a repeater function to turn off because you have transmitted for too long.

timer — a device that measures the length of each transmission and causes the repeater or a repeater function to turn off after a transmission has exceeded a certain length.

tone pad — an array of 12 or 16 numbered keys that generate the standard telephone dual-tone multi-frequency (***DTMF***) dialing signals. Resembles a standard telephone keypad. (see ***autopatch***)

Advantages of Using a Repeater

When we use the term *repeater* we are almost always talking about transmitters and receivers on VHF or higher bands, where radio-wave propagation is normally line of sight. Sometimes a hill or building in the path will allow refraction or other types of edge effects, reflections and bending. But for high quality, consistently solid communications, line of sight is the primary mode.

We know that the effective range of VHF and UHF signals is related to the height of each antenna. Since repeaters can usually be located at high points, one great advantage of repeaters is the extension of coverage area from low-powered mobile and portable transceivers.

Fig 23.7 illustrates the effect of using a repeater in areas with hills or mountains. The same effect is found in metropolitan areas, where buildings provide the primary blocking structures.

Siting repeaters at high points can also have disadvantages. When two nearby repeaters use the same frequencies, your transceiver might be able to receive both. But since it operates FM, the *capture effect* usually ensures that the stronger signal will capture your receiver and the weaker signal will not be heard — at least as long as the stronger repeater is in use.

It is also simpler to provide a very sensitive receiver, a good antenna system, and a slightly higher power transmitter at just one location — the repeater — than at each mobile, portable or home location. A superior repeater system compensates for the low power (5 W or less), and small, inefficient antennas that many hams use to operate through them. The repeater maintains the range or coverage we want, despite our equipment deficiencies. If both the hand-held transceiver and the repeater are at high elevations, for example, communication is possible over great distances, despite the low output power and inefficient antenna of the transceiver (see **Fig 23.8**).

Repeaters also provide a convenient meeting place for hams with a common interest.

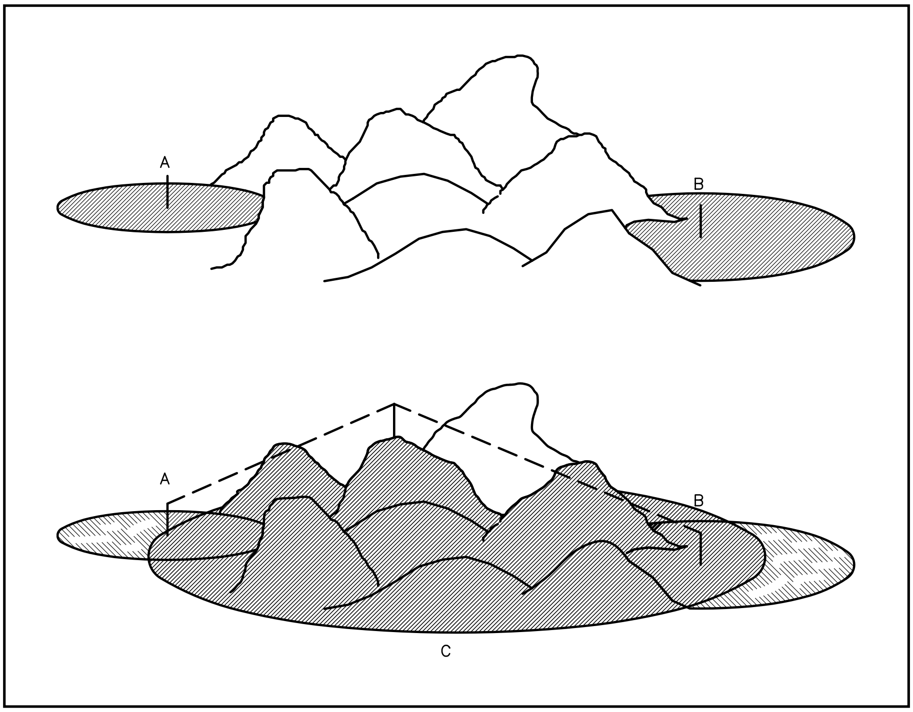


Fig 23.7 — In the upper diagram, stations A and B cannot communicate because their mutual coverage is limited by the mountains between them. In the lower diagram, stations A and B can communicate because the coverage of each station falls within the coverage of repeater C, which is on a mountaintop.

Fig 23.8 — In the Rocky Mountain west, hand-held transceivers can often cover great distances, thanks to repeaters located atop high mountains. *(photo courtesy WB0KRX and N0IET)*

It might be geographic — your town — or it might be a particular interest such as DX or passing traffic. Operation is channelized, and usually in any area you can find out which channel — or repeater — to pick to ragchew, get highway information, or whatever your need or interest is. The fact that operation is channelized also provides an increased measure of driving safety — you don't have to tune around and call CQ to make a contact, as on the HF bands. Simply call on a repeater frequency — if someone is there and they want to talk, they will answer you.

Emergency Operations

When there is a weather-related emergency or a disaster (or one is threatening), most repeaters in the affected area immediately spring to life. Emergency operation and traffic always take priority over other ham activities, and many repeaters are equipped with emergency power sources just for these occasions.

Almost all Amateur Radio emergency organizations use repeaters to take advantage of their extended range, uniformly good coverage and visibility. Most repeaters are well known — everyone active in an area with suitable equipment knows the local repeater frequencies. For those who don't, many transceivers provide the ability to scan for a busy frequency. See **Fig 23.9**.

Repeaters and the FCC

The law in the United States changes over time to adapt to new technology and changing times. Since the early 1980s, the trend has been toward deregulation, or more accurately in the case of radio amateurs, self-regulation. Hams have established band plans, calling frequencies, digital protocols and rules that promote efficient communication and interchange of information.

Originally, repeaters were licensed separately with detailed applications and control rules. Repeater users were forbidden to use their equipment in any way that could be interpreted as commercial. In some cases, even calling a friend at an office where the receptionist answered with the company name was interpreted as a problem.

The rules have changed, and now most nonprofit groups and public service events can be supported and businesses can be called — as long as the participating radio amateurs are not earning a living from this specific activity.

We can expect this trend to continue. For the latest rules and how to interpret them, see *QST* and *The FCC Rule Book*, published by the ARRL.

Fig 23.9 — During disasters like the Mississippi River floods of 1993, repeaters over a wide area are used solely for emergency-related communication until the danger to life and property is past. *(photo courtesy WA9TZL)*

Operating Techniques

There are almost as many operating procedures in use on repeaters as there are repeaters. Only by listening can you determine the customary procedures on a particular machine. A number of common operating techniques are found on many repeaters, however.

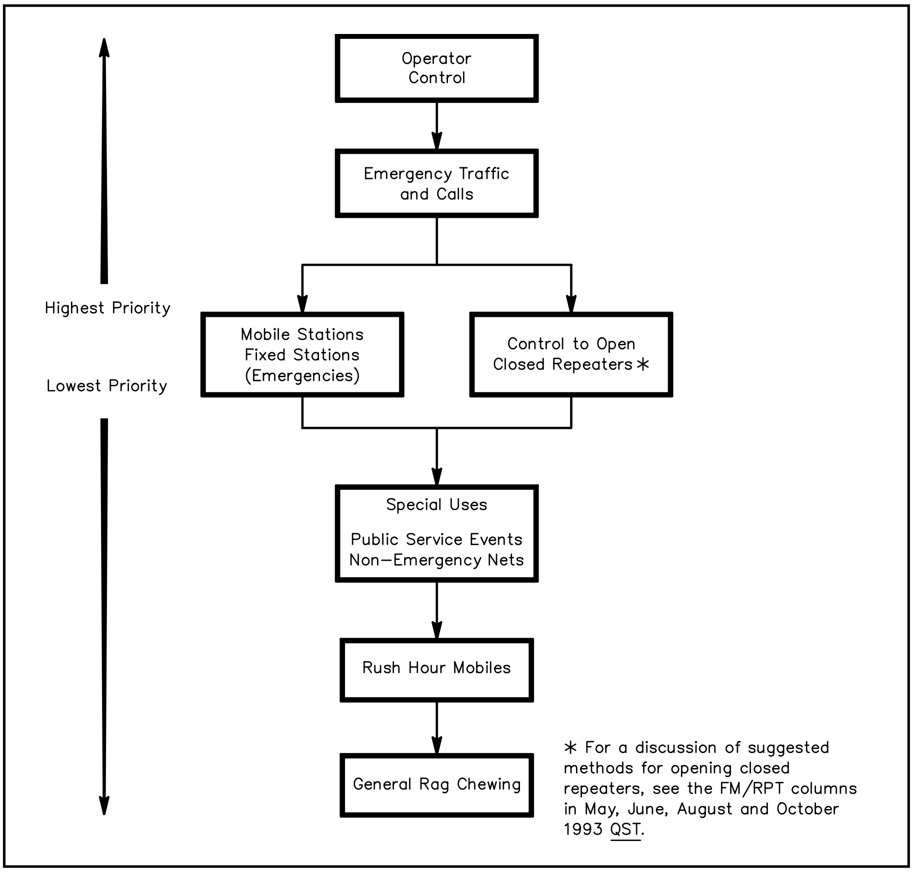
One such common technique is the transmission of *courtesy tones*. Suppose several stations are talking in rotation — one following another. The repeater detects the end of a transmission of one user, waits a few seconds, and then transmits a short tone or beep. The next station in the rotation waits until the beep before transmitting, thus giving any other station wanting to join in a brief period to transmit their call sign. Thus the term *courtesy tone* — you are politely pausing to allow other stations to join in the conversation.

Another common repeater feature that encourages polite operation is the *repeater timer*. Since repeater operation is channelized — allowing many stations to use the same frequency — it is polite to keep your transmissions short. If you forget this little politeness many repeaters simply cut off your transmission after 2 or 3 minutes of continuous talking. After the repeater "times out," the timer is reset and the repeater is ready for the next transmission. The timer length is often set to 3 minutes or so during most times of the day and 1 or 1$^1/_2$ minutes during commuter rush hours when many mobile stations want to use the repeater.

A general rule, in fact law — both internationally and in areas regulated by the FCC — is that emergency transmissions always have priority. These are defined as relating to life, safety and property damage. Many repeaters are voluntarily set up to give mobile stations priority, at least in checking onto the repeater. If there is going to be a problem requiring help, the request will usually come from a mobile station. This is particularly true during rush hours; some repeater owners request that fixed stations refrain from using the repeater during these hours. Since fixed stations usually have the advantages of fixed antennas and higher power, they can operate simplex more easily. This frees the repeater for mobile stations that need it.

A chart of suggested operating priorities is given in **Fig 23.10**. Many but not all repeaters conform to this concept, so it can be used as a general guideline.

The figure includes a suggested priority control for *closed repeaters*. These are repeaters whose owners wish, for any number of reasons, not to have them listed as available for general use. Often they require transmission of a *subaudible* or *CTCSS* tone (discussed later). Not all repeaters requiring a



∗ For a discussion of suggested methods for opening closed repeaters, see the FM/RPT columns in May, June, August and October 1993 QST.

Fig 23.10 — The chart shows recommended repeater operating priorities. Note that, in general, priority goes to mobile stations.

CTCSS tone are closed. Other closed repeaters require the transmission of a coded telephone push-button *(DTMF)* tone sequence to turn on. It is desirable that all repeaters, including generally closed repeaters, be made available at least long enough for the presence of emergency information to be made known.

Repeaters have many uses. In some areas they are commonly used for formal traffic nets, replacing or supplementing the nets usually found on 75-m SSB. In other areas they are used with tone alerting for severe-weather nets. Even when a particular repeater is generally used for ragchewing it can be linked for a special purpose. As an example, an ARRL volunteer official may hold a periodic section meeting across her state, with linked repeaters allowing both announcements and questions directed back to her.

One of the most common and important uses of a repeater is to aid visiting hams. Since repeaters are listed in the *ARRL Repeater Directory* and other directories, hams traveling across the country with mobile or hand-held radios often check into local repeaters asking for travel route, restaurant or lodging information. Others just come on the repeater to say hello to the local group. In most areas courtesy prevails — the visitor is given priority to say hello or get the needed help.

Detailed information on repeater operating techniques is included in a full chapter of the *ARRL Operating Manual*.

The Sounds of Amateur Radio

Listen to transmissions through a 2-meter FM repeater.

The Sounds of Amateur Radio

Listen to transmissions through a 10-meter FM repeater.

Home and Mobile Equipment

There are many options available in equipment used on repeaters—both home-built and commercial. It is common to use the same radio for both home station and mobile, or mobile and hand-held use. A number of these options are shown in **Fig 23.11**.

Hand-Held Transceivers

A basic hand-held radio with 100 mW to 5 W output can be mounted in an automobile with or without a booster amplifier or “brick.”

Several types of antennas can be used in the hand-held mode. The smallest and most convenient is a rubber flex antenna, known as a “rubber duckie,” a helically wound antenna encased in a flexible tube. Unfortunately, to obtain the small size the use of a wire helix or coil often produces a very low efficiency.

A quarter-wave whip, which is about 19 inches long for the 2-m band, is a good choice for enhanced performance. The rig and your hand act as a ground plane and a reasonably efficient result is obtained. A longer antenna, consisting of several electrical quarter-wave sections in series, is also commercially available. Although this antenna usually produces extended coverage, the mechanical strain of 30 or more inches of antenna mounted on the radio’s antenna connector can cause problems. After several months, the strain may require replacement of the connector.

Selection of batteries will change the output power from the lowest generally available — 0.1 or 0.5 W — to the 5-W level. Charging is accomplished either with a “quick” charger in an hour or less or with a trickle charger overnight.

Power levels higher than 7 W may cause a safety problem on hand-held units, since the antenna is usually close to the operator’s head and eyes. See the **Safety** chapter for more information.

For mobile operation, a 12-V power cord plugs into the auto cigarette lighter. In addition, commercially available brick amplifiers — available either assembled or as kits — can be used to raise the output power level of the hand-held radio to 10 to 70 W. These amplifiers often come with transmit-receive

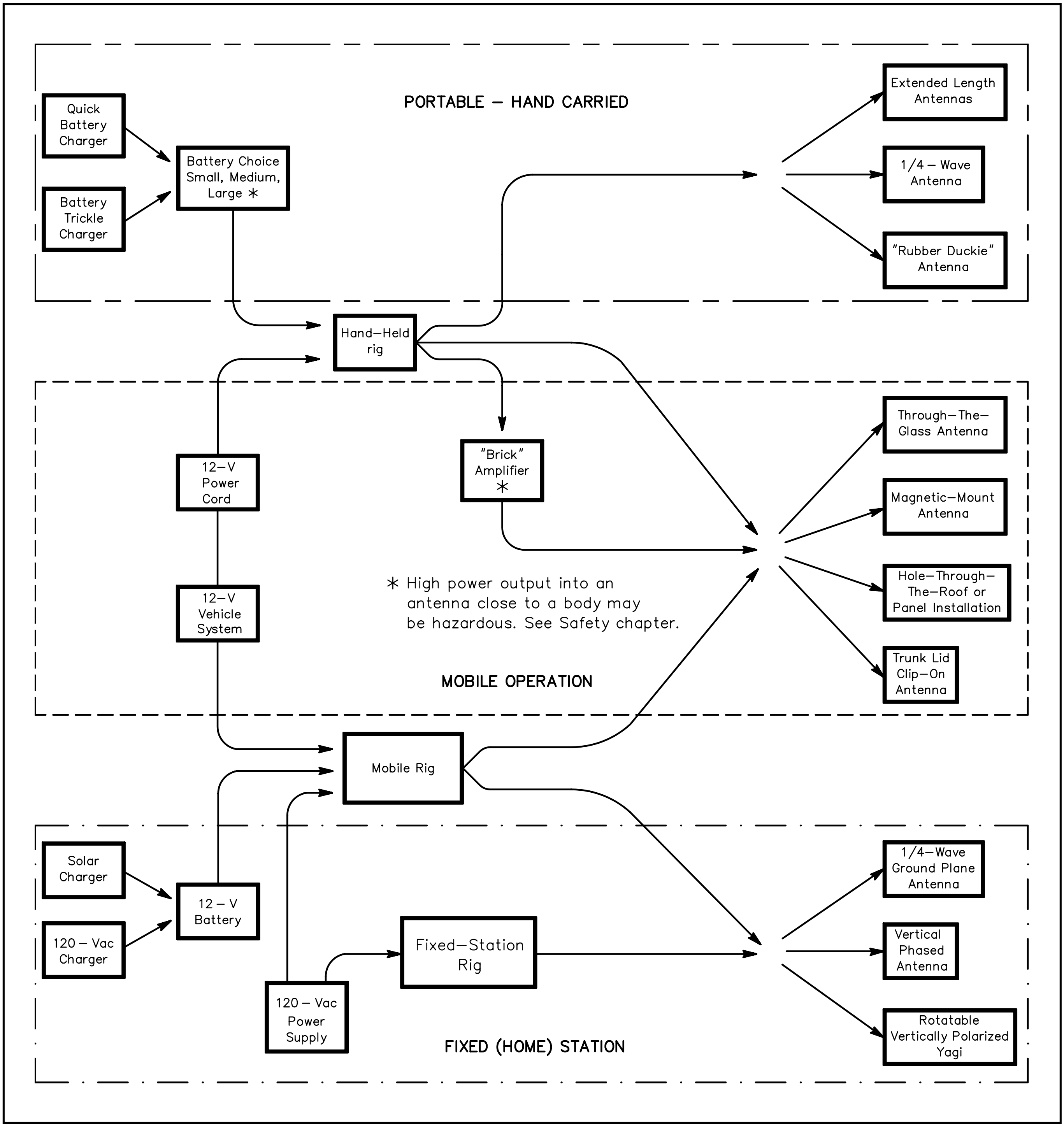


Fig 23.11 — Equipment choices for use with repeaters are varied. A hand-held transceiver is perhaps the most versatile type of radio, as it can be operated from home, from a vehicle and from a mountaintop.

sensing and optional preamplifiers. One such unit is shown in block form in **Fig 23.12**.

Mobile Equipment

Mobile antennas range from quick and easy "clip-it-on" mounting to "drill through the car roof" assemblies. The four general classes of mobile antennas shown in the center section of Fig 23.11 are the most popular choices. Before experimenting with antennas for your vehicle, there are some precautions to be taken.

Through-the-glass antennas: Rather than trying to get the information from your dealer or car manufacturer, test any such antenna first using masking tape or some other temporary technique to hold the antenna in place. Some windshields are metallicized for defrosting, tinting and AM car radio reception. Having this metal in the way of your through-the-glass antenna will seriously decrease its efficiency.

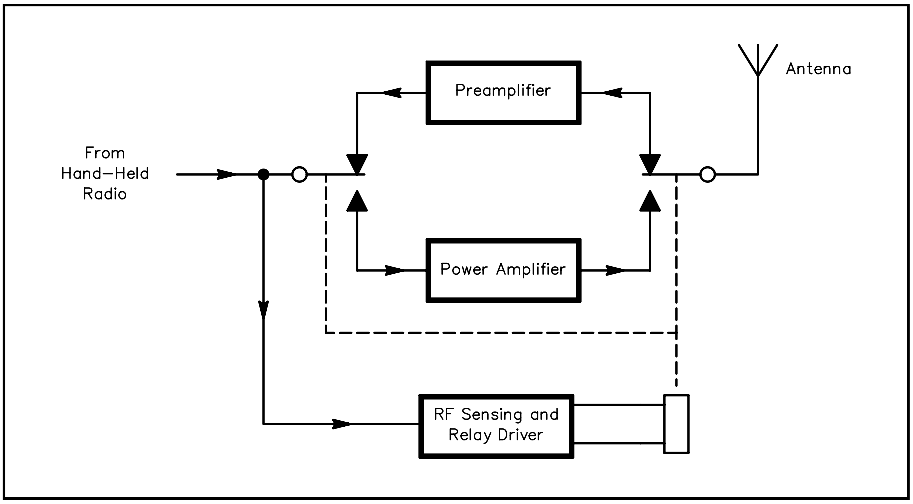


Fig 23.12 — This block diagram shows how a "brick" amplifier can be used with a receiver preamplifier. RF energy from the transceiver is detected, turns on the relay, and puts the RF power amplifier in line with the antenna. When no RF is sensed from the transceiver, the receiving preamp is in line.

Magnet-mount antennas are convenient, but only if your car has a metal roof. The metal roof serves as the ground plane.

Through-the-roof antenna mounting: Drilling a hole in your car roof may not be the best option unless you intend to keep the car for the foreseeable future. This mounting method provides the best efficiency, however, since the (metal) roof serves as a ground plane. Before you drill, carefully plan and measure how you intend to get the antenna cable down under the interior car headliner to the radio.

Trunk lid and clip-on antennas: These antennas are good compromises. They are usually easy to mount and they perform acceptably. Cable routing must be planned. If you are going to run more than a few watts, do not mount the antenna close to one of the car windows — a significant portion of the radiated power may enter the car interior.

Mobile rigs used at home can be powered either from rechargeable 12-V batteries or fixed power supplied from the 120-V ac line. Use of 12-V batteries has the advantage of providing back-up communications ability in the event of a power interruption. When a storm knocks down power lines and telephone service, it is common to hear hams using their mobile or 12-V powered rigs making autopatch calls to the power and telephone company to advise them of loss of service.

Home Station Equipment

The general choice of fixed-location antennas is also shown in Fig 23.11. A rotatable Yagi is normally not only unnecessary but undesirable for repeater use, since it has the potential of extending your transmit range into adjacent area repeaters on the same frequency pair. All antennas used to communicate through repeaters should be vertically polarized for best performance.

Both commercial and home-made $^1/_4$-λ and larger antennas are popular for home use. A number of these are shown in the **Antennas** chapter. Generally speaking, $^1/_4$-λ sections may be stacked up to provide more gain on any band. As you do so, however, more and more power is concentrated toward the horizon. This may be desirable if you live in a flat area. See **Fig 23.13**.

While most hams do not to try to build transceivers for use on repeaters, accessories provide a fertile area for construction and experimentation.

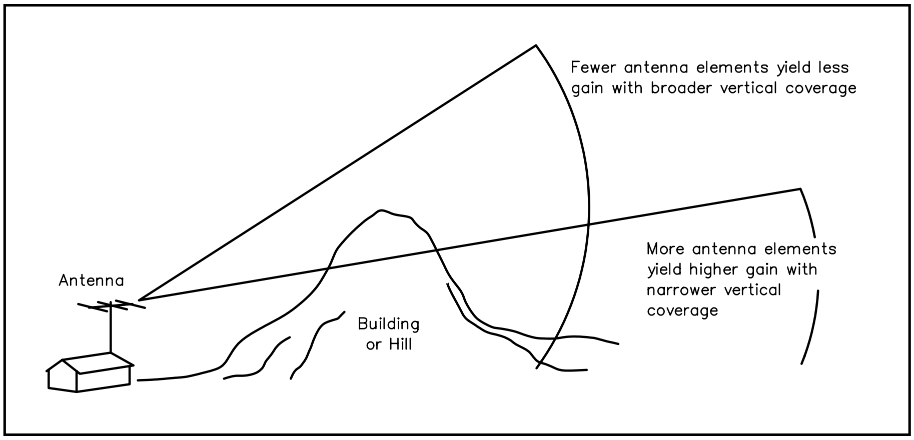


Fig 23.13 — As with all line-of-sight communications, terrain plays an important role in how your signal gets out.

Autopatches and Tones

One of the most attractive features of repeaters is the availability of autopatch services. This allows the mobile or portable station to use a standard telephone key pad to connect the repeater to the local telephone line and make outgoing calls.

Table 23.2 shows the tones used for these services. Some keyboards provide the standard 12 sets of tones corresponding to the digits 0 through 9 and the special signs # and *. Others include the full set of 16 pairs, providing special keys A through D. The tones are arranged in two groups, usually called the low tones and high tones. Two tones, one from each group, are required to define a key or digit. For example, pressing 5 will generate a 770-Hz tone and a 1336-Hz tone simultaneously.

The standards used by the telephone company require the amplitudes of these two tones to have a certain relationship. Fortunately, most tone generators used for this purpose have the amplitude relationship as part of their construction. Initially, many hams used surplus telephone company keypads. These units were easily installed — usually just two or three wires were connected. Unfortunately they were constructed with wire contacts and their reliability was not great when used in a moving vehicle.

Table 23.2
Standard Telephone (DTMF) Tones

Low Tone Group	*High Tone Group*			
	1209 Hz	*1336 Hz*	*1477 Hz*	*1633 Hz*
697 Hz	1	2	3	A
770 Hz	4	5	6	B
852 Hz	7	8	9	C
941 Hz	*	0	#	D

Many repeaters require pressing a code number sequence or the special figures * or # to turn the autopatch on and off. Out-of-area calls are usually locked out, as are services requiring the dialing of the prefix 0 or 1. "Speed dial" is often available, although occasionally this can conflict with the use of * or # for repeater control, since these special symbols are used by the telephone company for its own purposes.

Some repeaters require the use of *subaudible* or CTCSS tones to utilize the autopatch, while others require these tones just to access the repeater in normal use. Taken from the commercial services, subaudible tones are not generally used to keep others from using a repeater but rather are a method of minimizing interference from users of the same repeater frequency.

For example, in **Fig 23.14** a mobile station on hill A is nominally within the normal coverage area of the Jonestown repeater (146.16/76). The Smithtown repeater, also on the same fre-

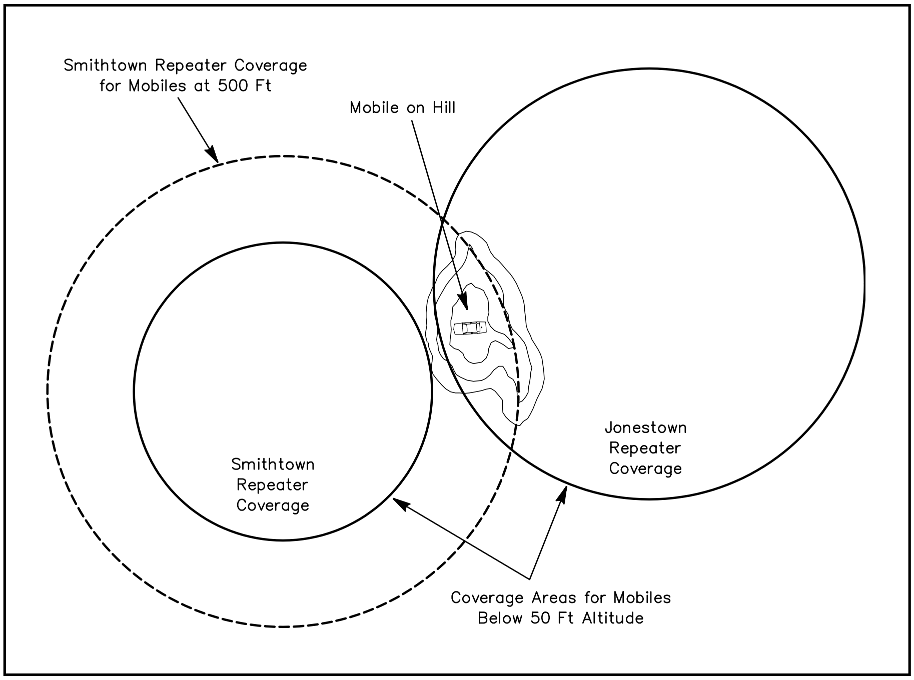


Fig 23.14 — When two repeaters operate on the same frequencies, a well-situated operator can key up both repeaters simultaneously. Frequency coordination prevents this occurrence.

quency pair, usually cannot hear stations 150 miles away but since the mobile is on a hill he is in the coverage area of both Jonestown and Smithtown. Whenever the mobile transmits he is heard by both repeaters.

The common solution to this problem, assuming it happens often enough, is to equip the Smithtown repeater with a CTCSS decoder and require all users of the repeater to transmit a CTCSS tone to access the repeater. Thus, the mobile station on the hill does not come through the Smithtown repeater, since he is not transmitting the required CTCSS tone.

Table 23.3 shows the available CTCSS tones. They are usually transmitted by adding them to the transmitter audio but at an amplitude such that they are not readily heard by the receiving station. It is common to hear the tones described by their code designators — a carryover from their use by Motorola in their commercial communications equipment.

Listings in the *ARRL Repeater Directory* include the CTCSS tone required, if any.

Table 23.3
CTCSS (PL) Tone Frequencies

The purpose of CTCSS (PL) is to reduce cochannel interference during band openings. CTCSS (PL) equipped repeaters would respond only to signals having the CTCSS tone required for that repeater. These repeaters would not respond to weak distant signals on their inputs and correspondingly not transmit and repeat to add to the congestion.

The standard ANSI/EIA frequency codes, in hertz, with their Motorola alphanumeric designators, are as follows:

67.0—XZ
69.3—WZ
71.9—XA
74.4—WA
77.0—XB
79.7—WB
82.5—YZ
85.4—YA
88.5—YB
91.5—ZZ
94.8—ZA
97.4—ZB
100.0—1Z
103.5—1A
107.2—1B
110.9—2Z
114.8—2A
118.8—2B
123.0—3Z
127.3—3A
131.8—3B
136.5—4Z
141.3—4A
146.2—4B
151.4—5Z
156.7—5A
159.8
162.2—5B
165.5
167.9—6Z
171.3
173.8—6A
177.3
179.9—6B
183.5
186.2—7Z
189.9
192.8—7A
199.5
203.5—M1
206.5—8Z
210.7—M2
218.1—M3
225.7—M4
229.1—9Z
233.6—M5
241.8—M6
250.3—M7
254.1—0Z

Frequency Coordination and Band Plans

Since repeater operation is channelized, with many stations sharing the same frequency pairs, the amateur community has formed coordinating groups to help minimize conflicts between repeaters and among repeaters and other modes. Over the years, the VHF bands have been divided into repeater and nonrepeater sub-bands. These frequency-coordination groups maintain lists of available frequency pairs in their areas. A complete list of frequency coordinators, band plans and repeater pairs is included in the *ARRL Repeater Directory*.

Each VHF and UHF repeater band has been subdivided into repeater and nonrepeater channels. In addition, each band has a specific *offset* — the difference between the transmit frequency and the receive frequency for the repeater. While most repeaters use these standard offsets, others use “oddball splits.” These nonstandard repeaters are generally also coordinated through the local frequency coordinator. **Table 23.4** shows the standard frequency offsets for each repeater band.

The 10-m repeater band offers an additional challenge for repeater users. It is the only repeater band where ionospheric propagation is a regular factor. Coupled with the limited number of repeater frequency assignments available, the standard in this band is to use CTCSS tones on a regional basis. **Table 23.5** lists the coordinated tone assignments. As can be seen, 10-m repeaters in the 4th call area will use either the 146.2 or 100.0 (4B or 1Z) CTCSS tone.

AT THE REPEATER SITE

For details on the many elements that go into planning and installing a repeater at a particular site, request the 96 Handbook Repeater template from the ARRL Technical Secretary. (There is a nominal charge for postage and handling.)

Table 23.4
Standard Frequency Offsets for Repeaters

Band	*Offset*
29 MHz	100 kHz
52 MHz	1 MHz
144 MHz	600 kHz
222 MHz	1.6 MHz
440 MHz	5 MHz
902 MHz	12 MHz
1240 MHz	12 MHz

Table 23.5
10-M CTCSS Frequencies

In 1980 the ARRL Board of Directors adopted the 10-m CTCSS (PL) tone-controlled squelch frequencies listed below for voluntary incorporation into 10-m repeater systems to provide a uniform national system.

Call Area	*Tone 1*		*Tone 2*	
W1	131.8 Hz	-3B	91.5 Hz	-ZZ
W2	136.5	-4Z	94.8	-ZA
W3	141.3	-4A	97.4	-ZB
W4	146.2	-4B	100.0	-1Z
W5	151.4	-5Z	103.5	-1A
W6	156.7	-5A	107.2	-1B
W7	162.2	-5B	110.9	-2Z
W8	167.9	-6Z	114.8	-2A
W9	173.8	-6A	118.8	-2B
W0	179.9	-6B	123.0	-3Z
VE	127.3	-3A	88.5	-YB

Satellites

Unless propagation enhancements are used, radio communication distances are essentially limited by the curvature of the Earth. Propagation effects that are dependent upon the atmosphere or ionosphere can be conditionally (and sometimes unpredictably) used to transmit radio signals around the Earth's curvature, thus thwarting the straight-line radio range concept, even at VHF and UHF frequencies. Communicating beyond line-of-sight distances, however, may require the use of high power and gain antennas. These types of communications are defined as "terrestrial communications."

Because objects in space are visible from a number of locations on the Earth at the same time, it is possible to predict communications between stations within this "circle of visibility." This can be achieved by using the space object as a passive reflector for radio energy, or if the space object contains a transponding radio transmitter/receiver, it can act as a radio relay. The predictable signal path to the space object and back avoids the uncertain attenuation inherent in terrestrial propagation.

Amateur Radio space communications have two major facets: artificial satellites and our natural satellite, the Moon. Together, they make VHF and higher frequencies usable for amateur intercontinental communications and push today's technology to the limit. This section, written by Robert Diersing, N5AHD, covers communication from and through artificial spacecraft. EME or moonbounce communication is covered later in this chapter.

THE AMATEUR SATELLITES

The Amateur Radio satellite program began with the design, construction and launch of OSCAR I in 1961 under the auspices of the Project OSCAR Association in California. The acronym "OSCAR," which has been attached to almost all Amateur Radio satellite designations on a worldwide basis, stands for ***O****rbiting* ***S****atellite* ***C****arrying* ***A****mateur* ***R****adio*. Project OSCAR was instrumental in organizing the construction of the next three Amateur Radio satellites — OSCARs II, III and IV. *The Radio Amateur's Satellite Handbook*, published by ARRL, has details of the early days of the amateur space program.

In 1969, the Radio Amateur Satellite Corporation (AMSAT) was formed in Washington, DC. AMSAT has participated in the vast majority of amateur satellite projects, both in the United States and internationally, beginning with the launch of OSCAR 5. Now, many countries have 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.

Beginning with OSCAR 6, amateurs started to enjoy the use of satellites with lifetimes measured in years as opposed to weeks or months. The operational lives of OSCARs 6, 7, 8 and 9, for example, ranged between four and eight years. All of these satellites were low Earth orbiting (LEO) with altitudes approximately 800-1200 km. LEO Amateur Radio satellites have also been launched by other groups not associated with any AMSAT organization such as the Radio Sputniks 1-8 and the ISKRA 2 and 3 satellites launched by the former Soviet Union.

The short-lifetime LEO satellites (OSCARs I through IV and 5) are sometimes designated the *Phase I* satellites, while the long-lifetime LEO satellites are sometimes called the *Phase II* satellites. There are other conventions in satellite naming that are useful to know. First, it is common practice to have one designation for a satellite before launch and another after it is successfully launched. Thus, OSCAR 10 (discussed later) was known as Phase 3B before launch. Next, the AMSAT designator may be added to the name, for example, AMSAT-OSCAR 10, or just AO-10 for short. Finally, some other designator may replace the AMSAT designator such as the case with Japanese-built Fuji-OSCAR 29 (FO-29).

In order to provide wider coverage areas for longer time periods, the high-altitude Phase 3 series was

Current Amateur Satellites

OSCAR 10, the second Phase 3 satellite, was launched on June 16, 1983, aboard an ESA Ariane rocket, and was placed in an elliptical orbit. OSCAR 10 carries Mode B and Mode L transponders. Due to internal damage, it is currently uncontrollable.

OSCAR 11, a scientific/educational low-orbit satellite, was built at the University of Surrey in England and launched on March 1, 1984. This UoSAT spacecraft has also demonstrated the feasibility of store-and-forward packet digital communications and is fully operational.

OSCAR 16, also known as PACSAT, was launched in January 1990. A digital store-and-forward packet radio file server, it has an experimental S-band beacon at 2401.143 MHz.

OSCAR 19, also known as LUSAT, was sponsored by AMSAT Argentina. Launched in January 1990, it is nearly identical to OSCAR 16.

OSCAR 20, launched into low Earth orbit in February 1990, is the second amateur satellite designed and built in Japan. It carries Mode J and Mode JD (digital store-and-forward) transponders. Its digital functions are no longer operational.

OSCAR 22, another of the UoSAT series for both amateur and commercial services, was launched in July 1991. UO-22 now operates in amateur store-and-forward service as well as a 110°-wide CCD camera viewing the Earth.

OSCAR 23, also known as KITSAT-A (the Korean Institute of Technology), was launched in August 1992, and is functionally very similar to UO-22 with its high speed digital BBS and CCD camera operations.

OSCAR 25, known as KITSAT-B, was launched in September 1993. It is a clone of OSCAR 23.

OSCAR 27 is a companion module aboard the commercial EyeSat-A microsat. Launched in September 1993, OSCAR 27 is an experimental platform designed by AMRAD. At the time of this writing, it is being used primarily as an FM voice repeater.

The Sounds of Amateur Radio

Listen to a QSO through the AMRAD-OSCAR 27 satellite.

OSCAR 28, also known as PoSAT, was launched in September 1993. Although the satellite is operational, it is not open for amateur use at this writing. Similar to KITSAT-OSCAR 23, it was built at the University of Surrey by a team of Portuguese engineers and the UoS staff.

RS 15, launched in December 1994, is a Mode A spacecraft; its uplink is on the 2-m band, and its downlink is on 10 m.

OSCAR 29, launched from Japan in 1996, is similar to OSCAR 20 with the exception that its packet BBS has 9600-baud capability.

OSCAR 31, launched in July 1998, is the first Thai microsat. Known as TMSat, it was constructed at the University of Surrey by Thai engineers and the UoS staff. Similar in construction to KITSAT-OSCAR 23, it has a Mode JD 9600-baud FSK digital transponder.

OSCAR 33, also known as SEDSAT-1 (Students for the Exploration and Development of Space Satellite 1), was designed and built at the University of Alabama, Huntsville. Launched in October 1998, it contains a digital packet store-and-forward repeater as well as an analog repeater system.

OSCAR 34, launched from the shuttle *Discovery* in October 1998, is also known as PANSAT, for Petite Amateur Navy Satellite. It carries a spread-spectrum communication package fabricated by student officers and faculty at the Naval Postgraduate School in Monterey, California. PANSAT is used for store-and-forward digital packet communication using direct sequence spread spectrum modulation.

OSCAR 35, launched in February 1999, is also called SUNSAT. Designed and built at the University of Stellenbosch in South Africa, it includes digital store-and-forward capability and a voice "parrot" repeater used primarily for educational purposes. SUNSAT also carried two NASA experiments and an experimental pushbroom imager capable of taking pictures of Earth.

initiated. Phase 3 satellites often provide 8-12 hours of communications for a large part of the Northern Hemisphere. After losing the first satellite of the Phase 3 series to a launch vehicle failure in 1980, AMSAT-OSCAR 10 was successfully launched and became operational in 1983. AMSAT-OSCAR 13, the followup to the AO-10 mission, was launched in 1988 and re-entered the atmosphere in 1996. AO-10 provides some wide-area communications capability at certain times of the year despite the failure of its onboard computer memory. The successor to AO-13, Phase 3D, is awaiting a launch opportunity at this writing.

With the availability of the long access time and wide coverage of satellites like AO-10 and the upcoming Phase 3D, it may seem that the lower altitude orbits and shorter access times of the Phase II series would be obsolete. This certainly might be true were it not for the incorporation of digital store-and-forward technology into many current satellites operating in low Earth orbit. Satellites providing store-and-forward communication services using packet radio techniques are generically called *PACSATs*. Files stored in a PACSAT message system can be anything from plain ASCII text to digitized pictures and voice.

The first satellite with a digital store-and-forward feature was UoSAT-OSCAR 11. UO-11's Digital Communications Experiment (DCE) was not open to the general Amateur Radio community although it was utilized by designated "gateway" stations. The first satellite with store-and-forward capability open to all amateurs was the Japanese Fuji-OSCAR 12 satellite, launched in 1986. FO-12 was succeeded by FO-20, launched in 1990, and FO-29, launched in 1996. In addition to providing digital store-and-forward service. FO-20 and FO-29 also have analog linear transponders for CW and SSB communication.

By far the most popular store-and-forward satellites are the *PACSATs* utilizing the PACSAT Broadcast Protocol. These PACSATs fall into two general categories — the *Microsats*, based on technology developed by AMSAT-NA, and the *UOSATs*, based on technology developed by the University of Surrey in the UK. While both types are physically small spacecraft, the Microsats represent a truly innovative design in terms of size and capability. A typical Microsat is a cube measuring 23 cm (9 in) on a side and weighing about 10 kg (22 lb). The satellite will contain an onboard computer, enough RAM for the message storage, two to three transmitters, a multichannel receiver, telemetry system, batteries and the battery charging/power conditioning system.

Amateur Radio satellites have evolved to provide two primary types of communication services — analog transponders for real-time CW and SSB communication and digital store-and-forward for non real-time communication. Which of the two types interest you the most will probably depend on your current Amateur Radio operating habits. If you enjoy real-time DX QSOs on the HF bands, you may be most interested in the high-altitude wide-coverage satellites such as the Phase 3D satellite. On the other hand, if you are a computer and terrestrial packet radio enthusiast you may be more interested in the digital store-and-forward satellites like AO-16, UO-22 and KO-23. Whatever your preference, the remainder of this section should provide the information to help you make a successful entry into the specialty of amateur satellite communications.

The Sounds of Amateur Radio

Listen to the Fuji-OSCAR 29 "DigiTalker" beacon ID in Japanese and English.

The Sounds of Amateur Radio

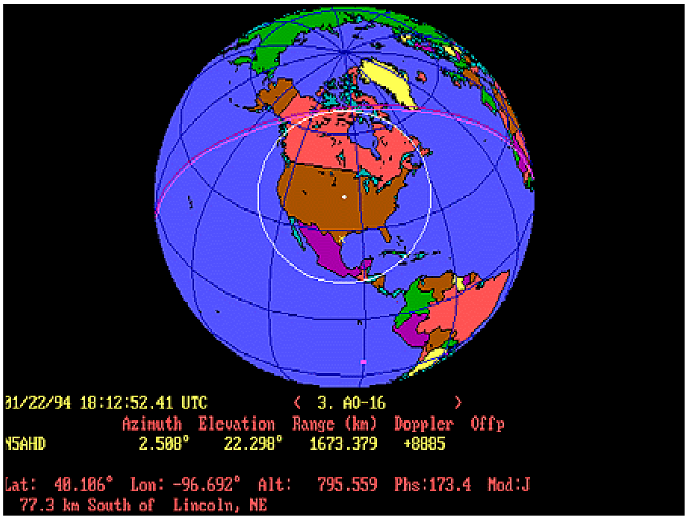
Listen to an SSB QSO via the Fuji-OSCAR 29 satellite.

Basic Operations and Terminology

Since both low and high Earth orbit (LEO and HEO) satellites are available for use, it would be a good idea to acquire a mental picture of the communication range for each type of orbit. In **Fig 23.15**, the white circle, centered roughly on the United States, is a typical footprint for a low Earth orbit satellite like AO-16. Stations within the footprint can store and/or retrieve messages to/from the store-and-forward message system. For satellites that are used for real-time SSB and CW QSOs, only stations that are in the footprint simultaneously can communicate.

In **Fig 23.16**, for the Phase 3D satellite at apogee, the range circle is quite substantial. Keep in mind that for LEO satellites like AO-16 the footprint is moving quickly, and for HEO satellites it is moving slowly. LEO satellites will typically have access times of 12 to 20 minutes while HEO satellites can have access times as long as 10 to 12 hours. For a more complete discussion of orbital mechanics and other topics in this section, see *The Radio Amateur's Satellite Handbook* published by the ARRL.

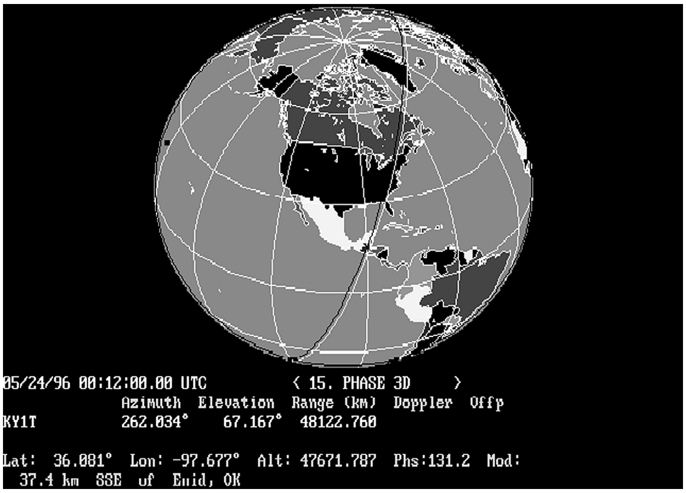
When accessing an Amateur Radio satellite, the ground station receiver is tuned to the satellite's *downlink* frequency. If the particular satellite supports two-way communication, the ground station transmits on the satellite's *uplink* frequency. The uplink and downlink frequencies will be in different bands, and each combination of bands used will have a *mode* designator. For example, the combination of an uplink in the 2-m band and a downlink in the 10-m band is called Mode A. More discussion of operating modes can be found in the next two sections, but you may wish to look at **Tables** 23.6 and 23.7 for some examples of the different modes available.



```
01/22/94 18:12:52.41 UTC          < 3. AO-16       >
               Azimuth  Elevation  Range (km)  Doppler  Offp
N5AHD           2.508°    22.298°   1673.379   +8885

Lat:  40.106°  Lon: -96.692°  Alt:   795.559  Phs:173.4  Mod:J
  77.3 km South of  Lincoln, NE
```

Fig 23.15— Communication range circle or "footprint" for AO-16.



```
05/24/96 00:12:00.00 UTC          < 15. PHASE 3D    >
               Azimuth  Elevation  Range (km)  Doppler  Offp
KY1T           262.034°   67.167°  48122.760

Lat:  36.081°  Lon: -97.677°  Alt: 47671.787  Phs:131.2  Mod:
  37.4 km  SSE  of  Enid, OK
```

Fig 23.16—The Earth as seen from the Phase 3D satellite at apogee, depicted by *InstantTrack* satellite-tracking software. The broad footprint brings nearly all of the US into range at the same time.

The exact manner in which satellite uplinks and downlinks are utilized depends on whether the primary purpose of the satellite is to provide analog or digital communication services. Satellites make use of *transponders*. Transponders regenerate all signals appearing in their input (uplink) frequency band on their output (downlink) frequency band. CW, SSB and FM signals appearing at the input will appear as CW, SSB, or FM signals on the output. Depending on the design of the transponder, USB on the input may appear either as USB or LSB on the output. The low-to-high frequency relationship of the uplink and downlink frequency bands may also differ. Note in Table 23.7, for example, that all downlink passbands are inverted from the uplink passbands. This means that a signal at the low end of the uplink will be retransmitted at the high end of the downlink. On the other hand, RS-15 Mode A uplink is 145.860 to 146.000 MHz, while the downlink is 29.360 to 29.400 MHz. Consequently, a signal at the low end of the uplink band will appear at the low end

Table 23.6
Analog Transponder Frequencies

RS Satellites

	RS-13	*RS-15*
Mode A		
Uplink	145.960-146.000	145.858-145.898
Downlink	29.460-29.500	29.354-29.394
Beacons	29.458/29.504	29.353/29.399
Mode A Robot		
Uplink	145.840	
Downlink	29.504	
Mode K		
Uplink	21.260-21.300	
Downlink	29.460-29.500	
Beacons	29.458/29.504	
Mode K Robot		
Uplink	21.138	
Downlink	29.504	
Mode T		
Uplink	21.260-21.300	
Downlink	145.960-146.000	
Beacons	145.862/145.908	
Mode T Robot		
Uplink	21.138	
Downlink	145.908	

Phase 3 Satellites

Satellite	*Mode*	*Uplink (MHz)*	*Downlink (MHz)*
AO-10	B	435.030-435.180	145.825-145.975
	Beacon		145.810

Other Satellites

Satellite	*Mode*	*Uplink (MHz)*	*Downlink (MHz)*
FO-20	J(A)	145.900-146.000	435.800-435.900
	Beacon		435.795
FO-29	J(A)	145.900-146.000	435.800-435.900
	Beacon		435.795

Table 23.7
Uplink and Downlink Frequencies for the Phase-3D Satellite

Uplinks

Band	*Digital (MHz)*	*Analog (MHz)*	*Center (MHz)*
15 m	N/A	21.210-21.250	21.230
12 m	N/A	24.920-24.960	24.940
2 m	145.800-145.840	145.840-145.990	145.915
70 cm	435.300-435.550	435.550-435.800	435.675
23 cm(1)	1269.000-1269.250	1269.250-1269.500	1269.375
23 cm(2)	1268.075-1268.325	1268.325-1268.575	1268.450
13 cm(1)	2400.100-2400.350	2400.350-2400.600	2400.475
13 cm(2)	2446.200-2446.450	2446.450-2446.700	2446.575
6 cm	5668.300-5668.550	5668.550-5668.800	5668.675

Downlinks

Band	*Digital (MHz)*	*Analog (MHz)*	*Center (MHz)*
2 m	145.955-145.990	145.805-145.955	145.880
70 cm	435.900-436.200	435.475-435.725	435.600
13 cm	2400.650-2400.950	2400.225-2400.475	2400.350
3 cm	10451.450-10451.750	10451.025-10451.275	10451.150
1.5 cm	24048.450-24048.750	24048.025-24048.275	24048.150

All downlink passbands are inverted from the uplink passbands.

Beacons *Band*	*General Beacon (MHz)*	*Middle Beacon (MHz)*	*Engineering Beacon (MHz)*
2 m	N/A	145.880	N/A
70 cm	435.450	435.600	435.850
13 cm (1)	2400.200	2400.350	2400.600
13 cm (2)	2401.200	2401.350	2401.600
3 cm	10451.000	10451.150	10451.400
1.5 cm	24048.000	24048.150	24048.400

Note: The absence of a 2-m beacon is due strictly to characteristics of the IF Matrix and the limited bandwidth available on that band. The beacons on the other bands are for various purposes, including providing spacecraft engineering data to the command stations. All beacons can be modulated with 400 bits per second BPSK and possibly other formats.

of the downlink band. The band plan used on most OSCAR satellites is given in **Fig 23.17**. FM is rarely used on amateur satellite transponders.

In contrast to a satellite such as RS-10, whose primary mission is providing linear transponders for CW and SSB communications, uplink and downlink frequencies on digital communications satellites are usually channelized. **Table 23.9** shows that specific frequencies are used for both uplink and downlink. The reason for multiple uplinks and a single downlink on some satellites is the uncoordinated *Aloha* access used by ground stations. Generally, the satellite can handle requests from more than one ground station without overloading its own downlink.

Remember that the ground station will experience *Doppler* shift of the downlink frequency as the satellite moves with re-

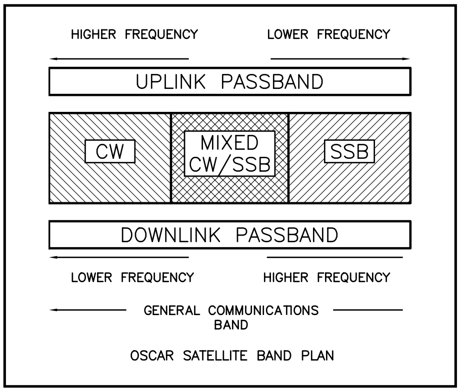


Fig 23.17 — The OSCAR satellite band plan allows for CW-only, mixed CW/SSB, and SSB-only operation. Courteous operators observe this voluntary band plan at all times.

Table 23.9
Uplink and Downlink Frequencies for Satellites with Two-Way Digital Communications Links

		Uplink			*Downlink*		
Satellite	*Mode*	*Freq (MHz)*	*Modulation*	*Rate (bps)*	*Freq (MHz)*	*Modulation*	*Rate (bps)*
AO-16	JD	145.900 145.920 145.940 145.960	Manchester Encoded AFSK		437.051 437.026 2401.143	RCBPSK	1200
LO-19	JD	145.840 145.860 145.880 145.900	Manchester Encoded AFSK	1200	437.154 437.126	BPSK RCBPSK	1200 1200
UO-22	JD	145.900 145.975	FSK	9600	435.120	FSK	9600
KO-23	JD JD	145.850 145.900	FSK	9600	435.175	FSK	9600
KO-25	JD	145.980	FSK	9600	436.500	FSK	9600
TO-31	JD	TBA	—	—	436.923	—	—
TO-32	JD	TBA	—	—	435.325/ 435.225	—	—

spect to the observer. For satellites with linear transponders, operating procedures have been established to minimize interference to other stations in the passband while staying tuned to the desired station. For digital satellites, the modem usually tunes the receiver frequency to compensate for Doppler shift.

Satellites with Analog Transponders

Table 23.6 is a list of frequencies for all Amateur Radio satellites providing linear transponder communication facilities, and Table 23.7 contains the Phase 3D frequencies. Both were accurate as of 1999.

A sensible approach for getting started in amateur satellite communication is to choose one of the low Earth orbit satellites (RS-15, for example) operating on frequencies for which you already have equipment. Even though the access times will be much shorter than with the higher orbit satellites, experience can be gained using existing equipment and simple antennas. Then, if the bug bites hard, assemble a station to work the wider coverage birds.

There is so much emphasis on the wide-area coverage of high altitude satellites, that the low Earth orbit (LEO) satellites often do not receive proper attention. There is a great amount of satisfaction to be gained from working other stations via LEO satellites, however. Moreover, such contacts provide practice at tracking and tuning that will prove valuable no matter which satellite is eventually used.

A first attempt at amateur satellite communication should be undertaken as inexpensively as possible. Successful operation on LEO satellites can be realized using omnidirectional antennas, an uplink power in the area of 100 W EIRP and a good receiver. If Mode A is used, a 10-m receive preamp might prove useful. Similarly, if Mode J is used, a 70-cm preamp could be beneficial. One goal of an entry-level approach is to eliminate the complexity of high-gain steerable antennas. A power level of 50-100 W into an omnidirectional antenna is more than adequate for CW QSOs and at times will support SSB QSOs.

Glossary of Satellite Terminology

AMSAT — A registered trademark of the Radio Amateur Satellite Corporation, a nonprofit 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, PO Box 27, Washington, DC 20044.)

Anomalistic period — The elapsed time between two successive perigees of a satellite.

AO-# — The designator used for AMSAT OSCAR spacecraft in flight, by sequence number.

AOS — Acquisition of signal. The time at which radio signals are first heard from a satellite, usually just after it rises above the horizon.

Apogee — The point in a satellite's orbit where it is farthest from Earth.

Area coordinators — An AMSAT corps of volunteers who organize and coordinate amateur satellite user activity in their particular state, municipality, region or country. This is the AMSAT grassroots organization set up to assist all current and prospective OSCAR users.

Argument of perigee — The polar angle that locates the perigee point of a satellite in the orbital plane; drawn between the ascending node, geocenter, and perigee; and measured from the ascending node in the direction of satellite motion.

Ascending node — The point on the ground track of the satellite orbit where the sub-satellite point (SSP) crosses the equator from the Southern Hemisphere into the Northern Hemisphere.

Az-el mount — An antenna mount that allows antenna positioning in both the azimuth and elevation planes.

Azimuth — Direction (side-to-side in the horizontal plane) from a given point on Earth, usually expressed in degrees. North = 0° or 360°; East = 90°; South = 180°; West = 270°.

Circular polarization (CP) — A special case radio energy emission where the electric and magnetic field vectors rotate about the central axis of radiation. As viewed along the radiation path, the rotation directions are considered to be right-hand (RHCP) if the rotation is clockwise, and left-hand (LHCP) if the rotation is counterclockwise.

Descending node — The point on the ground track of the satellite orbit where the sub-satellite point (SSP) crosses the equator from the Northern Hemisphere into the Southern Hemisphere.

Desense — A problem characteristic of many radio receivers in which a strong RF signal overloads the receiver, reducing sensitivity.

Doppler effect — An apparent shift in frequency caused by satellite movement toward or away from your location.

Downlink — The frequency on which radio signals originate from a satellite for reception by stations on Earth.

Earth station — A radio station, on or near the surface of the Earth, designed to transmit or receive to/from a spacecraft.

Eccentricity — The orbital parameter used to describe the geometric shape of an elliptical orbit; eccentricity values vary from e = 0 to e = 1, where e = 0 describes a circle and e = 1 describes a straight line.

EIRP — Effective isotropic radiated power. Same as ERP except the antenna reference is an isotropic radiator.

Elliptical orbit — Those orbits in which the satellite path describes an ellipse with the Earth at one focus.

Elevation — Angle above the local horizontal plane, usually specified in degrees. (0° = plane of the Earth's surface at your location; 90° = straight up, perpendicular to the plane of the Earth).

Epoch — The reference time at which a particular set of parameters describing satellite motion (***Keplerian elements***) are defined.

EQX — The reference equator crossing of the ascending node of a satellite orbit, usually specified in UTC and degrees of longitude of the crossing.

ERP — Effective radiated power. System power output after transmission-line losses and antenna gain (referenced to a dipole) are considered.

ESA — European Space Agency. A consortium of European governmental groups pooling resources for space exploration and development.

FO-# — The designator used for Japanese amateur satellites, by sequence number. Fuji-OSCAR 12 and Fuji-OSCAR 20 were the first two such spacecraft.

Geocenter — The center of the Earth.

Geostationary orbit — A satellite orbit at such an altitude (approximately 22,300 miles) over the equator that the satellite appears to be fixed above a given point.

Groundtrack — The imaginary line traced on the surface of the Earth by the subsatellite point (SSP).

Inclination — The angle between the orbital plane of a satellite and the equatorial plane of the Earth.

Increment — The change in longitude of ascending node between two successive passes of a specified satellite, measured in degrees West per orbit.

Iskra — Soviet low-orbit satellites launched manually by cosmonauts aboard Salyut missions. Iskra means “spark” in Russian.

JAMSAT — Japan AMSAT organization.

Keplerian Elements — The classical set of six orbital element numbers used to define and compute satellite orbital motions. The set is comprised of inclination, Right Ascension of Ascending Node (RAAN), eccentricity, argument of perigee, mean anomaly and mean motion, all specified at a particular epoch or reference year, day and time. Additionally, a decay rate or drag factor is usually included to refine the computation.

LHCP — Left-hand circular polarization.

LOS — Loss of signal — The time when a satellite passes out of range and signals from it can no longer be heard. This usually occurs just after the satellite goes below the horizon.

Mean anomaly (MA) — An angle that increases uniformly with time, starting at perigee, used to indicate where a satellite is located along its orbit. MA is usually specified at the reference epoch time where the Keplerian elements are defined. For AO-10 the orbital time is divided into 256 parts, rather than degrees of a circle, and MA (sometimes called phase) is specified from 0 to 255. Perigee is therefore at MA = 0 with apogee at MA = 128.

Mean motion — The Keplerian element to indicate the complete number of orbits a satellite makes in a day.

Microsat — Collective name given to a series of small amateur satellites having store-and-forward capability (OSCARs 14-19, for example).

NASA — National Aeronautics and Space Administration, the US space agency.

Nodal period — The amount of time between two successive ascending nodes of satellite orbit.

Orbital elements — See ***Keplerian Elements***.

Orbital plane — An imaginary plane, extending throughout space, that contains the satellite orbit.

OSCAR — Orbiting Satellite Carrying Amateur Radio.

PACSAT— Packet radio satellite (see ***Microsat*** and ***UoSAT-OSCAR***).

Pass — An orbit of a satellite.

Passband — The range of frequencies handled by a satellite translator or transponder.

Perigee — The point in a satellite’s orbit where it is closest to Earth.

Period — The time required for a satellite to make one complete revolution about the Earth. See ***Anomalistic period*** and ***Nodal period***.

Phase I — The term given to the earliest, short-lived OSCAR satellites that were not equipped with solar cells. When their batteries were depleted, they ceased operating.

Phase 2 — Low-altitude OSCAR satellites. Equipped with solar panels that powered the spacecraft systems and recharged their batteries, these satellites have been shown to be capable of lasting up to five years (OSCARs 6, 7 and 8, for example).

Phase 3 — Extended-range, high-orbit OSCAR satellites with very long-lived solar power systems (OSCARs 10 and 13, for example).

Phase 4 — Proposed OSCAR satellites in geostationary orbits.

Precession — An effect that is characteristic of AO-10 and Phase 3 orbits. The satellite apogee SSP will gradually change over time.

Project OSCAR — The California-based group, among the first to recognize the potential of space for Amateur Radio; responsible for OSCARs I through IV.

QRP days — Special orbits set aside for very low power uplink operating through the satellites.

RAAN — Right Ascension of Ascending Node. The Keplerian element specifying the angular distance, measured eastward along the celestial equator, between the vernal equinox and the hour circle of the ascending node of a spacecraft. This can be simplified to mean roughly the longitude of the ascending node.

Radio Sputnik — Russian Amateur Radio satellites (see ***RS*** #).

Reference orbit — The orbit of Phase II satellites beginning with the first ascending node during that UTC day.

RHCP — Right-hand circular polarization.

RS # — The designator used for most Russian Amateur Radio satellites (RS-1 through RS-15, for example).

Satellite pass — Segment of orbit during which the satellite "passes" nearby and in range of a particular ground station.

Sidereal day — The amount of time required for the Earth to rotate exactly 360° about its axis with respect to the "fixed" stars. The sidereal day contains 1436.07 minutes (see ***Solar day***).

Solar day — The solar day, by definition, contains exactly 24 hours (1440 minutes). During the solar day the Earth rotates slightly more than 360° about its axis with respect to "fixed" stars (see ***Sidereal day***).

Spin modulation — Periodic amplitude fade-and-peak resulting from the rotation of a satellite's antennas about its spin axis, rotating the antenna peaks and nulls.

SSC — Special service channels. Frequencies in the downlink passband of AO-10 that are set aside for authorized, scheduled use in such areas as education, data exchange, scientific experimentation, bulletins and official traffic.

SSP — Subsatellite point. Point on the surface of the Earth directly between the satellite and the geocenter.

Telemetry — Radio signals, originating at a satellite, that convey information on the performance or status of onboard subsystems. Also refers to the information itself.

Transponder — A device onboard a satellite that receives radio signals in one segment of the spectrum, amplifies them, translates (shifts) their frequency to another segment of the spectrum and retransmits them. Also called linear translator.

UoSAT-OSCAR (UO #) — Amateur Radio satellites built under the coordination of radio amateurs and educators at the University of Surrey, England.

Uplink — The frequency at which signals are transmitted from ground stations to a satellite.

Window — Overlap region between acquisition circles of two ground stations referenced to a specific satellite. Communication between two stations is possible when the subsatellite point is within the window.

The author has had many satellite contacts using the approach described here. **Fig 23.18** shows a few QSL cards from contacts made from his QTH on the lower Texas Gulf Coast. Fig 23.19 shows the ground plane and small Yagi antennas used on the 2-m and 70-cm bands. On 10 m, either a dipole or wire loop antenna was used.

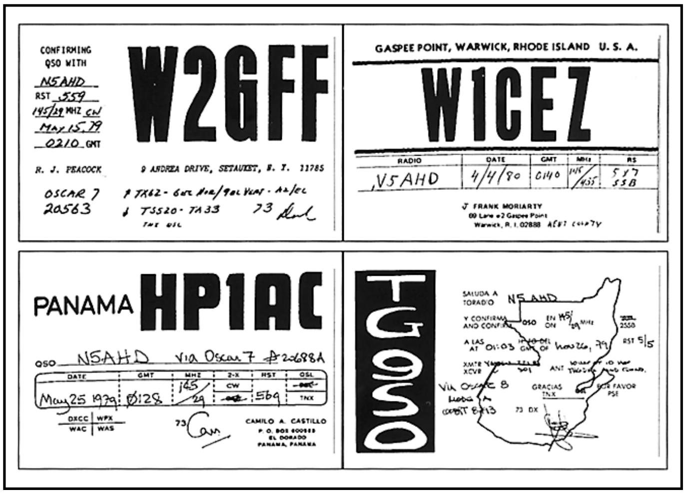


Fig 23.18 — Some stations worked from a QTH on the lower Texas Gulf Coast using simple antennas.

Assembling a Mode B Station

If antenna installation restrictions and budget constraints are not a problem, you may want to try the high-orbit satellites using Mode B (430 MHz up, 145 MHz down). This section gives the important considerations for assembling this type of station. Obviously, these requirements

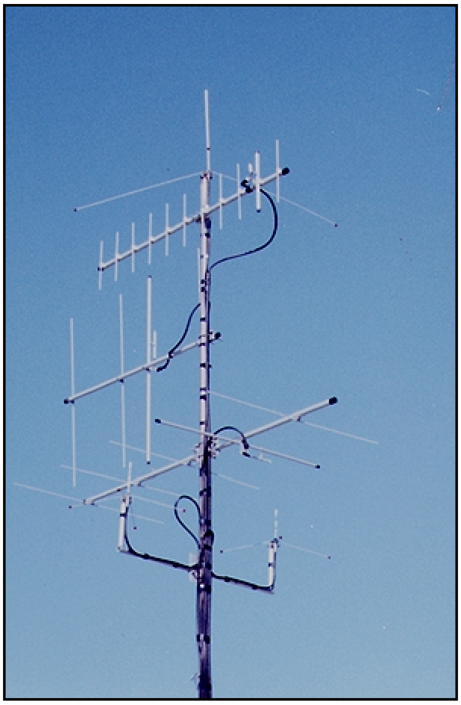


Fig 23.19 — Simple ground plane and Yagi antennas can be used for low-Earth-orbit (LEO) satellite contacts.

can be realized in many different system configurations. More information can be found in the section on equipping a station.

A typical station will use a 145-MHz circularly polarized antenna of at least 13 dBic having switchable polarization sense between RHCP and LHCP. If switchable polarization is not available, then RHCP is the preferred choice. Even though antennas with gain exceeding 18 dBi are available, they are not cost effective because the local noise floor becomes the limiting factor. Keep in mind that this antenna is used for both the Mode B downlink and the Mode J uplink.

Similarly, the 435-MHz antenna should be circularly polarized and have at least 13 dBic gain. Higher gains, in the range of 14 to 18 dBic, are preferred. Switchable polarization is even more desirable because the 435-MHz antenna serves as the uplink on Modes B and S as well as the downlink for Mode J. Increased antenna gain is more usable because the local noise floor is not usually a limiting factor as it is at 145 MHz.

The 1269-MHz Mode-L uplink antenna should have at least 20-dBic gain. Due to the short wavelength (23 cm), the required gain is achievable with relatively small antenna arrays such as four phased helices. Arrays of loop Yagis and standard horizontally polarized Yagis can be used but there will be a 3-dB penalty for polarization mismatch.

The 2400-MHz Mode-S downlink antenna should have at least 26 dBic gain. However, the required gain is easily achievable using a 4-ft parabolic dish or a quad helix array.

The antenna array must be steerable in both azimuth and elevation. The elevation rotator boom must be made of a nonmetallic material such as fiberglass. Feed-line loss should be held below 2 dB, and less than 1 dB is preferable.

The EIRP of the 435 and 145-MHz transmitting system should be no more than 1000 W and adjustable, allowing the lowest required power level to be used. For Modes B and J most communications can be conducted using 100 to 300 W EIRP. A higher EIRP may be needed on Mode S, but the requirement will still be below the 1000 W EIRP level. For Mode L, the required EIRP at 1269 MHz is between 3000 and 5000 W.

The 145-MHz receiving system should have a noise figure no greater than 2 dB but less than 1 dB is probably not usable even if it can be achieved. The 435 and 2400-MHz receiving system noise figures should be less than 1 dB.

Using high altitude satellites should be considered weak signal work. Always improve the receiving system first before increasing transmit EIRP. Once Phase 3D is operating, the downlink gain requirements will be much lower due to the higher transmitter powers used at the spacecraft.

ASSEMBLING A STATION FOR PHASE 3D

This section was written by ARRL Lab Engineer Zack Lau, W1VT.

If all goes well, Phase 3D will be similar to OSCAR 13, but much more “user friendly” for voice users. Thus, a station that did well with OSCAR 13 has little to worry about; the equipment will be more than enough for Phase 3D. Those building new stations can take advantage of technology improvements in the satellite, and get acceptable performance with more modest SSB/CW stations. Due to the laws of physics, those expecting loud signals like those of low Earth orbit satellites will still be disappointed. A station 100 times farther away is 40 dB weaker (400 km vs 40,000 km). Thus, digital users won’t see any signal strength improvement compared to low Earth orbit satellites currently in use—the extra distance will eliminate improvements in power and antennas.

Perhaps the biggest change is the orbit—it will repeat every two days. Thus, manually rotated or even fixed antennas will become much more practical, possibly eliminating the need for an expensive rotator system, for those who just want to maintain a schedule with another station. Stations without rotators may wish to use smaller antennas to maximize their operating time. This generally requires more power and better receivers to compensate. Mast mounting equipment near the antenna will reduce needed antenna size. Using circularly polarized antennas as opposed to higher gain linearly polarized antennas will help considerably toward optimizing your satellite time if the antennas don't move. However, rotatable linear arrays are probably preferred for local use. Horizontal polarization is the standard for terrestrial SSB/CW.

The next biggest change for most users will be on the 2401-MHz downlink—there will be a linear 60-W PEP transponder, as opposed to the 1-W experiment aboard OSCAR 13. Thus, it becomes possible to use a simple RHCP 16-turn helix instead of a 2-ft dish. However, it may be more cost effective to use a 2-ft dish with a 1.8 dB NF receiver than to obtain a 0.6-dB NF receiver for the helix. Since these are system noise figures, it isn't unusual to need a 0.4-dB NF preamp to get that 0.6-dB NF receiver. The dish with a no-tune preamp and receive converter makes a lot more sense for a builder with minimal test equipment. The antenna gain to receiver temperature ratio (G/T) to shoot for is 0.53/kelvin. There will also be a 13-cm uplink—plan on +27-dBWic. This is 5 W at the feed of a 20-dBic 2-ft dish. 10 W to a loop Yagi would also work; the extra 3 dB compensates for the polarization mismatch. However, the satellite won't be capable of in-band full duplex—a band can only be used on transmit or receive, not both simultaneously. Thus, since the 13-cm downlink is expected to be used heavily, the uplink is likely to get little use.

The 436-MHz uplink will need about 20 dBWic—10 W to a 5-turn 3-ft boom helix or a 5-ft boom circularly polarized Yagi. Slightly larger antennas can compensate for feed-line loss. Chances are, there will be little benefit to running a big amplifier—there will be an automatic notcher called LEILA to prevent stations from hogging the transponder. Hopefully, this will force stations to improve receive capability, when they find it difficult to hear themselves on the satellite.

On 436-MHz receive, you want a gain to system noise temperature ratio of 0.032/kelvin. A 12-dB antenna has a gain of 16. Thus, for a 12-dBic antenna you need a noise temperature under 500 kelvins, or 4 dB. Earth noise, feed-line noise and antenna noise all add to the receiver noise. A mast-mounted preamplifier and a small Yagi will work quite well. If the feed-line run is short, perhaps 50 ft, a larger antenna would allow having the preamplifier near the operating position.

The 1269-MHz uplink will need about 26-dBWic—8 W to a 12-ft boom loop Yagi, 10 W to an RHCP 16-turn helix, or 6 W to a 3-ft dish. Current rules prohibit having a 1269-MHz downlink, so this isn't planned for any of the satellites.

The 146-MHz uplink will need about 18 dBWic—10 W to a 5-ft boom circularly polarized Yagi or 3-turn helix. Again, this is power at the feed of the antenna.

The 146-MHz downlink depends heavily on your local noise level. Amateurs in rural areas can do just fine with a 2-dB system noise figure and an 8-dBic antenna. The predicted G/T needed is 0.008/kelvin. Those in heavily populated urban areas may be disappointed with the results—even with a big circularly polarized beam and a mast-mounted preamplifier. These amateurs should consider using a quieter band for the downlink.

Two meters does have a distinct advantage in one area—less attenuation through trees. As the frequency goes up, so does the attenuation through trees. Thus, while it is possible to hear the 2.4-GHz downlink indoors, tree blockages often degrade signals. It gets worse if you are using a small antenna with a low-noise preamplifier. Not only does a tree block more of a small antenna, but it also acts as a warm noise source. This noise adds to the system noise figure, degrading signals even more.

Amateurs attempting to contact the satellite on the horizon with microwaves may notice two degradations to the path. Atmospheric loss can add another 1.6 dB of path loss at 2.4 GHz, increasing to 3 dB at 10 GHz, though this is typically under 0.1 dB at 10 GHz for vertical paths. An antenna fixed on the horizon will also see noise from the warm Earth, reducing system sensitivity. A more serious problem may be finding excellent locations where one can worry about such details.

It is easy to overestimate the ease of obtaining a low noise figure, particularly at microwaves. A single bad connector, adapter or piece of coax can stop the system from meeting expectations. Avoid cheap connectors and coax. Getting all the pieces to work properly together can be a challenge. Fortunately, MMICs and computer aided design have resulted in designs that reduce potential problems. Still, it is possible to have pieces that work fine by themselves, but poorly as a system. People have even had problems with poorly designed power supplies generating spurs or modulating received signals. Fortunately microwave ovens have not interfered with 2.4-GHz amateur satellite work. Similarly, it is easy to underestimate the ease of obtaining low angle radiation at 2 m. The antenna height required may not be practical. It is often wise to have a bit of excess capability, often called link margin. If you do have excess uplink power, you should have a method of easily scaling it back.

While they are not expected to be as popular as the lower bands, a 5668-MHz uplink (34 dBWic), a 60-W PEP 10451-MHz downlink (G/T=13/kelvin) and a 24048-MHz downlink will be included. Even with state-of-the-art equipment, it is likely that the latter will not be heard on long LOS paths due to atmospheric absorption.

Simple antennas like the turnstile work well with the satellite overhead, but not so well near the horizon. A simple vertical works better near the horizon. It makes a lot of sense to match the orbit track with the antenna pattern, keeping in mind that some computer simulations aren't accurate with wires close to real ground. Ionized atmospheric layers can significantly disturb satellite communications by blocking signals to and from the satellite. There may also be a 21-MHz uplink, but it is likely that it will not work well for many users, due to the high galactic noise, and the modest antenna on the satellite.

The picture isn't quite so rosy for digital users—the 146-MHz uplink will need +22 dBWic, 10 W to a 12-ft boom circularly polarized Yagi. The 1270-MHz uplink will need +34 dBWic, or 10 W to a 6-ft dish.

The 436-MHz downlink will require a G/T of 0.12/kelvin, or a 13 dBic antenna with a 1 dB preamp (allowing 50 kelvins for sky and antenna noise, and 0.5 dB extra receiver noise).

DIGITAL COMMUNICATIONS SATELLITES

The amateur satellite enthusiast with an interest in digital communications will find a multitude of satellites with which to experiment. All of the digital communications satellites currently operating in the Amateur Satellite Service are in low Earth orbit. At first, it might seem that the short access times of LEO satellites would not support useful communications services. But, as will be seen shortly, this is certainly not the case.

There are three general categories of Amateur Radio satellites having digital communications links. First, there are those that transmit telemetry and other information of interest using digital codes but do not provide store-and-forward message service. Satellites in this cate-gory include DOVE-OSCAR 17 (DO-17) and UoSAT-OSCAR 11 (UO-11). Also, KITSAT-OSCAR 23 transmits images of the Earth (see **Fig 23.20**). Satellites such as DO-17 and UO-11 provide an excellent opportunity to learn the mechanics of tracking LEO spacecraft and decoding their digital transmissions. At the same time, study of the captured telemetry data will provide an appreciation of many aspects of spacecraft engineering.

Another class of LEO satellites are those that provide

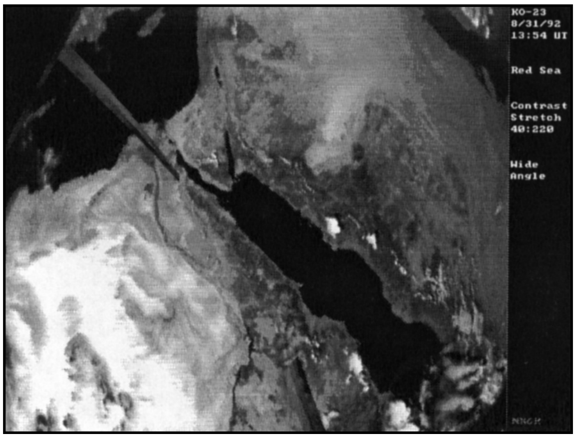


Fig 23.20 — This image of the Red Sea was downloaded from KITSAT-OSCAR 23. *(photo courtesy Harold Price, NK6K)*

store-and-forward message services via a user interface similar to those found on terrestrial packet radio bulletin board systems.

Finally, there are many satellites that provide store-and-forward services using the PACSAT Broadcast Protocol developed by Ward and Price. Satellites using the PACSAT Broadcast Protocol include: AMSAT-OSCAR 16 (AO-16), LUSAT-OSCAR 19 (LO-19), UoSAT-OSCAR 22 (UO-22), KITSAT-OSCAR 23 (KO-23) and KITSAT-OSCAR 25 (KO-25). In addition to these satellites, there are other projects in the design and construction stages that will also use the PACSAT Broadcast Protocol (PBP). Table 23.9 contains a list of the digital store-and-forward satellites operating at the time of publication.

The Sounds of Amateur Radio

Listen to 9600-baud packet transmissions on the KITSAT-OSCAR 25 (KO-25) downlink.

Satellites Transmitting Digital Telemetry Data Only

Monitoring satellites transmitting digital telemetry data provides an excellent receive-only introduction to amateur satellite operations for the computer enthusiast. Of course, one could monitor telemetry from any of the digital satellites, but this section will deal with UO-11 because it does not provide two-way communication capabilities.

UoSAT-OSCAR 11

UO-11 transmits various kinds of data on its 2-m downlink (145.825 MHz) and most of it is plain-text ASCII, including bulletins and spacecraft telemetry. It is important to note that UO-11 transmits plain text and not packets such as those used in terrestrial 2-m packet radio networks. This means that a packet radio TNC is not required at the ground station.

Fig 23.21 shows a typical equipment configuration for receiving UO-11 transmissions. As can be seen, all that is necessary is to connect the receiver audio output to the demodulator input and the serial data output from the demodulator to the computer serial port. If a modem is purchased at a flea market or other used equipment outlet, be sure that it a Bell 202 standard as opposed to Bell 212. The type of modem is usually obvious from the model number but the 212 is much more common than the 202. Kits for Bell 202 demodulators are available commercially and construction plans have also been published in *QST*.

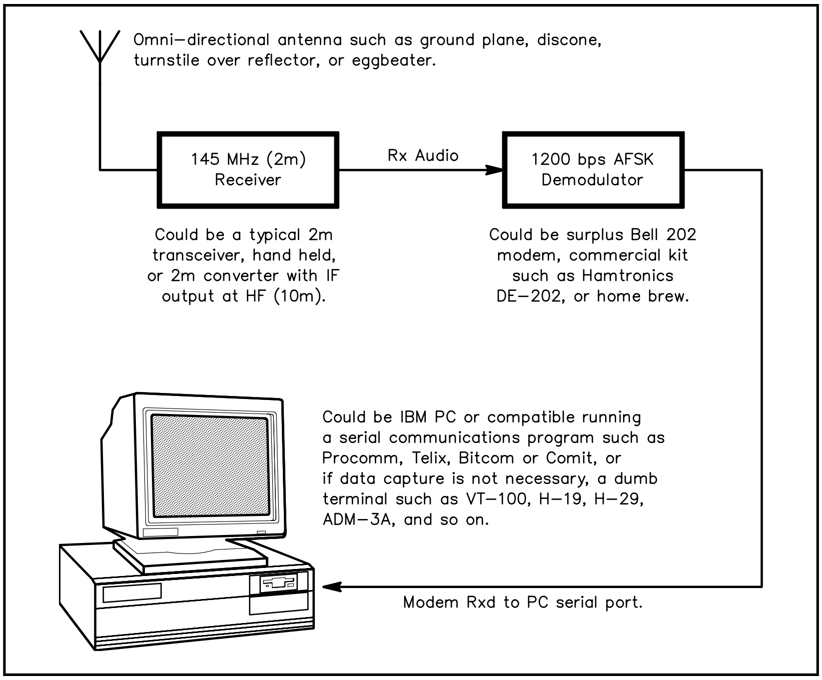
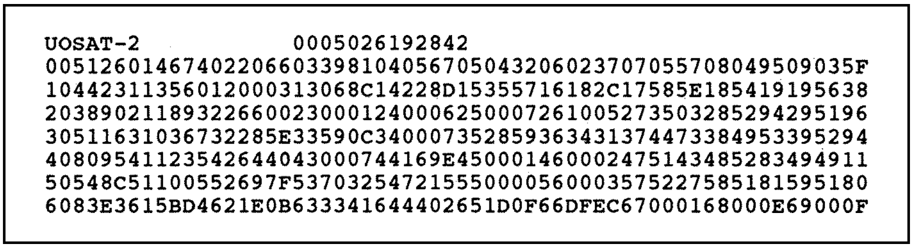


Fig 23.21 — Equipment needed to monitor digital transmissions from UoSAT-OSCAR 11.

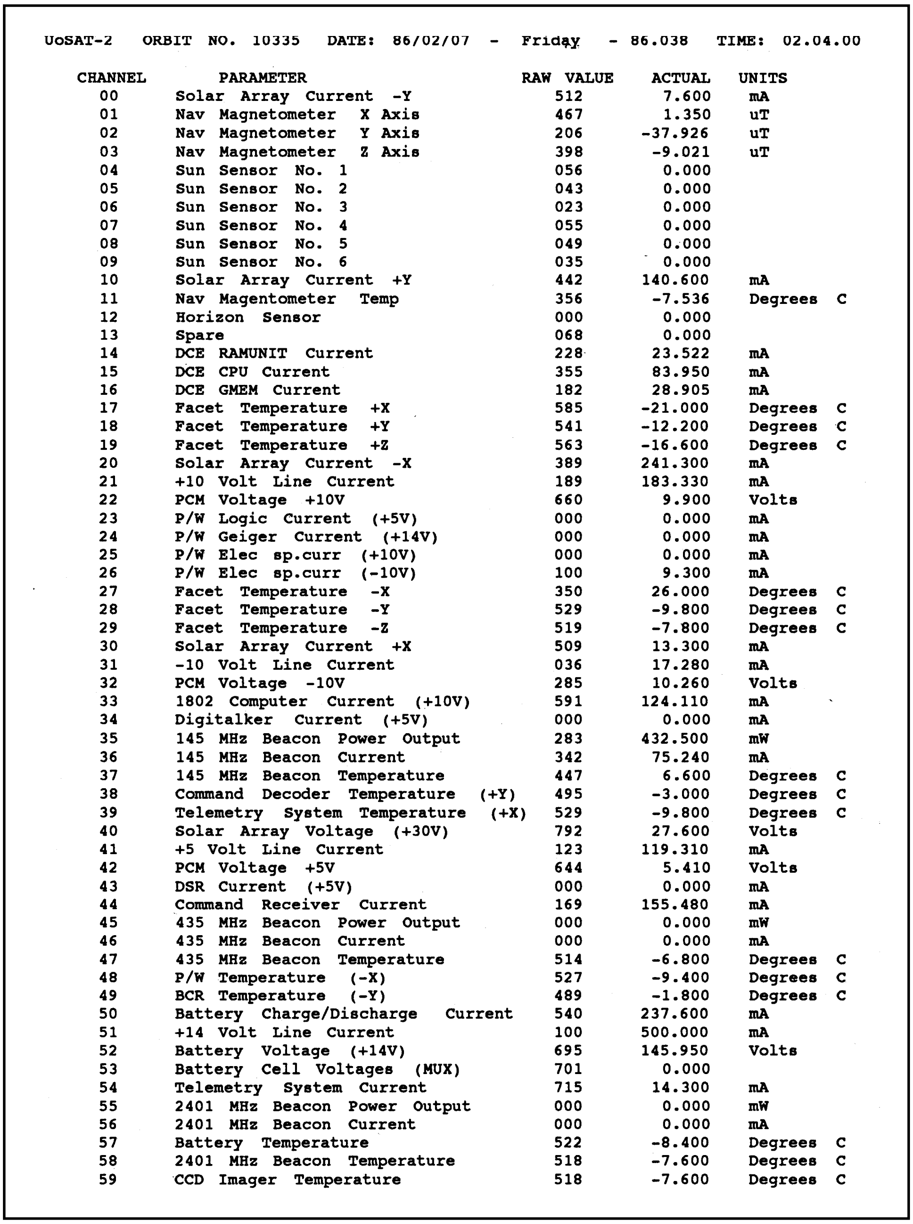
In a minimal equipment configuration it is also possible to eliminate the expense of a computer and substitute a serial terminal instead. However, capturing the received telemetry for later decoding or real-time telemetry decoding will require a computer. In this regard, remember that 80286 and earlier PCs are now sold at very reasonable prices and even discarded outright. These machines are entirely adequate to serve as substitutes for serial terminals and can perform the telemetry capture and decoding functions as well.

Fig 23.22 shows a typical UO-11 raw telemetry frame while **Fig 23.23** shows a telemetry frame decoded to engineering data. Telemetry capture and decoding software for UO-11 is available from AMSAT-NA and AMSAT-UK.



```
UOSAT-2           0005026192842
0051260146740220660339810405670504320602370705570804950903 5F
104423113560120003130 68C14228D15355716182C17585E185419195638
2038902118932266002300012400062500072610052735032852942 95196
3051163103673228 5E33590C340007352859363431374473384953395294
408095411235426440430007441 69E450001460002475143485283494911
50548C51100552697F537032547215550000560003575227585181595180
6083E3615BD4621E0B633341644402651D0F66DFEC67000168000E69000F
```

Fig 23.22 — A UoSAT-OSCAR 11 (UoSAT-2) telemetry frame as monitored.



```
UoSAT-2   ORBIT  NO.  10335   DATE:  86/02/07  -  Friday   - 86.038   TIME:  02.04.00

  CHANNEL        PARAMETER                         RAW  VALUE    ACTUAL    UNITS
     00      Solar  Array  Current  -Y                512          7.600    mA
     01      Nav  Magnetometer   X Axis               467          1.350    uT
     02      Nav  Magnetometer   Y Axis               206        -37.926    uT
     03      Nav  Magnetometer   Z Axis               398         -9.021    uT
     04      Sun  Sensor  No.  1                      056          0.000
     05      Sun  Sensor  No.  2                      043          0.000
     06      Sun  Sensor  No.  3                      023          0.000
     07      Sun  Sensor  No.  4                      055          0.000
     08      Sun  Sensor  No.  5                      049          0.000
     09      Sun  Sensor  No.  6                      035          0.000
     10      Solar  Array  Current  +Y                442        140.600    mA
     11      Nav  Magentometer   Temp                 356         -7.536    Degrees  C
     12      Horizon  Sensor                          000          0.000
     13      Spare                                    068          0.000
     14      DCE  RAMUNIT  Current                    228         23.522    mA
     15      DCE  CPU  Current                        355         83.950    mA
     16      DCE  GMEM  Current                       182         28.905    mA
     17      Facet  Temperature   +X                  585        -21.000    Degrees  C
     18      Facet  Temperature   +Y                  541        -12.200    Degrees  C
     19      Facet  Temperature   +Z                  563        -16.600    Degrees  C
     20      Solar  Array  Current  -X                389        241.300    mA
     21      +10  Volt  Line  Current                 189        183.330    mA
     22      PCM  Voltage  +10V                       660          9.900    Volts
     23      P/W  Logic  Current  (+5V)               000          0.000    mA
     24      P/W  Geiger  Current  (+14V)             000          0.000    mA
     25      P/W  Elec  sp.curr  (+10V)               000          0.000    mA
     26      P/W  Elec  sp.curr  (-10V)               100          9.300    mA
     27      Facet  Temperature   -X                  350         26.000    Degrees  C
     28      Facet  Temperature   -Y                  529         -9.800    Degrees  C
     29      Facet  Temperature   -Z                  519         -7.800    Degrees  C
     30      Solar  Array  Current  +X                509         13.300    mA
     31      -10  Volt  Line  Current                 036         17.280    mA
     32      PCM  Voltage  -10V                       285         10.260    Volts
     33      1802  Computer  Current  (+10V)          591        124.110    mA
     34      Digitalker  Current  (+5V)               000          0.000    mA
     35      145  MHz  Beacon  Power  Output          283        432.500    mW
     36      145  MHz  Beacon  Current                342         75.240    mA
     37      145  MHz  Beacon  Temperature            447          6.600    Degrees  C
     38      Command  Decoder  Temperature  (+Y)      495         -3.000    Degrees  C
     39      Telemetry  System  Temperature  (+X)     529         -9.800    Degrees  C
     40      Solar  Array  Voltage  (+30V)            792         27.600    Volts
     41      +5  Volt  Line  Current                  123        119.310    mA
     42      PCM  Voltage  +5V                        644          5.410    Volts
     43      DSR  Current  (+5V)                      000          0.000    mA
     44      Command  Receiver  Current               169        155.480    mA
     45      435  MHz  Beacon  Power  Output          000          0.000    mW
     46      435  MHz  Beacon  Current                000          0.000    mA
     47      435  MHz  Beacon  Temperature            514         -6.800    Degrees  C
     48      P/W  Temperature   (-X)                  527         -9.400    Degrees  C
     49      BCR  Temperature   (-Y)                  489         -1.800    Degrees  C
     50      Battery  Charge/Discharge   Current      540        237.600    mA
     51      +14  Volt  Line  Current                 100        500.000    mA
     52      Battery  Voltage  (+14V)                 695        145.950    Volts
     53      Battery  Cell  Voltages  (MUX)           701          0.000
     54      Telemetry  System  Current               715         14.300    mA
     55      2401  MHz  Beacon  Power  Output         000          0.000    mW
     56      2401  MHz  Beacon  Current               000          0.000    mA
     57      Battery  Temperature                     522         -8.400    Degrees  C
     58      2401  MHz  Beacon  Temperature           518         -7.600    Degrees  C
     59      CCD  Imager  Temperature                 518         -7.600    Degrees  C
```

Fig 23.23 — A UoSAT-OSCAR 11 (UoSAT-2) telemetry frame decoded to engineering units.

Satellites Utilizing the PACSAT File Broadcast Protocol

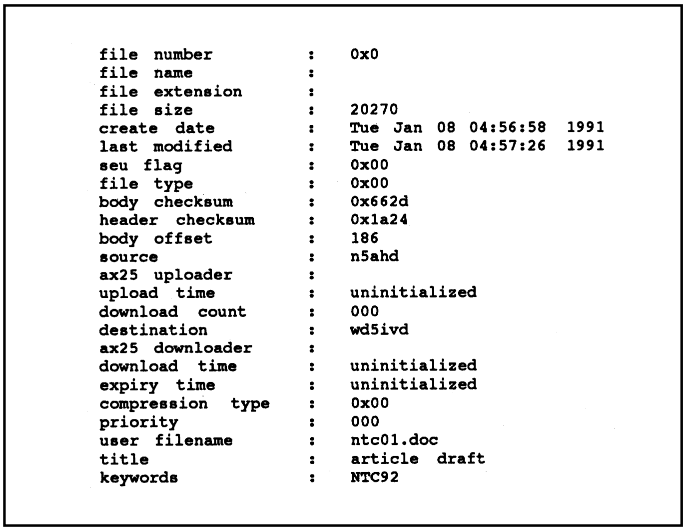
Many Amateur Radio operators make use of terrestrial packet radio bulletin board systems (PBBS). These PBBSs are the Amateur Radio counterpart of microcomputer-based bulletin board systems, which use the public telephone network. However, much of the activity on terrestrial PBBSs is taken up with the repeated retrieval of information of general interest. For example, Amateur Radio operators interested in satellite operations may access a PBBS to obtain the reference elements used in their orbital prediction programs. Consequently, the exact same information may be transmitted many times. On terrestrial networks, repeated transmission of the same data can be tolerated because the system capacity is available by virtue of the 24-hour per day access time and multiple stations providing PBBS service. Such capacity obviously does not exist in the case of a LEO satellite-based system with limited visibility time at any particular ground station location. What is needed is a way for multiple users to benefit from the same transmission of a particular file since many users are within the satellite footprint at the same time.

Satellites such as AO-16 and UO-22 are in low Earth orbits at an average altitude of 800 km. From that vantage point, over populated areas such as the continental United States, hundreds and perhaps even thousands of potential users are within the satellite's footprint. Although at any given ground station location (in the middle latitudes) there will be only 50 to 60 minutes of access time per day, there is still sufficient time for any individual station to receive a large amount of data. For example, with AO-16 operating at 1200 bps, it is possible to receive approximately 500 kbytes of data per day. For UO-22, operating at 9600 bps, about 4 Mbytes of data could be received. This assumes, of course, that the ground station is in operation for all times the satellite is visible.

Based on the nature of the system components and on the experience gained with the UoSAT-2 Digital Communications Experiment (DCE)[1], Ward and Price have developed the PACSAT Protocol Suite, which is fully documented in Notes 2-6. Look to these references for the complete details of the protocol implementation. The data-link layer protocol used is AX.25.[7] The PACSAT Protocol Suite implements a file broadcast mode and a file server mode using a common file format. Each of these two modes will be described briefly. The hardware and software required to access the satellite will be presented in the next section.

PACSAT File Header

Files being transmitted in broadcast mode and files being uploaded in file server mode make use of the PACSAT file header. **Fig 23.27** shows an example of the information contained in the file header. In broadcast mode, an individual data-link layer frame information field contains only the file number (ID), file type and the offset to the location in the file where the data belongs. The other information needed to identify the file and its attributes are contained in the file header. User software (PFHADD) has been provided to add a PACSAT file header to a file before it is uploaded and to remove or display a file header after the file has been downloaded (PHS).



```
file  number          :    0x0
file  name            :
file  extension       :
file  size            :    20270
create  date          :    Tue  Jan  08  04:56:58  1991
last  modified        :    Tue  Jan  08  04:57:26  1991
seu  flag             :    0x00
file  type            :    0x00
body  checksum        :    0x662d
header  checksum      :    0x1a24
body  offset          :    186
source                :    n5ahd
ax25  uploader        :
upload  time          :    uninitialized
download  count       :    000
destination           :    wd5ivd
ax25  downloader      :
download  time        :    uninitialized
expiry  time          :    uninitialized
compression  type     :    0x00
priority              :    000
user  filename        :    ntc01.doc
title                 :    article  draft
keywords              :    NTC92
```

Fig 23.27 — PACSAT file header contents.

File and Directory Broadcast Mode

The PACSAT Broadcast Protocol has the following attributes: (1) Any frame, when received independently, can be placed in the proper location within the file to which it belongs; (2) When all frames have been received, the receiving station can tell that the file is complete; and (3) For file types where it makes sense, partial files are usable. This implies that if a data compression scheme is used, it should be possible to incrementally decompress the file.

The broadcast mode transmits files in the message system memory and their directory entries by giving each file on the broadcast queue a certain amount of downlink time. The broadcasts continue in a round-robin fashion until the user's request has been filled.

File broadcasting is done as a series of AX.25[7] unnumbered information (UI) frames. UI frames are not acknowledged by the receiver and order of delivery is not guaranteed. The terminal node controller (TNC) passes the frame on to the application program only if the frame is correctly received. Error checking of the frame is done via CRC-16 by the TNC. The format of the information field of a broadcast frame is shown below.

<flags> <file id> <file type> <offset> <data> <crc>

In the information field format above, the file ID field is a file number assigned by the file server system when the file is uploaded rather than an ASCII character string file name. The offset gives the position relative to the beginning of the file where the data belongs. The CRC shown is a check on the I-field contents only and is included to allow detection of errors on the serial link between the TNC and the computer.

Requests to place files in the broadcast queue are likewise done with UI frames. The spacecraft does respond to broadcast requests but not in terms of a data-link layer acknowledgment. It only sends a UI frame with “OK” in the information field to the station making a successful broadcast request. Error indications, such as broadcast queue full, are also transmitted as UI frames.

Even though a station may also access the satellite in a connected-mode transaction (described in the next section), the file and directory broadcast mode is the primary method of operation. Since multiple users in the satellite footprint may want to capture the same files and update their directories at the same time, downlink utilization is maximized when broadcasting is used. Individual users may request fills of specific “holes” in their captured files and directories, but the rebroadcast of entire files or directories for multiple users is eliminated.

File Server Mode

AO-16, UO-22 and similar satellites can also operate in file server mode, which is transaction oriented. Currently, the file server mode is used only for uploading files to the message system. An upload transaction can be resumed later if it was previously interrupted (by LOS, for example).

When using the file server mode, an AX.25 connection exists between the ground station and the spacecraft. Standard balanced-mode HDLC procedures control the exchange at the data-link layer. The transaction-oriented operation ensures that the availability of the uplinks is maximized.

PACSAT Ground Station Equipment

A typical equipment configuration for utilizing AO-16 and UO-22 is shown in **Fig 23.28**. Even though the diagram shows a station set up to operate on both AO-16 and UO-22, a sensible approach would be to set up for AO-16 operation first and then progress to UO-22. This is particularly true if you had been operating on FO-20 because the radios and modems are already in place and attention can be focused on installing and using the PB and PG software. Even if you have not used FO-20 it is still easier to set up for AO-16 first: 1200 bps operation does not usually require any internal connections and/or modifications to the transmitter and receiver, whereas 9600 bps operation usually does require some internal connections.

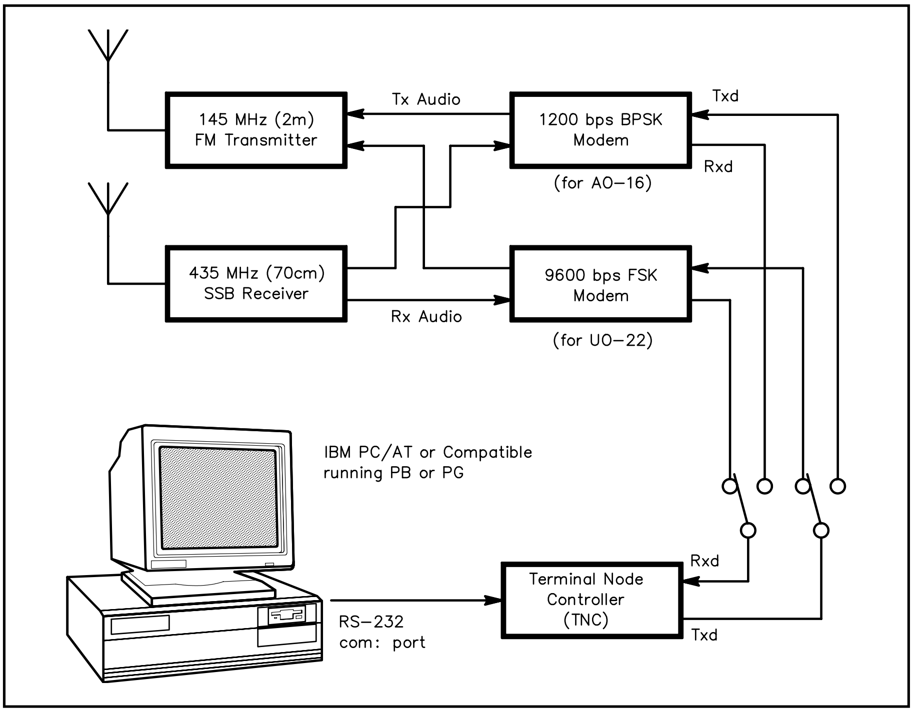


Fig 23.28 — Typical equipment configuration for utilizing the AMSAT-OSCAR 16 and UoSAT-OSCAR 22 satellites.

PACSAT Ground Station Software Capabilities and Operation

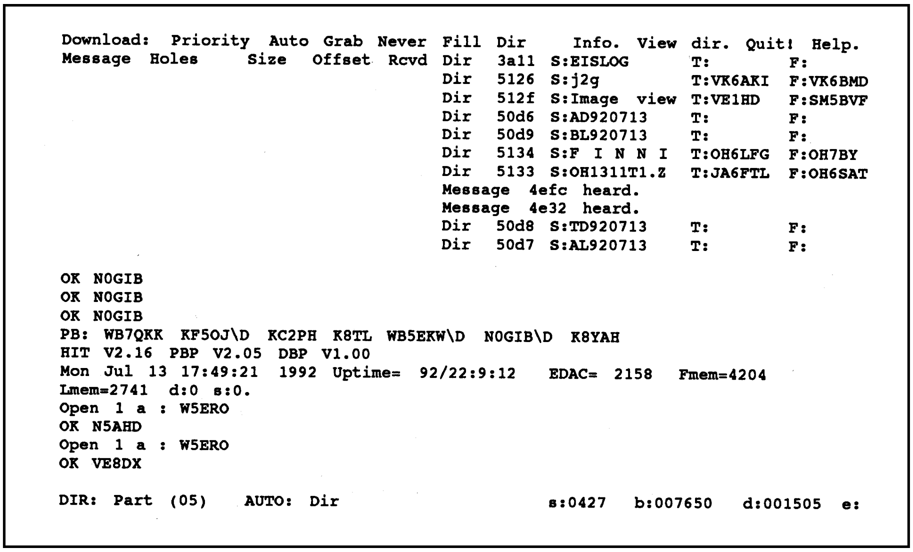
To use all of the communication facilities available, four computer programs, PB, PG, PHS and PFHADD, are available free of charge to the Amateur Radio community. PB allows files and directories being broadcast to be captured on the receiving station's computer. PB also allows a station to request the broadcast of hole fills in partially received files and directories. PG is used to upload files to the spacecraft for later broadcast. PFHADD adds the header required for uploading a user file. PHS will display or remove the file header after downloading a file. PB, PG, PFHADD and PHS run on IBM-PC/AT and compatible systems.

Recall that file and directory broadcasting is done in AX.25 unconnected mode and file uploads are done in AX.25 connected mode. Consequently, PB looks for UI frames from the spacecraft and places them in the proper location in the file being received if the user has requested that the file be captured. PG, on the other hand, establishes a connection with the file server and attempts to complete the transaction requested by the user. The following brief discussion of user software operation will provide some insight into the mechanics of utilizing the communications facilities of the satellites.

A user wishing to monitor files and directories being broadcast on the downlink would configure his/her station equipment as shown in Fig 23.28 and execute the PB program on the station computer. **Fig 23.29** shows a typical screen display from the PB program while monitoring UO-22 downlink traffic. The lower half of the screen shows certain informational messages exactly as they appear on the downlink. The upper left corner of the screen shows files for which capture is in progress (in this case none), and the upper right corner shows directory headers and message numbers being heard on the downlink.

The last line of the screen is a status line. "DIR: Part (05)" means that an updated directory has been partially received and there are five holes (missing pieces). "AUTO: Dir" shows that the ground station computer directory is being updated automatically from the monitored directory data. "Dir" could be replaced by a file number being downloaded. The values labeled "s:," "b:," "d:" and "e:" stand for data rate in bytes per second for the last five seconds, number of bytes monitored from broadcast files, number of bytes monitored from broadcast directories and number of CRC errors between the TNC and the ground station computer.

The line beginning with "PB:" shows which stations have made requests for files or directories (or hole fills) to be broadcast. Station call signs with the suffix "\D" have made directory requests while the others have made file broadcast requests. The message "Open: 1 a: W5ERO" shows that station W5ERO is a connected-mode user (probably doing a file upload) on uplink 2 and that uplink 1 is available for another user.



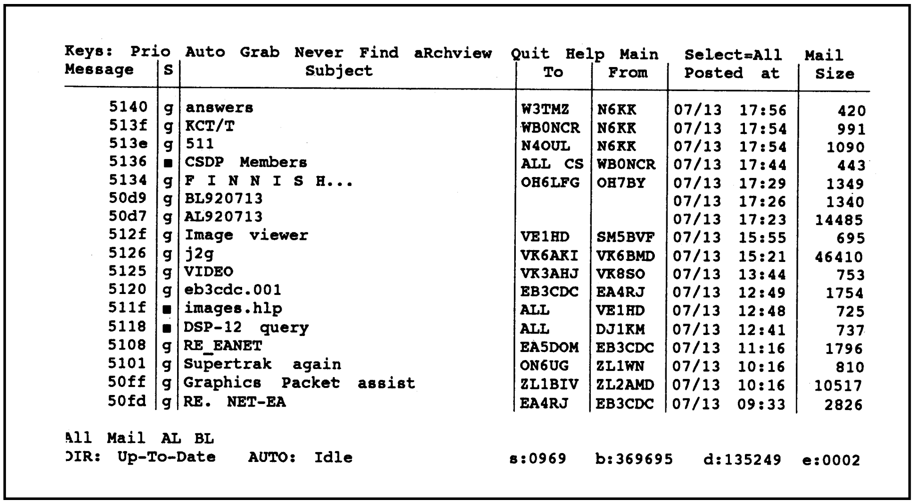
```
Download:  Priority  Auto  Grab  Never  Fill  Dir     Info.  View  dir.  Quit!  Help.
Message  Holes     Size    Offset  Rcvd  Dir    3a11  S:EISLOG         T:        F:
                                         Dir    5126  S:j2g            T:VK6AKI  F:VK6BMD
                                         Dir    512f  S:Image  view    T:VE1HD   F:SM5BVF
                                         Dir    50d6  S:AD920713       T:        F:
                                         Dir    50d9  S:BL920713       T:        F:
                                         Dir    5134  S:F  I  N  N  I  T:OH6LFG  F:OH7BY
                                         Dir    5133  S:OH1311T1.Z     T:JA6FTL  F:OH6SAT
                                         Message  4efc  heard.
                                         Message  4e32  heard.
                                         Dir    50d8  S:TD920713       T:        F:
                                         Dir    50d7  S:AL920713       T:        F:

OK  N0GIB
OK  N0GIB
OK  N0GIB
PB:  WB7QKK  KF5OJ\D  KC2PH  K8TL  WB5EKW\D  N0GIB\D  K8YAH
HIT  V2.16  PBP  V2.05  DBP  V1.00
Mon  Jul  13  17:49:21  1992  Uptime=  92/22:9:12   EDAC=  2158   Fmem=4204
Lmem=2741  d:0  s:0.
Open  1  a  :  W5ERO
OK  N5AHD
Open  1  a  :  W5ERO
OK  VE8DX

DIR:  Part  (05)   AUTO:  Dir                   s:0427   b:007650   d:001505   e:
```

Fig 23.29 — PB display while receiving data from UoSAT-OSCAR 22 satellite downlink.

Fig 23.30 shows a portion of the ground station computer directory after it has been captured from the downlink traffic. The upper right corner of the screen shows the file broadcast selection criteria in the message "Select = All Mail." This means that message traf-



```
Keys:  Prio  Auto  Grab  Never  Find  aRchview  Quit  Help  Main   Select=All   Mail
Message  | S |                  Subject            |  To    |  From  |  Posted  at  |  Size
------------------------------------------------------------------------------------------
    5140 | g | answers                             | W3TMZ  | N6KK   | 07/13  17:56 |   420
    513f | g | KCT/T                               | WB0NCR | N6KK   | 07/13  17:54 |   991
    513e | g | 511                                 | N4OUL  | N6KK   | 07/13  17:54 |  1090
    5136 | ■ | CSDP  Members                       | ALL  CS| WB0NCR | 07/13  17:44 |   443
    5134 | g | F  I  N  N  I  S  H...              | OH6LFG | OH7BY  | 07/13  17:29 |  1349
    50d9 | g | BL920713                            |        |        | 07/13  17:26 |  1340
    50d7 | g | AL920713                            |        |        | 07/13  17:23 | 14485
    512f | g | Image  viewer                       | VE1HD  | SM5BVF | 07/13  15:55 |   695
    5126 | g | j2g                                 | VK6AKI | VK6BMD | 07/13  15:21 | 46410
    5125 | g | VIDEO                               | VK3AHJ | VK8SO  | 07/13  13:44 |   753
    5120 | g | eb3cdc.001                          | EB3CDC | EA4RJ  | 07/13  12:49 |  1754
    511f | ■ | images.hlp                          | ALL    | VE1HD  | 07/13  12:48 |   725
    5118 | ■ | DSP-12  query                       | ALL    | DJ1KM  | 07/13  12:41 |   737
    5108 | g | RE_EANET                            | EA5DOM | EB3CDC | 07/13  11:16 |  1796
    5101 | g | Supertrak  again                    | ON6UG  | ZL1WN  | 07/13  10:16 |   810
    50ff | g | Graphics  Packet  assist            | ZL1BIV | ZL2AMD | 07/13  10:16 | 10517
    50fd | g | RE.  NET-EA                         | EA4RJ  | EB3CDC | 07/13  09:33 |  2826

All  Mail  AL  BL
DIR:  Up-To-Date    AUTO:  Idle                     s:0969   b:369695   d:135249  e:0002
```

Fig 23.30 — A display of a portion of a downloaded directory from UoSAT-OSCAR 22.

fic addressed to "All" or traffic to this specific station's call sign will be downloaded automatically. These criteria can be changed to suit the station operator through selection equations employing relational and logical operators that test appropriate fields in the PACSAT File Header. Consistent with the selection of "All," note that file numbers 5136, 511f and 5118 have a square block in the "S(tatus)" column. This indicates that these files, which have a "to" address of "ALL," have already been downloaded. At the lower left corner of the screen the message "All Mail AL BL" appears. These are the selection criteria for the directory display, as opposed to the criteria for automatic file downloading. Thus, the directory display will show AL (activity log) and BL (broadcast log) files in addition to files addressed to other satellite users.

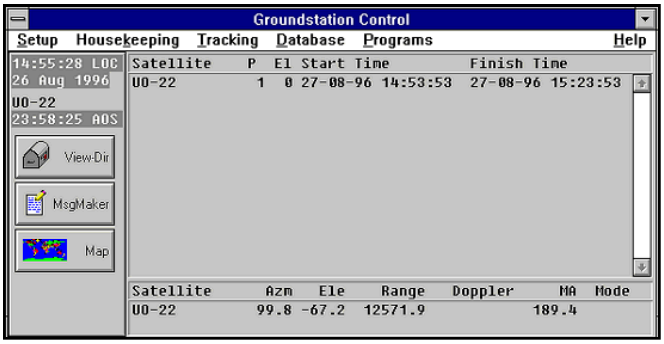
A user wishing to upload a file would first attach the PACSAT file header to the file and then use the PG program to upload it to the satellite. PG is used only for file uploading and operates in connected mode using the AX.25 data link layer protocol. When using PG, a connection is established, an upload transaction executed and the connection terminated as a result of a single operator command. The one-transaction-per-connection philosophy ensures maximum utilization of the uplinks in connected mode. There is no wasted time while a ground station operator executes a command and then pauses deciding what to do next.

[This section, including Figs 23.29 and 23.30, is reprinted with permission from "The Development of Low-Earth-Orbit Store-and-Forward Satellites in the Amateur Radio Service," *Proc IEEE International Phoenix Conference on Computers and Communications*, Tempe, AZ, March 23-26, 1993, pp 378-386, ©1993 IEEE.]

WiSP

The software package just described, consisting of the PB, PG, PHS and PFHADD programs, is the set of programs initially made available for accessing satellites utilizing the PACSAT Broadcast Protocol (PBP). More recently, considerable software development activity has resulted in several alternatives to the original program suite. The most significant of these new programs is the Windows application WiSP developed by Chris Jackson, ZL2TPO. An alternative to PB called XPB has been developed for the Linux X-Windows environment by John Melton, G0ORX/N6LYT, and Jonathan Naylor, G4KLX. Finally, a version of PB designed specifically for the IBM OS/2 environment is currently in development. The WiSP and XPB packages are available via FTP from several different sites including ftp.amsat.org. WiSP requires the payment of a registration fee to your national AMSAT organization while XPB fall under the GNU Public License. A brief explanation and a few examples of WiSP operation follow.

Fig 23.31 shows the display produced by the WiSP ground station control (GSC) program. Although the display shows only one satellite, the program may be configured to track multiple satellites with priorities assigned to each. **Fig 23.32** shows the graphical tracking feature of WiSP that may be invoked by the user if desired. When a satellite comes into view, a user-specified program can be run. This

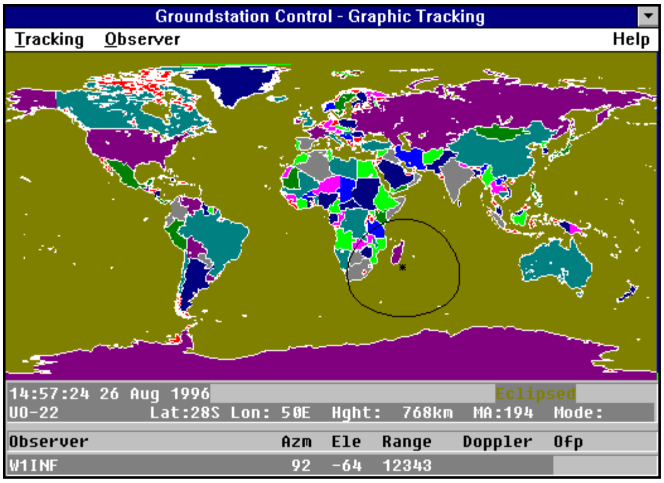


```
14:55:28 LOC
26 Aug 1996
UO-22
23:58:25 AOS
```

```
Satellite        P  El Start Time          Finish Time
UO-22            1   0 27-08-96 14:53:53  27-08-96 15:23:53
```

```
Satellite          Azm   Ele    Range   Doppler      MA   Mode
UO-22             99.8 -67.2  12571.9              189.4
```

Fig 23.31—WiSP ground station control (GSC) screen showing the next visibility times for UO-22 along with the current clock time and the countdown to next AOS timer.



```
14:57:24 26 Aug 1996                          Eclipsed
UO-22          Lat:28S Lon: 50E  Hght:  768km  MA:194  Mode:

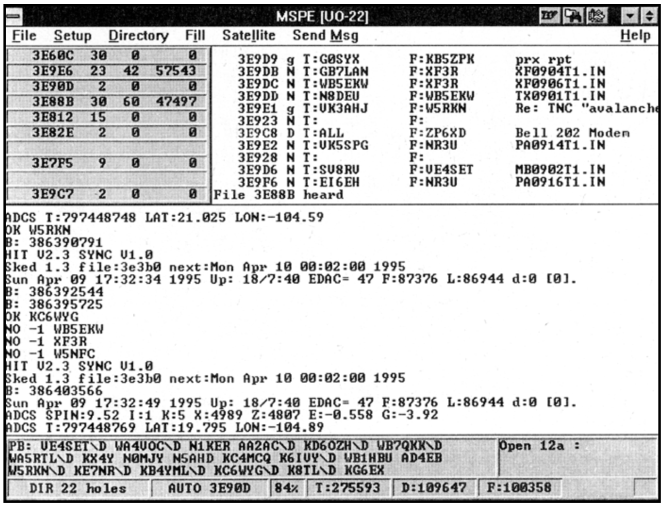
Observer                    Azm  Ele  Range   Doppler  Ofp
W1INF                        92  -64  12343
```

Fig 23.32—WiSP graphical tracking screen.

program could be something as simple as a terminal program to display raw downlink data. For the digital store-and-forward satellites like AO-16, LO-19, UO-22, KO-23 and KO-25, the MSPE program that is part of the WiSP package will usually be run. **Fig 23.33** shows a typical screen produced by MSPE while monitoring UO-22. Notice that this is WiSP's equivalent to Fig 23.29 produced by the original PB program. Users may select which files should be automatically downloaded and processed for later reading. Finally, **Fig 23.34** shows a display produced by the View Dir(ectory) function. Once again there is a close parallel between the information shown my View-Dir and that shown in Fig 23.30 from PB. The WiSP package also has radio tuning and rotator control features. Sophisticated ground station software packages such as WiSP truly demonstrate the maturity of the ground segment that supports digital store-and-forward Amateur Radio satellites.

EQUIPPING A STATION

The previous sections have shown there are many satellites supporting Amateur Radio communications in many different modes. The satellite enthusiast must take into consideration his/her own desires, goals and financial resources when purchasing and assembling equipment for an amateur satellite ground



```
   3E60C  30   0      0
   3E9E6  23  42  57543
   3E90D   2   0      0
   3E88B  30  60  47497
   3E812  15   0      0
   3E82E   2   0      0

   3E7F5   9   0      0

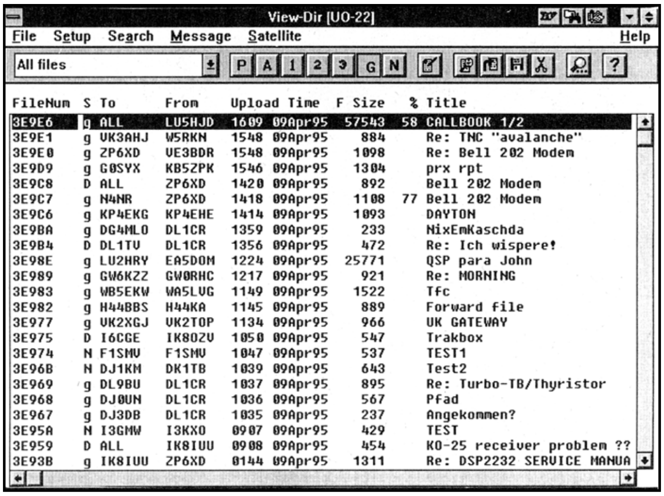
   3E9C7   2   0      0
```

```
    3E9D9 g T:G0SYX        F:KB5ZPK       prx rpt
    3E9DB N T:GB7LAN       F:XF3R         XF0904T1.IN
    3E9DC N T:WB5EKW       F:XF3R         XF0906T1.IN
    3E9DD N T:N8DEU        F:WB5EKW       TX0901T1.IN
    3E9E1 g T:VK3AHJ       F:W5RKN        Re: TNC "avalanche
    3E923 N T:             F:
    3E9C8 D T:ALL          F:ZP6XD        Bell 202 Modem
    3E9E2 N T:VK5SPG       F:NR3U         PA0914T1.IN
    3E928 N T:             F:
    3E9D6 N T:SV8RV        F:VE4SET       MB0902T1.IN
    3E9F6 N T:EI6EH        F:NR3U         PA0916T1.IN
File 3E88B heard
```

```
ADCS T:797448748 LAT:21.025 LON:-104.59
OK W5RKN
B: 386390791
HIT V2.3 SYNC V1.0
Sked 1.3 file:3e3b0 next:Mon Apr 10 00:02:00 1995
Sun Apr 09 17:32:34 1995 Up: 18/7:40 EDAC= 47 F:87376 L:86944 d:0 [0].
B: 386392544
B: 386395725
OK KC6WYG
NO -1 WB5EKW
NO -1 XF3R
NO -1 W5NFC
HIT V2.3 SYNC V1.0
Sked 1.3 file:3e3b0 next:Mon Apr 10 00:02:00 1995
B: 386403566
Sun Apr 09 17:32:49 1995 Up: 18/7:40 EDAC= 47 F:87376 L:86944 d:0 [0].
ADCS SPIN:9.52 I:1 K:5 X:4989 Z:4807 E:-0.558 G:-3.92
ADCS T:797448769 LAT:19.795 LON:-104.89
```

```
PB: VE4SET\D WA4VOC\D N1KER AA2AC\D KD6OZH\D WB7QKK\D     Open 12a :
WA5RTL\D KX4Y N0MJY N5AHD KC4MCQ K6IVY\D WB1HBU AD4EB
W5RKN\D KE7NR\D KB4YML\D KC6WYG\D K8TL\D KG6EX
  DIR 22 holes   AUTO 3E90D  84%  T:275593  D:109647  F:100358
```

Fig 23.33—WiSP real-time downlink data display screen. This is the WiSP equivalent to Fig 23.29 for PB.



```
FileNum  S To      From    Upload Time  F Size  % Title
3E9E6    g ALL     LU5HJD  1609 09Apr95  57543 58 CALLBOOK 1/2
3E9E1    g VK3AHJ  W5RKN   1548 09Apr95    884    Re: TNC "avalanche"
3E9E0    g ZP6XD   VE3BDR  1548 09Apr95   1098    Re: Bell 202 Modem
3E9D9    g G0SYX   KB5ZPK  1546 09Apr95   1304    prx rpt
3E9C8    D ALL     ZP6XD   1420 09Apr95    892    Bell 202 Modem
3E9C7    g N4NR    ZP6XD   1418 09Apr95   1108 77 Bell 202 Modem
3E9C6    g KP4EKG  KP4EHE  1414 09Apr95   1093    DAYTON
3E9BA    g DG4MLO  DL1CR   1359 09Apr95    233    NixEmKaschda
3E9B4    D DL1TV   DL1CR   1356 09Apr95    472    Re: Ich wispere!
3E98E    g LU2HRY  EA5DOM  1224 09Apr95  25771    QSP para John
3E989    g GW6KZZ  GW0RHC  1217 09Apr95    921    Re: MORNING
3E983    g WB5EKW  WA5LVG  1149 09Apr95   1522    Tfc
3E982    g H44BBS  H44KA   1145 09Apr95    889    Forward file
3E977    g VK2XGJ  VK2TOP  1134 09Apr95    966    UK GATEWAY
3E975    D I6CGE   IK8OZV  1050 09Apr95    547    Trakbox
3E974    N F1SMV   F1SMV   1047 09Apr95    537    TEST1
3E96B    N DJ1KM   DK1TB   1039 09Apr95    643    Test2
3E969    g DL9BU   DL1CR   1037 09Apr95    895    Re: Turbo-TB/Thyristor
3E968    g DJ0UN   DL1CR   1036 09Apr95    567    Pfad
3E967    g DJ3DB   DL1CR   1035 09Apr95    237    Angekommen?
3E95A    N I3GMW   I3KXO   0907 09Apr95    429    TEST
3E959    D ALL     IK8IUU  0908 09Apr95    454    KO-25 receiver problem ??
3E93B    g IK8IUU  ZP6XD   0144 09Apr95   1311    Re: DSP2232 SERVICE MANUA
```

Fig 23.34—WiSP display produced by the View-DIR function. This is the WiSP equivalent to Fig 23.30 for PB.

station. Because there are so many different combinations of station equipment possible, it would be a good idea to define some broad categories that arise naturally from a combination of the available satellites, individual operating goals and required expenditures.

One possible set of categories for amateur satellite stations consists of: (1) receive-only stations; (2) stations to work LEO satellites with analog transponders; (3) stations to work LEO digital store-and-forward satellites; (4) stations to work HEO satellites with analog transponders; and (5) stations utilizing satellites with uplinks and/or downlinks in the microwave bands (above 450 MHz [70 cm]). As always, there are many trade-offs that can be made. Some of the common ones will be mentioned later.

Perhaps the biggest difference between terrestrial and satellite communications is that the latter is full-duplex operation. This means that you transmit and receive simultaneously. When communicating through an analog transponder, you can hear your own downlink signal while transmitting, as well as that of the station being worked. Full duplex provides the opportunity for a fully interactive conversation, as if the other station is in the very same room.

Successful satellite operation demands that you can locate and hear your own signal from the spacecraft. Choose equipment with this goal in mind. Equipping a station for full-duplex operation is not too difficult because the transmitter is on a different band than the receiver. Ground-station configurations for high-altitude satellites vary according to the communications "mode" being used. **Figs 23.35**, **36**, **37** and **38** show several different configurations suitable for Modes B, J, L and S. An example of an entry-level receive-only station can be seen in **Fig 23.39**.

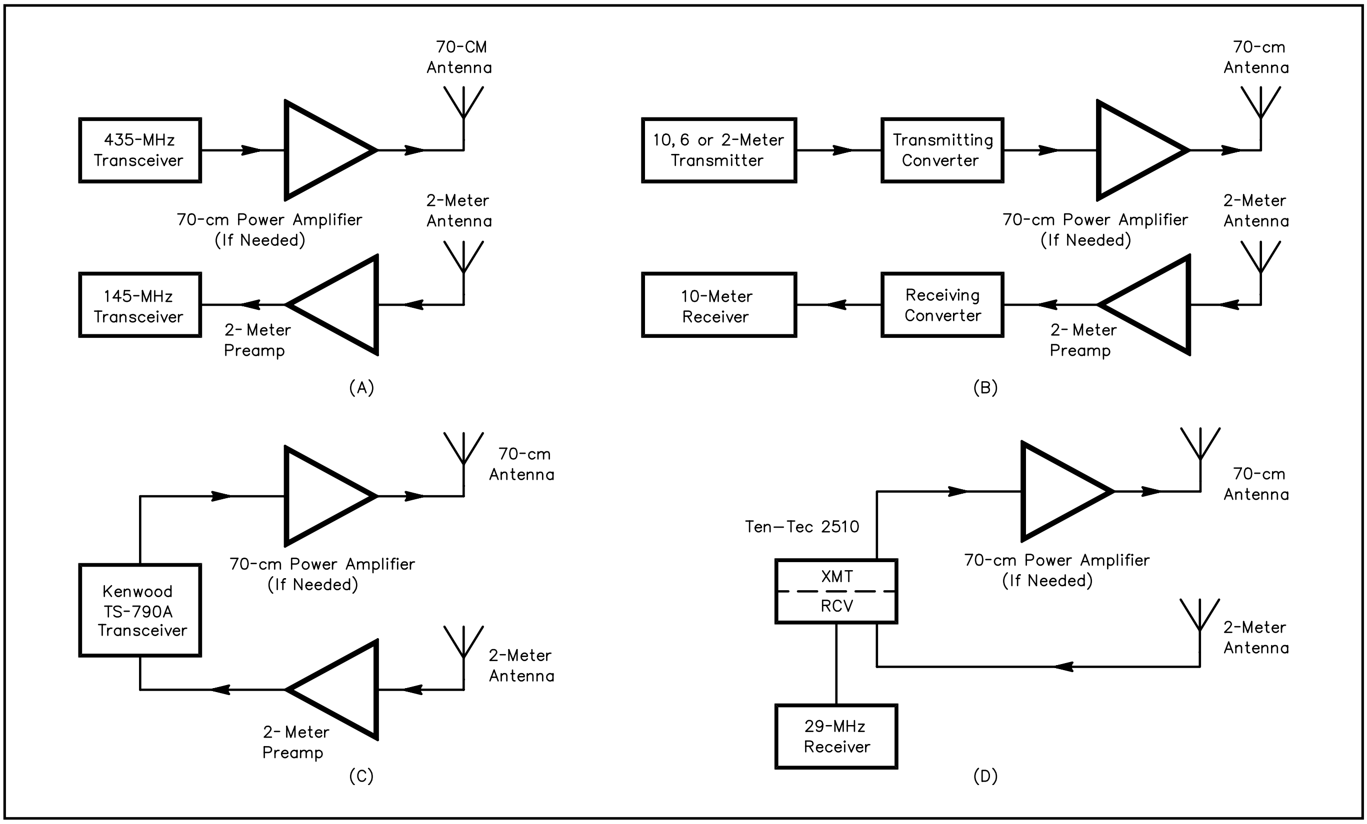


Fig 23.35 — Several different Mode-B satellite-station configurations are shown here. At A, separate VHF/UHF multimode transceivers are used for transmitting and receiving. The configuration shown at B uses transmitting and receiving converters or transverters with HF equipment. At C, a multimode, multiband transceiver can perform both transmitting and receiving function, full duplex, in one package. The Ten-Tec 2510 shown at D contains a 435-MHz transmitter and a 2 m to 10-m receiving converter.

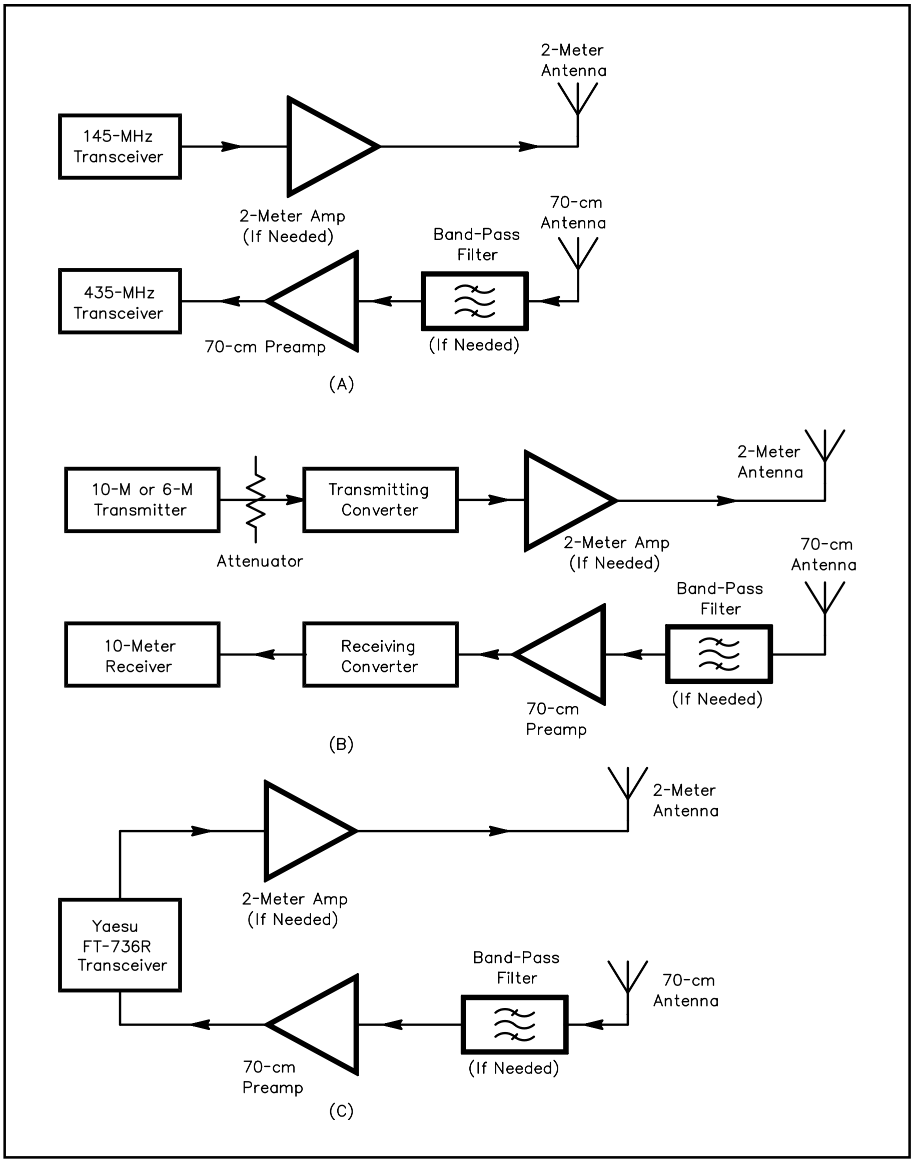


Fig 23.36 — Several different Mode-J satellite-station configurations are shown here. At A, separate VHF/UHF multimode transceivers are used for transmitting and receiving. The configuration shown at B uses transmitting and receiving converters or transverters with HF equipment. At C, a multimode, multiband transceiver can perform both transmitting and receiving functions, full duplex, in one package.

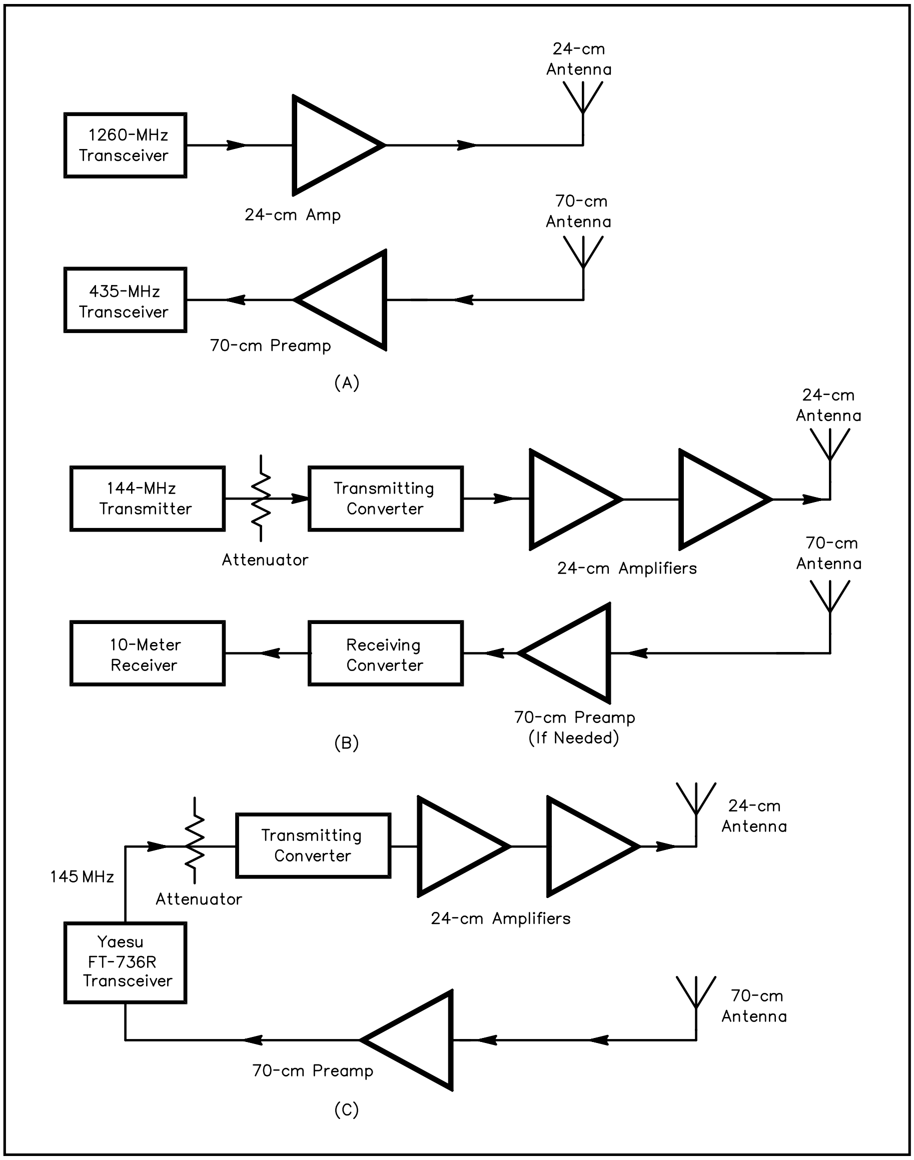


Fig 23.37 — Several different Mode-L satellite-station configurations are shown here. At A, separate VHF/UHF multimode transceivers are used for transmitting and receiving. The configuration shown at B uses transmitting and receiving converters or transverters with HF equipment. At C, a multimode, multiband transceiver can be used for full duplex receiving and transmitting (with the addition of a 2-m to 24-cm transmitting converter).

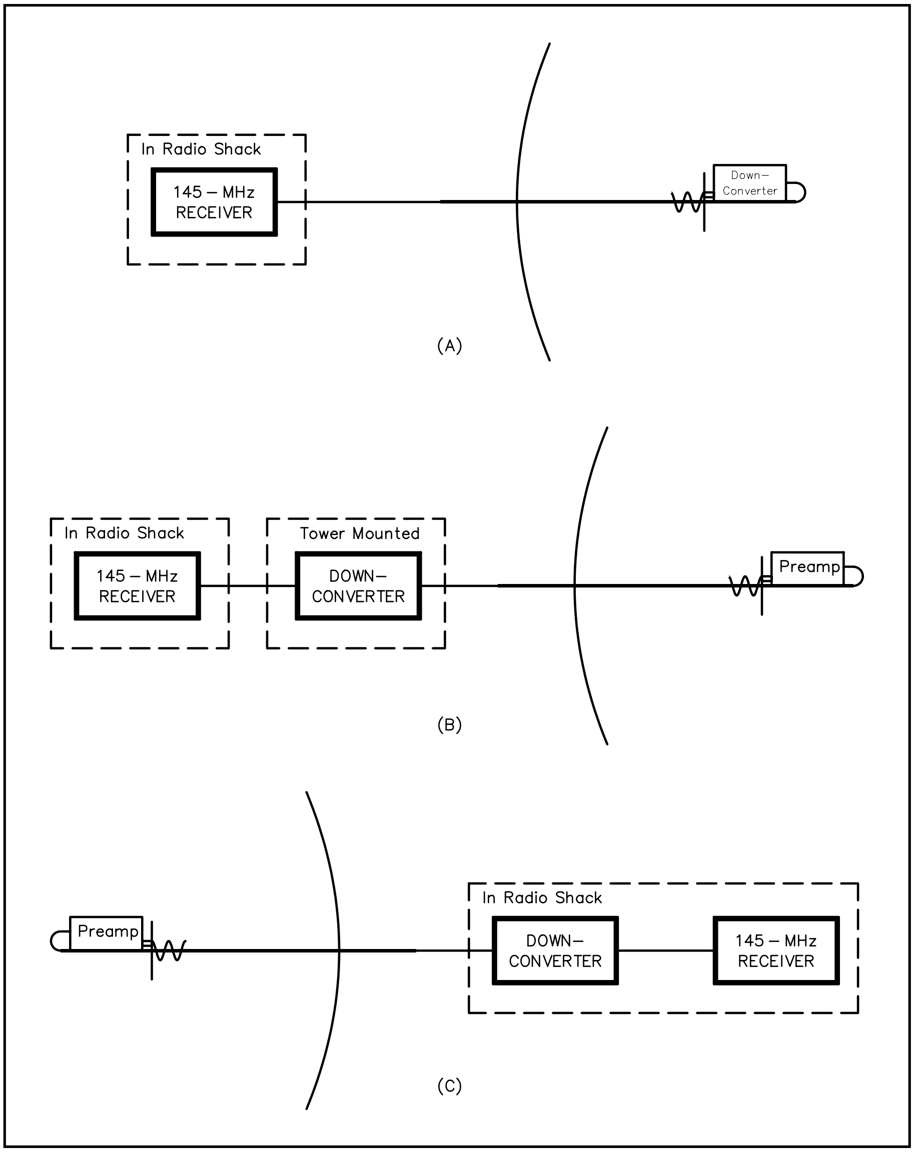


Fig 23.38 — Several different Mode-S satellite-station configurations are shown here.

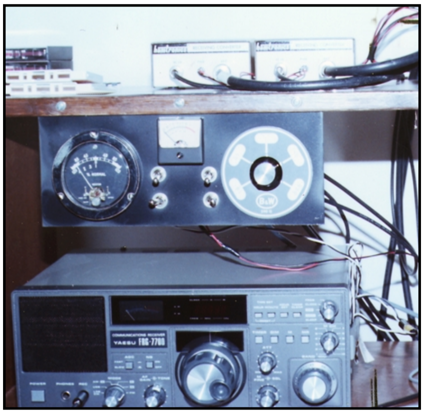


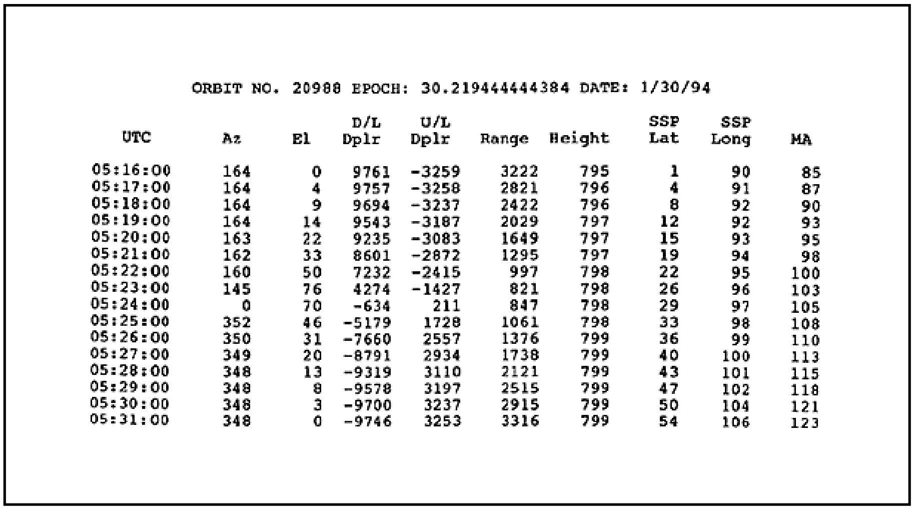
Fig 23.39 — An entry-level receiving station using 2 m and 70-cm converters and a general coverage communications receiver.

Computer System

The main reason for mentioning computer equipment in this section is that in many cases some other part of the station will be used in conjunction with a computer. For example, automatic antenna positioning may be done using a computer and appropriate rotator control interface.

One of the most common uses for a computer in the amateur satellite station is determining when and where a particular satellite will be visible. When considering this aspect of satellite operations, think carefully about what you really need and what "would be nice." If you are an entry-level operator and using omnidirectional antennas, a simple listing of AOS, LOS and position at 1-minute intervals is sufficient. Many different orbital prediction programs are available; they range in complexity from those that produce simple time, heading and position printed output (see **Fig 23.40**) to those that produce graphical displays in real time (see Figs 23.15 and 16).

You may be better off with one computer dedicated to satellite-related functions rather than trying to do orbit prediction, antenna pointing, radio frequency control and your word processing and financial records all on the same machine. There is nothing more annoying than stopping in the middle of some other important work to get the right programs going for the next satellite contact. With every new generation of microprocessor, systems using the preceding technologies become more plentiful at rea-



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                ORBIT NO. 20988 EPOCH: 30.21944444384 DATE: 1/30/94

                                 D/L    U/L                          SSP     SSP
   UTC            Az     El     Dplr   Dplr    Range   Height       Lat    Long      MA

05:16:00         164      0     9761  -3259     3222      795         1      90      85
05:17:00         164      4     9757  -3258     2821      796         4      91      87
05:18:00         164      9     9694  -3237     2422      796         8      92      90
05:19:00         164     14     9543  -3187     2029      797        12      92      93
05:20:00         163     22     9235  -3083     1649      797        15      93      95
05:21:00         162     33     8601  -2872     1295      797        19      94      98
05:22:00         160     50     7232  -2415      997      798        22      95     100
05:23:00         145     76     4274  -1427      821      798        26      96     103
05:24:00           0     70     -634    211      847      798        29      97     105
05:25:00         352     46    -5179   1728     1061      798        33      98     108
05:26:00         350     31    -7660   2557     1376      799        36      99     110
05:27:00         349     20    -8791   2934     1738      799        40     100     113
05:28:00         348     13    -9319   3110     2121      799        43     101     115
05:29:00         348      8    -9578   3197     2515      799        47     102     118
05:30:00         348      3    -9700   3237     2915      799        50     104     121
05:31:00         348      0    -9746   3253     3316      799        54     106     123
```

Fig 23.40 — Tabular output from an orbit prediction program showing time and position information for AO-16.

sonable prices. As your interest in amateur satellite operations solidifies, keep your eye open for a good computer buy at the next hamfest.

Other Microprocessor-Based Equipment

If you develop a serious interest in the digital satellites, you will want to consider a DSP-based TNC. Since digital amateur satellites tend to use different modulation techniques than terrestrial packet radio, TNCs will usually require an additional external or internal modem. Although choosing a DSP-based TNC will result in a higher initial cost, the modem then becomes a matter of software rather than additional hardware. Consequently, as new modulation techniques require new modems, only software has to be changed, either by downloading from a PC or changing ROM chips in the TNC.

Antennas

Antennas for receive-only and entry-level stations will usually be simple fixed-position types such as ground plane, turnstile over reflector, dipole and wire loop. High-orbit satellites such as AO-10 require high-gain antennas that are movable in both azimuth and elevation. In between these two extremes are the antenna requirements for the typical LEO satellite station that has evolved beyond the entry level. In this case the gain requirements are not as high as for AO-10 but for serious, dependable, day-to-day operation, automated azimuth and elevation positioning will become most desirable.

The best antennas for use in the amateur satellite service are circularly polarized (CP). The present trend in satellite arrays for 145 and 435 MHz is to use two complete Yagis mounted perpendicular to each other on the same boom. One set of elements is mounted 1/4 wavelength ahead of the other. The antennas are fed in phase and are switchable from RHCP to LHCP. This is in contrast to using helical antennas. Circularly polarized Yagi antenna arrays are manufactured by KLM, Cushcraft, Telex/HyGain, M^2 and others. A typical set of crossed-Yagi antennas is shown in **Fig 23.41**.

Satellite antennas should be mounted as close to the station as possible. Height above ground makes no difference for satellite work, except that the antennas must be mounted high enough that trees and other obstructions do not block the view of the satellite at low elevations. A low mount allows use of shorter feed lines (lower losses) and often reduces noise pickup by the antennas. Many operators are able to set up their antennas on a 10 to 15-ft mast right next to the shack and have only 20 ft of feed line. Plan to use good-quality, low-loss coaxial cable from the start, such as Belden 9913. Even better are runs of Hardline coaxial cable, available from a number of manufacturers.

Mode L transmitting antennas and Mode S receiving antennas have taken numerous forms, mostly based on the technology needed for EME communications. Loop Yagis are popular, as are the large parabolic reflector antennas seen in EME and TVRO services. While higher gain means lower transmitter power, the narrow beamwidths require the operator to reposition the antenna more often.

Although a practical CP Yagi for 24 cm has not yet been demonstrated, such an approach may be feasible. As Mode L is only operated near the satellite apogee, essentially on the satellite antenna pattern

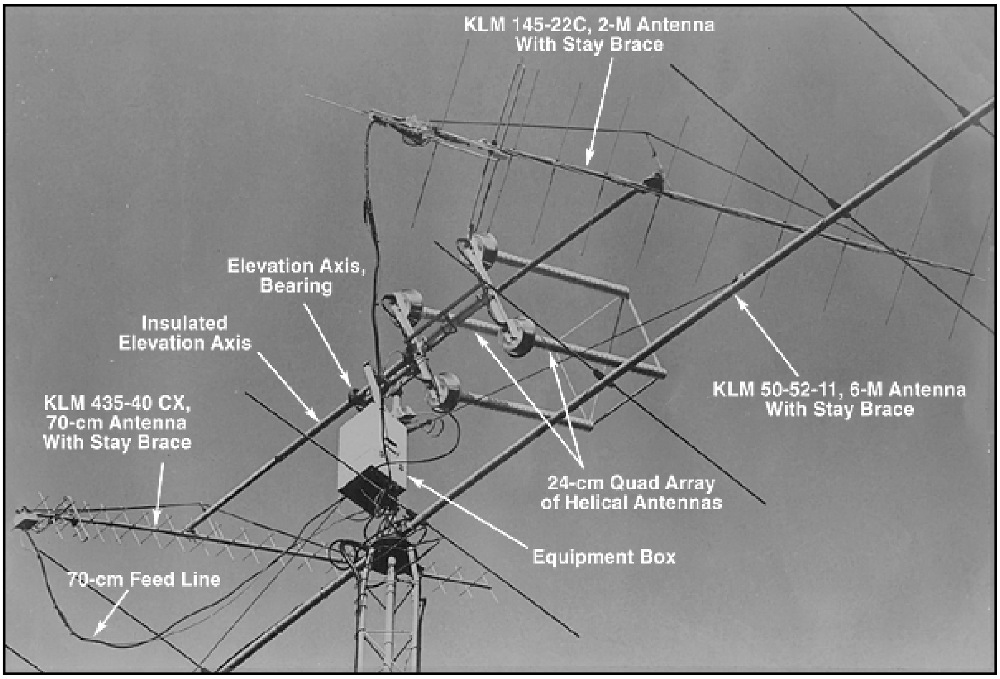

Fig 23.41 — A popular commercially manufactured antenna array for AO-10 Modes B and J, is a pair of KLM crossed Yagis. Shown also are Mode-L helical antennas. The large box on the mast contains a 2-m and 70-cm preamplifier, coaxial relays, a 24-cm transverter and power amplifier, and power-supply regulators.

main lobe, RHCP operation is the only CP sense needed. This makes the use of a helical antenna attractive. A home-built Mode L helical antenna array is shown in Fig 23.41. Active Mode L operators have also found that a small parabolic dish (6 ft in diameter, or larger) with a circularly polarized feed can make a fine Mode L antenna. A number of reasonably priced TVRO dishes are available; they require only the addition of a suitable feed for Mode L service. For TVRO dishes of 12 ft diameter, a dual-band (70 cm and 24 cm) feed for Mode L is a possibility, as the gain at 70 cm is sufficient for excellent reception, and the gain is very substantial for QRP 24-cm transmissions.

For Mode S reception, the most commonly used antennas are a small helix (16 turns) or a small parabolic dish (less than 3 ft).

Antenna Accessories

Long-boom Yagis, such as the KLM antennas shown in Fig 23.41, can suffer from boom sag that might cause pattern distortion and pointing errors. In addition, a boom support is desirable in areas where high winds or ice are a problem. To avoid possible interference with the antenna pattern, the boom brace must be made from nonconductive material such as Phillystran HPTG2100 guy cable. Details for the brace are shown in Fig 23.42.

The vertical boom-brace support member is nonconductive and made from a fiberglass fishing rod blank. A short piece of threaded stainless-steel rod inserted in the top of the tube is used to adjust tension on the boom brace. A 2-inch piece of $^5/_{16}$-inch copper tubing brazed across the threaded rod in a "T" fashion holds the Phillystran cable in place. Jam nuts secure the threaded rod once the boom is straight.

Experience with the exposed relays on the polarity switchers used on some commercial antennas has shown that they are prone to failure caused by an elusive mechanism known as "diurnal pumping." The relay is covered with a plastic case, and the seam between the case and PC board is sealed with a silicone sealant. It is not hermetically sealed, however. As a result, the day/night temperature swings pump air and moisture in and out of the relay case. Under the right conditions of temperature and moisture content, moisture from the air will condense inside the relay case when the air cools. Water builds up inside the case, promoting extensive corrosion and unwanted electrical conduction, seriously degrading relay performance in a short time.

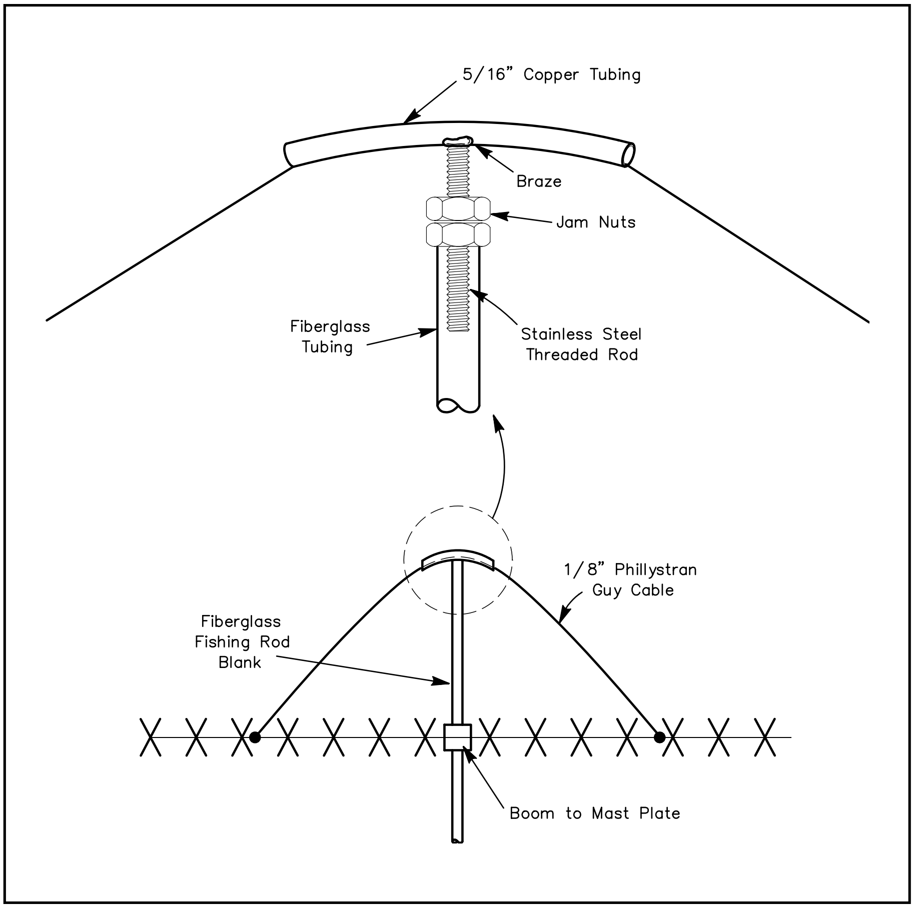

Fig 23.42 — A boom brace may be desirable for long Yagis. This arrangement is made from non-conductive material to prevent undesirable effects on the antenna pattern.

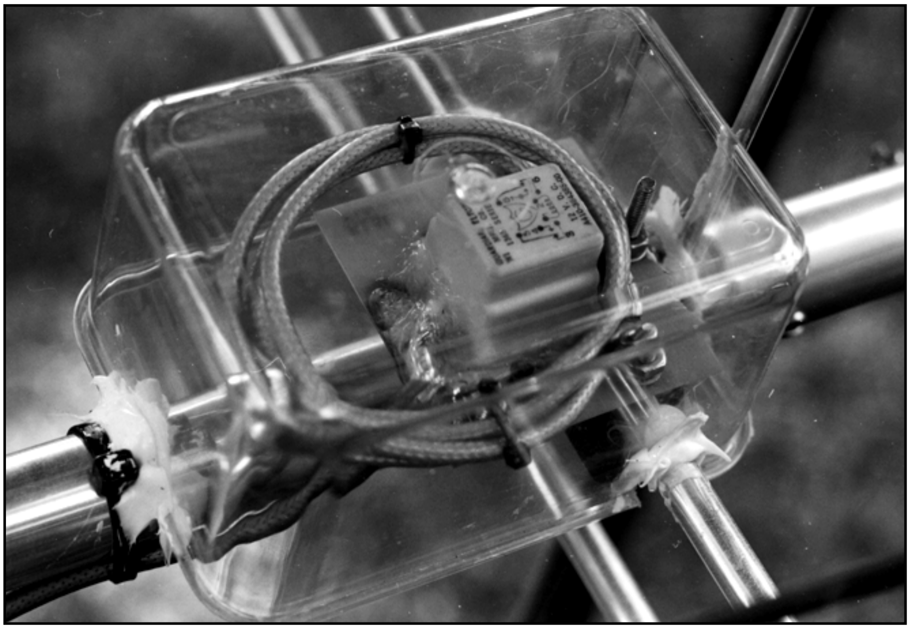

Fig 23.43 — KLM 2M-22C antenna CP switching relay with relocated balun and protective cover.

If you have antennas with sealed plastic relays, such as the KLM CX series, you can avoid problems by making the modifications shown in **Fig 23.43**. Relocate the 4:1 balun as shown and place a clear polystyrene plastic refrigerator container over the relay. Notch the container edges for the driven element and the boom so the container will sit down over the relay, sheltering it from the elements. Bond the container in place with a few dabs of RTV adhesive sealant.

Position the antenna in an "X" orientation, so neither set of elements is parallel to the ground. The switcher board should now be canted at an angle, and one side of the relay case should be lower than the other. Carefully drill, by hand, a pair of $^{3}/_{32}$-inch holes through the low side to vent the relay case. The added cover keeps rain water off the relay, and the holes will prevent any build-up of condensation inside the relay case. Relays so treated have remained clean and operational over periods of years without any problems.

Antenna Rotators

Unlike stations located on the surface of the Earth, AO-10 and Phase 3D will be found somewhere in the sky above. Operators commonly aim antennas toward another station by changing the pointing angle, or *azimuth* (sometimes called az). Aiming antennas toward AO-10 and Phase 3D requires the control of antenna *elevation* (el). Satellite antennas must be able to rotate from side to side and up and down simultaneously. While the use of electrically controlled antenna rotators will be discussed here, it might be noted that Phase 3 satellite motions are slow enough that hand-operated, “armstrong” antenna control is feasible. At times, the antennas may not need repositioning for periods of up to four hours. On the other hand, the fast-moving LEO satellites such as AO-16 and UO-22 will almost certainly require an automatic positioning system.

Azimuth rotators are commonly used for positioning terrestrial HF and VHF antennas. Antennas for low-orbit satellites can be on the smaller and lighter side, so light-duty TV-antenna rotators such as those sold by Alliance, Channel Master, Radio Shack and others could be used for the azimuth rotator. Today’s high-gain satellite arrays are a bit large for these light-duty rotators. Look for something more robust, such as a rotator recommended for turning a small HF beam or VHF array. Various models manufactured by Alliance, Daiwa, Kenpro, Telex and others are advertised in *QST*.

Elevation rotator selection is more limited. Commercially manufactured models such as the Yaesu G-500A and G-5400B are available. The G-500A has been available in the past under different designations such as KLM and Kenpro KR-500 and is designed for elevating small-to medium-size VHF or UHF arrays. The G-5400B is a combined azimuth and elevation rotator. See **Fig 23.44**. Home-built elevation mounts can also be fabricated from TVRO antenna jack-screw motion controls or other similar muscular devices.

A lower cost alternative is the Alliance U110 TV-antenna rotator. Rotators of this type have been used successfully by satellite operators for many years. Despite its relatively light construction, the U110 will handle antenna loads weighing up to 40 pounds. The key to success is to achieve a static balance of the antenna mass so the rotator does not have to elevate a “dead” load. A highly attractive feature of the elevation rotators noted above is that the cross boom to be rotated passes completely through the rotator. This allows the mounting of one antenna on each side of center and the adjustment of their respective positions for a side-to-side balanced load.

Automatic Antenna Positioning

Several products are now available to automatically steer a satellite antenna array under computer control. Automatic antenna pointing is particularly useful when operating the OSCARs in low Earth orbit. Among the products available are the Kansas City Tracker/Tuner sold by L. L. Grace Co and the TrakBox sold by TAPR. There are other sources for similar products but these two represent the two general approaches to automated antenna control. The Kansas City Tracker is installed in an existing station computer while the TrakBox is a standalone controller with its own built-in microprocessor.

The Kansas City Tracker is available either as a tracker only or with the tuner option which sets and corrects the radio frequency throughout a

Fig 23.44 — The Yaesu G-5400B azimuth-elevation rotator includes a DIN computer connection.

pass. In either case, the tracking and/or tuning functions are carried out by the rotator control card in conjunction with Terminate and Stay Resident (TSR) programs running in the computer. Position and Doppler frequency correction information for the TSRs is supplied by the tracking program. Some rotators, such as the Yaesu G-5400B, already have a connector for the computer interface.

The TrakBox and similar units are specialized microprocessor-based control units. Usually, the position information is downloaded from a PC to the control box. After receiving the position information, the controller operates in a standalone mode. Devices such as the TrakBox have an LCD display that shows the operational status of the controller.

Whether to use a tracker and/or tuner that plug into the PC expansion bus or a standalone unit is a complicated question involving both technical matters and personal preference. If your station computer is using at least an 80386 class processor, the question is largely a matter of preference. In the case of 80286 class or lower processors, it may be a good idea to offload the work of tracking and/or tuning to an independent unit. Consider the situation of working one of the digital satellites like UO-22. With everything running in a single computer that machine must: update antenna position, set the radio frequency often enough to keep up with the Doppler shift, accept data from the TNC at a rate of 19,200 bps, update files and directories on disk as data is being captured, and update the screen display.

Finally, even though a tracker/tuner construction project has not been included in this section, it is an area where home-brew systems are certainly a possibility. Relay drivers can be built to control the rotators via signals from a parallel port. Analog-to-digital converters can be used to read the position indicating voltage from the meter circuit. Furthermore, most modern transceivers can be controlled by commands from a serial I/O port. Consequently, it is not beyond the capabilities of someone with programming and hardware experience to build an antenna and frequency control system.

The Sounds of Amateur Radio

Listen to the effect of Doppler shift on the tone of the Fuji-OSCAR 29 CW beacon.

Antenna Cross-Boom Construction

One requirement not commonly discussed is that of using a nonmetallic elevation axis boom for antennas that have their boom-to-mast mounting hardware in the center of the boom. A metal cross boom will seriously distort the beam pattern of a circularly polarized antenna, so it is important to make those portions of the cross boom nearest to the antennas from nonmetallic materials.

From a structural standpoint, the best nonmetallic material for this job is glass-epoxy composite tubing, because its stiffness is excellent. Lengths of this material may be found at an industrial supply house that specializes in plastics. Also, KLM sells lengths of $1^{1}/_{2}$ in. OD fiberglass masting for this purpose, and Telex/HyGain includes fiberglass masting with their OSCAR antennas. If you have a rotator that will accept a $1^{1}/_{2}$ in. elevation boom, then your best bet is to use a single piece of this tubing. The $1^{1}/_{2}$ in. OD fiberglass tubing also slides into the ID of the $1^{1}/_{2}$ in. pipe used for the heavy-duty elevation axis.

A less expensive alternative is to make the cross boom from a combination of metallic and nonmetallic tubing. For strength and stiffness, use a short length of steel or aluminum tubing through the middle of the rotator. Let the metal tubing extend for about 6 in. on each side of the rotator. Then install nonmetallic masting, such as common PVC pipe, over the steel stubs.

The elevation boom pictured in Fig 23.41 was constructed with this method. The center piece that fits through the U110 is a 2-ft section of 1.33-in.-OD steel tubing that originally was part of the top support rail of a chain-link fence. Attached to the steel stub on each side of the rotator is a 4-ft length of $1^{1}/_{4}$ in., schedule-40 PVC pipe. This pipe slipped nicely over the center stub. The fit is perfect — no machining was needed.

Unlike glass-epoxy tubing, PVC pipe is not very stiff. The secret to making PVC pipe capable of supporting satellite Yagis is to insert a wooden dowel into the PVC pipe, along its entire length. The finished dimension of $1^{3}/_{8}$ in. wooden clothes-rod dowel (the kind you might hang inside a closet) is just perfect for a slide fit into the pipe. This material is available from most lumber yards. Add a few $^1/_4$ in. bolts to each side to secure the pieces, and you have a sturdy, inexpensive, nonmetallic elevation boom.

Receivers

The old adage “You can’t work 'em if you can’t hear ’em” especially applies to satellite operation. Receiving requirements for AO-10 are demanding, but pleasurable results can be achieved with the right kind of equipment. OSCAR operation is a weak-signal mode where contacts can be made with signals that are only 4 dB stronger than the noise. Conversational quality can be assured with signals that are 6 to 9 dB above the noise.

The first step to be taken before attempting to work such high altitude satellites as AO-10 is to assemble the best receiving setup possible. There is no point in getting transmitting capability until the satellite signals can be comfortably heard.

Amateurs active on 2 m with a multimode transceiver already have the basic building block for receiving Mode B and transmitting on Modes J and L (with an additional transmitting converter). If you currently have no VHF equipment, consider that a multimode, multiband transceiver will also allow you to explore the exciting world of terrestrial 2-m and 70-cm SSB operations. The basic requirements are that the rig includes SSB and CW modes and that it covers the entire 144-MHz band and (most of the) 420-MHz band. A multimode transceiver also makes an excellent replacement for an FM-only 144-MHz rig.

The equipment manufacturers listed in **Table 23.10** all make suitable transceivers, either single-band or multiband units. The current crop of base-station rigs includes the Kenwood single-band transceivers TS-711A (2 m) and TS-811 (70 cm), and multiband transceiver TS-471H and IC-475H (70 cm). Yaesu offers their multiband FT-726R and FT-736R transceivers. There are also several compact multimode radios intended for mobile use that will be quite usable. These include the Yaesu single-band FT-290R and FT-790R, Kenwood single-band TR-751A and TR-851A, and the ICOM single-band IC-290H. In addition, there are often good buys on the used market, if you’re interested in an older radio. Gear such as the Kenwood TS-700 series, Yaesu FT-225RD and ICOM IC-251 are still popular. Many of these transceivers have been reviewed in *QST*.

Table 23.10

Suppliers of Equipment of Interest to Satellite Operators

Contact information appears in the *Handbook* Address List in the **References** chapter. Send updates to the *Handbook* Editor at ARRL Headquarters.

Multimode VHF and UHF Transceivers and Specialty Equipment

ICOM America
Kenwood Communications
Yaesu USA

Converters, Transverters and Preamplifiers

Advanced Receiver Research
Angle Linear
Hamtronics
Henry Radio
The PX Shack
Radio Kit
RF Concepts
Spectrum International
SSB Electronics

Power Amplifiers

Alinco Electronics
Communications Concepts
Down East Microwave
Encomm
Falcon Communications
Mirage Communications
RF Concepts
TE Systems

Antennas

Cushcraft Corp
Down East Microwave
KLM Electronics
Telex Communications

Rotators

Alliance
Daiwa
Electronic Equipment Bank
Kenpro
M^2 Enterprises
Telex
Yaesu USA

Other Suppliers

AEA
ATV Research
Down East Microwave
Electronic Equipment Bank
Grove Enterprises
M^2 Enterprises
Microwave Components of Michigan
PacComm
SHF Microwave Parts
Tucson Amateur Packet Radio (TAPR)

Note: This is a partial list. The ARRL does not endorse specific products.

Users of Mode L may want to consider the use of a full transceiver in the station for the 24-cm transmissions, as such a unit will also allow operations on the 23-cm band (1296 MHz). Kenwood and Yaesu offer 23-cm modules for their multiband transceivers for this service. ICOM also offers the single-band IC-271A. Alternatively, there are some 24-cm transmitting converters and transverters offered that employ a 2-m IF.

An excellent solution to receiving Modes B, J and L satellite signals can be found in the form of receiving converters used with a high-quality HF transceiver or receiver. The 2-m and 70-cm receiving converter consists of a mixer and a local oscillator and may contain a preamplifier. The local oscillator frequency is usually chosen so that signals will be converted to the 10-m band. In addition, a number of manufacturers offer transverters that include receiving and transmitting converters in the same package. Receiving converters are available from several suppliers listed in Table 23.10.

There are several advantages to using a receiving converter. Modern HF transceivers and receivers most likely have excellent frequency stability, a frequency readout in 1 kHz or smaller steps, good SSB and CW crystal filters, an effective noise blanker and high dynamic range. Chances are good that a multimode VHF transceiver will offer some, but not all, of these features. Cost is another factor. If you already own an HF rig, but are not interested in terrestrial VHF/UHF SSB operation (you don't need 2-m transmit capability for Mode B), the cost of building or buying a superior receiving converter will be significantly less than that of even an older multimode transceiver. One commercial example of a Mode-B-only unit is the Ten-Tec 2510B, providing an excellent 2-m receiving converter and a complete 70-cm SSB/CW transmitter, all with coupled VFOs for simultaneous tracking on both bands. While the '2510 is an economical way to get into satellite operation, it is limited to Mode B service only and cannot provide any help for Mode J and L services.

Experience has shown that daytime noise will often raise the practical 2-m receiver noise floor by 10 to 20 dB, thus making Mode B daytime communications difficult, at best. Weak downlink signals are often no match for the noise. In general, noise is not a problem on 70-cm (for Mode J and Mode L reception), but in some areas interference from airport radar can be troublesome. In addition, local FM repeaters may be heard in the satellite passband of the ground-based receiver because the VHF transceiver may offer poor rejection of strong nearby signals. Use of a high-dynamic-range receiving converter with a good HF transceiver has been shown to solve both of these problems. The lesson is that many VHF transceivers have noise blankers that are inadequate for VHF/UHF satellite operation and some VHF transceivers do not work well in areas with many nearby, strong signals. Consequently, in some cases, better results may be achieved with a receiving converter than with a VHF multimode transceiver.

Receiving Accessories

For those stations using a receiving converter and an HF receiver for downlink reception, an in-line switchable attenuator, installed between the converter output and the antenna jack of the 10-m receiver, may prove useful. Such an attenuator can be used to lower the AGC level and improve the perceived signal-to-noise ratio. In addition, by adjusting the attenuator so that the S meter on the HF rig rests at zero at no signal, more accurate signal reports can be given. An attenuator circuit is shown in the **Test Equipment** chapter. A useful modified form may in-

The Yaesu 736R is a multimode transceiver for 2 m (144-148 MHz) and 70 cm (430-450 MHz). It can be used for full-duplex receiving and transmitting on AO-10 Mode B and AO-13 Modes B and J. An optional 23-cm module covers 1230-1300 MHz (Mode L). Approximate power output: 20 W on 2 m and 70 cm, and 10 W on 23 cm.

clude only three steps — 5, 10 and 20 dB. These three settings allow attenuation in 5-dB steps from 0 to 35 dB.

Preamplifiers

No discussion of satellite receiving systems would be complete without mentioning preamplifiers. Good, low-noise preamplifiers are essential for receiving weak downlink signals. Multimode rigs and most transverters will hear much better with the addition of a GaAsFET preamplifier ahead of the receiver front end, albeit at the expense of a considerable reduction in the third-order intercept point of the receiver. While a preamplifier can be added right at the receiver in the station, it may not do much good there. Considerably better results can be obtained if the preamp is mounted near the antenna. Indeed, antenna mounting of a preamp is essential for UHF and higher operation. Losses in the feed line will seriously degrade the noise figure of even the best preamplifier mounted at the receiver, while an antenna-mounted preamplifier can overcome nearly all of these noise figure problems.

Kenwood's TS-790A is a dual-band (144-148 MHz and 430-450 MHz) multimode transceiver. A 23-cm (1240-1300 MHz) module is optional. Power output is 35-45 W on 144 MHz, 30-40 W on 430 MHz and 10 W on 1240 MHz.

Table 23.10 lists several sources of commercially built preamplifiers. These are available in several configurations. Some models are designed to be mounted in a receive-only line, for use with a receiving converter or transverter. Others, designed with multimode transceivers in mind, have built-in relays and circuitry that automatically switch the preamplifier out of the antenna line during transmit. Still others are housed, with relays, in weatherproof enclosures that mount right at the antenna. For the equipment builder, several suitable designs appear in *The Radio Amateur's Satellite Handbook*.

Tower-Mounted Preamplifiers

Mast-mounting of sensitive electronic equipment has been a fact of life for the serious VHF/UHFer for years, although it may seem to be a strange or difficult technology for many HF operators. To get the most out of your satellite station, you'll need to mount a low-noise preamplifier on the tower or mast, near the antenna, so that feed-line losses do not degrade low-noise performance. Feed-line losses ahead of the preamplifier add directly to receiver noise figure. A preamp with a 0.5-dB noise figure will not do you much good if there is 3 dB of feed-line loss between it and the antenna.

In Fig 23.41, note the large white box located below the elevation rotator. **Fig 23.45** shows the interior of this box. A close look shows a 2-m preamplifier for the Mode B downlink and relays to switch it in and out of the line to the antenna. This setup is designed to beat excessive feed-line losses for basic stations. Transmitting equipment for the 70-cm and 24-cm bands is also housed in the same enclosure. Normal installations may require only the receiving preamplifier (2 m for Mode B and 70 cm for Mode J and L) to be mounted on the mast. The transmitting equipment is discussed further in the next section.

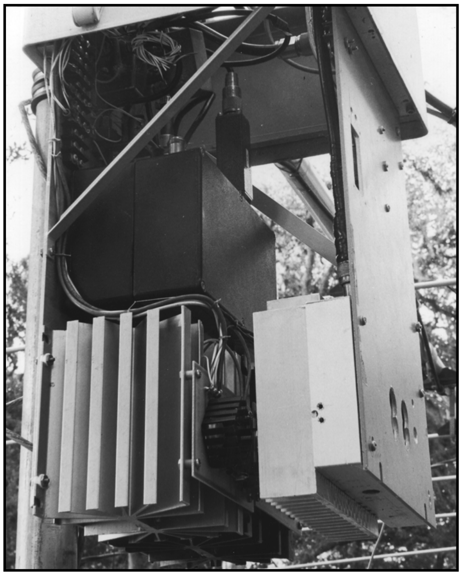

Fig 23.45 — Interior of the tower-mounted equipment rack with the cover removed. The 70-cm equipment is on the left, while power-supply regulators, a 24-cm transmit converter and a 2-m preamp are mounted on the right.

Transmitters

The AO-10 Mode B uplink requires a controllable 5 to 50 W of 435-MHz RF power at the antenna. This assumes a good antenna, which will be discussed later. Feed-line losses in a typical 435-MHz installation can easily run 3 dB, so you'll need anywhere between 10 and 100 W output from your transmitter.

Since there are many combinations of transmitter power and antenna gain that will result in a satisfactory signal through AO-10, satellite users generally talk about their uplink capability in terms of effective radiated power (ERP). ERP takes into account antenna gain, feed-line loss and RF output power. For example, a 10-W signal into a 3-dB-gain antenna will have an ERP of 20 W (3 dB greater than, or twice as strong as, 10 W). This assumes no loss in the feed line and all 10 W from the transmitter reaches the antenna. If the signal is 10 W into a 10-dB-gain antenna, the ERP is 100 W. The same 100-W ERP can be achieved with a 50-W transmitter and a 3-dB-gain antenna.

Stations with an uplink ERP as low as 10 W can be copied through AO-10, Modes B and J, but ERP levels of 100 to 400 W are the norm. No matter what your ERP, your signal on the downlink should never be stronger than the general beacon at 145.81 MHz (Mode B) and 435.65 MHz (Mode J). As a reminder, satellite service ground stations do not have to be as strong as the beacon to provide excellent communications; good operators will adjust their signals to just the level needed for the QSO. You must have a way of adjusting your uplink signal power so that your downlink is no stronger than the beacon. These points are discussed in detail in *The ARRL Operating Manual*.

If the Mode-B satellite ground station has a 10-W transmitter, a short run of low-loss feed line and good antenna gain, an additional amplifier would probably not be needed. If losses and gains do not add up to the required ERP, a 30 to 40-W amplifier may be needed. Some operators have 100-W amplifiers, but with the antennas available today, use of that much power is guaranteed to create an uplink signal that far exceeds the beacon level. This is considered by good operators to be an antisocial action. Considerate operators with the 100-W amplifiers quickly reduce drive power to lower the ERP to acceptable levels.

Most satellite operators use UHF multimode transceivers to generate Mode B uplink signals. The manufacturers listed in Table 23.10 make 70-cm multimode transceivers that are similar to the 2-m units as described earlier. Although most of these transceivers provide 10-W output, some can deliver 25 W or more.

Earlier satellites in the AMSAT programs created and fostered the need for good multimode 2-m transceivers, as they formed the nucleus of the satellite station. Current and future satellite programs will find the 70-cm transceiver as the focal point of the satellite station, emphasizing the trend to even higher frequencies.

For Mode L transmitting, there are several transmitting converters, transverters, amplifiers and even a multimode transceiver available from the suppliers listed in Table 23.10.

The ICOM IC-820H is a state-of-the-art transceiver designed especially for satellite use.

Transmitting Accessories

The tower-mounted equipment rack shown in Fig 23.45 contains the 70-cm and 24-cm power amplifiers. Tower mounting of a transmitter is probably unnecessary for 70-cm, but becomes much more important for higher frequencies. Feed-line losses at 70 cm are generally twice those of 2 m, while those at 24 cm are about twice those of 70 cm, or four times those of 2 m. For an 80-ft feed line, the losses at 24 cm can easily reach 6 dB for even the best coaxial cable. Consequently, a 100-W amplifier in the shack will only yield 25 W at the antenna. A good alternative is to place the transmitting converter and a 20-W solid-state amplifier in the tower-mounted box near the antennas. The results are nearly the same, and you avoid the time and money needed to generate high power that will just be lost in the feed line anyway.

A coaxial RF sampler is connected to the output of the 70-cm amplifier since it is good amateur practice to monitor the power at the antenna to be sure the transmitter is working properly. Coaxial relays are used for proper switching of the power amplifiers and 70-cm preamp for OSCAR Mode J and L operation as well as for terrestrial communications.


The Yaesu FT-847's satellite mode provides the user with a full featured satellite transceiver. As a bonus, it also covers all the HF bands!

One very important aspect of using GaAsFET preamps with transmitting equipment is getting everything to switch at the proper time. If transmitters, amplifiers and antenna relays are keyed simultaneously, it's likely that RF will be applied to the feed line before the relays are fully connected to the antenna load. Such hot switching can easily arc the contacts on expensive coaxial relays. In addition, if the TR relay is not fully closed, RF may be applied to the preamplifier. Such bursts of RF energy are guaranteed to destroy the GaAsFET in the preamplifier. Many pieces of transmitting equipment (especially multimode transceivers) emit a short burst of RF power when switched on or off, so there is the risk of transmitting into your preamp even if you are careful to pause before keying.

Ideally, keying of a transmitter should follow a timing sequence that will ensure the safety of the equipment. When you switch into transmit from receive, the coaxial relays change state to remove the preamplifier from the line. Next, the power amplifier is keyed on. The last thing that happens is that the transmitter RF is enabled. When switching back to receive, the sequence is just the opposite. First, the transmitter RF is switched off, the power amplifier is disabled, and then the TR relays change state to place the preamp back in service. Solid-state sequencers to control station TR switching are shown in the **Station Accessories** chapter.

Specialized Transceivers

Separate transceivers or transmitting and receiving converters are no longer the only way to go. Modern equipment offerings by ICOM, Kenwood, Yaesu and Ten-Tec, tailored for the satellite user, do it all in one package.

The Yaesu FT-847, for example, covers all bands through 450 MHz—including HF. In satellite mode, it has duplex crossband capability. Its dual VFOs can be tied together, making it easy to track frequencies. This is particularly helpful when using satellites with inverting transponders, such as FO-29 and the upcoming Phase 3D. When the radio is in this configuration, tuning the uplink VFO causes the downlink VFO to tune automatically in the opposite direction.


ICOM's IC-821A is another modern, full-featured transceiver designed for satellite use.

ICOM's IC-821H is a dual-band (2-m/70 cm) multimode transceiver that also features a handy satellite mode. Like the FT-847, its dual-VFO design makes it easy to tune satellites with inverting transponders. In satellite mode, the Main (transmit) and Sub band frequencies follow each other, either in the same direction or in reverse.

The Kenwood TR-790A and Yaesu FT-726R and FT-736R units start out as 2-m multimode transceivers. They are, however, expandable to work on other bands with the addition of optional modules. The Mode-B satellite operator would most likely be interested in the TR-790A or FT-726R/FT-736R with the stock 144-MHz and 430-MHz modules. These same RF modules will also serve well for Mode J directly and Mode L using an outboard 23-cm transmitting converter. Both manufacturers also offer 23-cm transceive modules, for Mode L, for their multiband units. To tie it all together, these Kenwood and Yaesu transceivers also both offer satellite modules (stock or optional) that allow the amateur to transmit on one band for the uplink while receiving on another band for the downlink. This is full duplex operation; the effect is the same as having two separate radios in one box.

Tower-Mounted Equipment Shelters

A great many amateurs seem apprehensive about placing their valuable radio equipment outdoors. Such fears are unfounded if adequate care is taken to protect the equipment from the elements. The equipment shown in the photos has been outdoors for years without any adverse effects.

Fig 23.46 shows the basic scheme for weatherproofing tower-mounted equipment. The fundamental concept is to provide a cover to shelter equipment from rain. A deep drawn aluminum pan can make an excellent shelter. A trip to the housewares section of the local department store will reveal a variety of plastic and aluminum trays and pans that can make suitable rain covers. Polyethylene plastic is not durable in the sunlight. Clear polystyrene refrigerator containers work better than those made of polyethylene, and aluminum is best of all. Choose a cover that is large enough for your equipment; remember to leave room for connecting cables.

The bottom of the rain cover is open to the elements. This is done on purpose and will not cause any problems. Do not try to hermetically seal the enclosure. By leaving the bottom open, adequate ventilation will prevent accumulation of water condensation. Just make sure that water cannot run into the enclosure by way of cables coming from above. Form the cables as shown in Fig 23.46 to provide drip loops. Adding a piece of window screen over the opening should be considered to avoid infestations of nesting insects, such as wasps, and the wire-hungry ravages of squirrels.

The mast-mounted enclosure shown earlier is a welded aluminum box purchased from a surplus dealer. It was used because it was available and the price was right. You don't really need a big box like this if you just want to protect a preamp and relays.

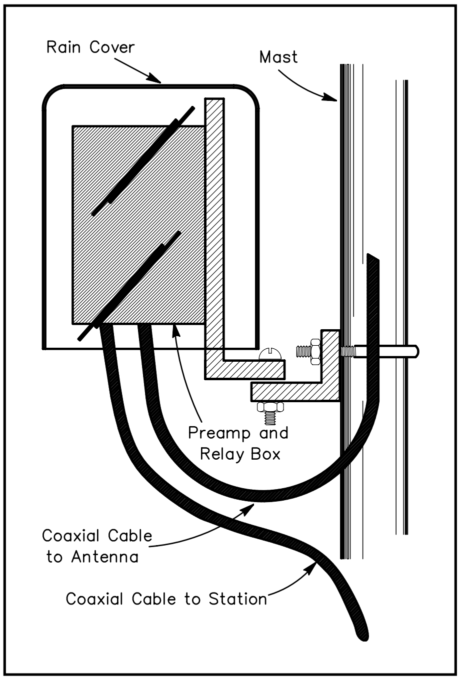

Fig 23.46 — Protection for tower-mounted equipment need not be elaborate. Be sure to dress the cables as shown so that water drips off the cable jacket before it reaches the enclosure.

Station Control

Fig 23.47 is a schematic diagram of the control circuitry for the 2-m side tower-mounted rack. Parts of this diagram will be helpful, even if only the preamp is mounted at the antenna. Note that this circuit is designed around the surplus coaxial relays that were available at the time. Your version will probably be different and will depend on the relays available to you.

This circuitry performs several functions. For starters, it places the preamp in the line only during receiving periods and takes it

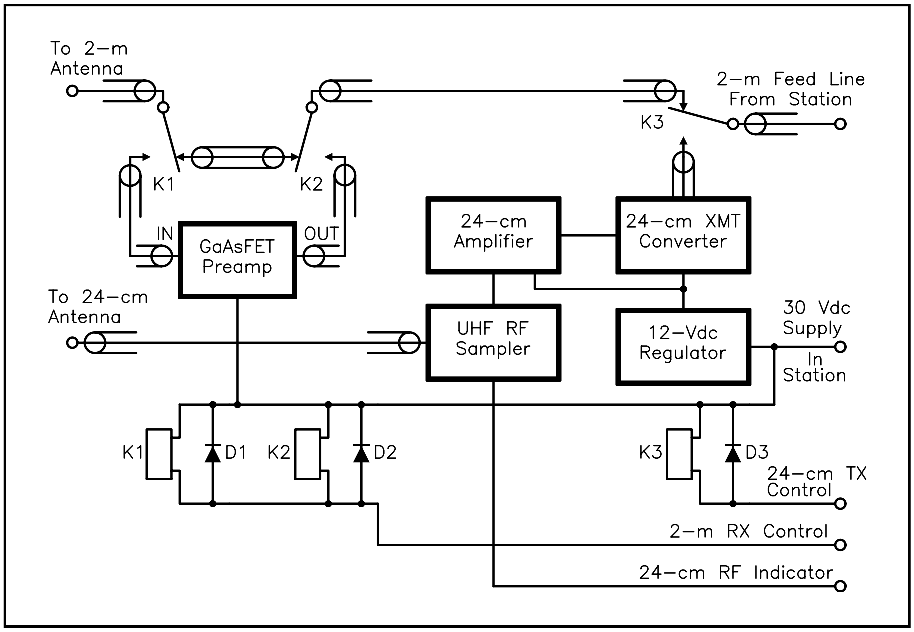

Fig 23.47 — Control circuitry for the mast-mounted 2-m preamplifier and 24-cm Mode-L transmitter. K1-K3 are surplus coaxial relays.

out of the line during transmitting periods as well as at those times when the station is not in use. This is needed if the satellite array is used for terrestrial transceive operation as well. The switching arrangement shown also protects the preamp from stray electromagnetic pulses (EMP), such as lightning strokes, when the station is not in use. EMP protection is desirable even if the antenna and preamp are used only for receiving satellite signals.

Fig 23.47 is only a little more complicated than the average mast-mounted preamp setup because it also allows 2-m RF to drive a 24-cm Mode L transmitting converter. An extra relay (K3) is used to switch between 2-m and 24-cm operation. K1, an SPDT transfer relay, switches the antenna between the input of the preamp and a through line to K2. K2, another SPDT relay, switches the feed line, from the shack, between the preamp output and K1. The relays are connected so that they must be energized to place the preamp in line, thus ensuring that the preamp is disconnected when not in use.

Depending on the complexity of your satellite station, you might want to combine most of the switching and control circuitry into a single box so that it provides ready access to all controls. **Fig 23.48** shows a Minibox cut to a low profile (beneath the multi-antenna rotator control unit) that contains all of the switches needed to control the station accessories. It houses a TR sequencer circuit board as well. This box controls the following functions: change antenna polarization from RHCP to LHCP on 2 m and 70 cm; switch the 2-m and 70-cm preamplifiers in and out of the circuit; and switch the power amplifier in or out of the line. The box also contains a high performance 2-m receive converter, for use with the station HF transceiver, when the Mode B conditions get to be really difficult. As shown, home-built control unit

Fig 23.48 — The satellite station at WD4FAB, with a home-brew antenna controller mounted above a low-profile station controller. On the right is a Yaesu FT-726R transceiver, with a power meter, clock and 23-cm transverter mounted on top.

boxes can be dressed up with the addition of a plotted or printed label on white paper. The label is bonded to the panel with the use of thin double-sided adhesive tape. A covering of clear label tape protects the label from smudges and dirt.

Station Equipment Summary

Satellite communication, like any other facets of Amateur Radio, requires some specialized station equipment and accessories. Having the best equipment does not necessarily guarantee success. There are a number of "hints-and-kinks" type ideas that can make OSCAR operation far more satisfying. Some of the equipment items that have been discussed here provide capabilities beyond the bare minimum needed for successful satellite operation. They may also be of value in VHF and UHF terrestrial work. Design your station to suit your own needs. Some operators may continually tinker with their station equipment, making frequent improvements, as part of their participation in the Amateur Radio hobby.

SUPPORTING CONCEPTS AND THEORY

Previous sections have described the satellites and communication modes available as well as various types of equipment needed for successful satellite operations. As is often the case with other specialized communications systems, there are certain concepts and theory peculiar to satellite communication. The purpose of this section is to review some topics that range in importance from "essential" to "interesting to know."

Orbital mechanics and tracking will be examined first. The material presented here will be more descriptive than mathematical. For a complete treatment of this subject, the reader is directed to *The Radio Amateur's Satellite Handbook* published by the ARRL. The need to use circularly polarized antennas was mentioned in the discussion of equipping a station. This section includes a more complete discussion of circular polarization along with a related phenomenon whose effects can be mitigated somewhat by using circularly polarized antennas — spin modulation. The sections on path loss and link budget will help explain why certain combinations of receiving and transmitting equipment and antennas were recommended.

Tracking and Orbital Mechanics

In order to complete a QSO via an Amateur Radio satellite, the ground station operators must be able to predict when the satellite will be visible at their respective locations. Previous sections have recommended a stepwise approach to the complexities of amateur satellite operation. Expertise in the area of satellite tracking can be gained in a similar manner.

One method of tracking that is adequate for operations using omnidirectional antennas on LEO satellites uses the *Oscar-locator,* published by the ARRL as part of *The Satellite Handbook*. The *Oscarlocator* is a graphical tracking aid that consists of a satellite ground track indicator and a set of range circles overlaid on a polar projection map of the world. Since the ground track is calibrated in minutes, it is only necessary to position the track at the correct equator crossing location and note how many minutes later the satellite will cross inside the range circle.

There are, of course, many computer programs available for satellite tracking. These range in complexity from those that produce text output such as shown in Fig 23.40 to those that produce graphical output in real-time such as seen in Figs 23.15 and 16. It is also possible to obtain real-time tracking programs that will, in conjunction with the proper antenna controller, position your antennas automatically.

All of these programs rely on what is called a reference *Keplerian element set* for their operation. The Keplerian element sets for Amateur Radio satellites are distributed via on-the-air nets, terrestrial and packet radio networks and printed media.

The reference element sets used by the program need to be updated periodically. This is necessary because a future position is being computed based on a known previous position specified by the element set. As the length of time between the reference element set and the future prediction increases, the predictions are prone to inaccuracies due to perturbations of the orbit such as atmospheric drag.

How often the reference elements should be updated is dependent on the satellite. Reference elements for LEO satellites should probably be updated about once per month. Element sets for HEO satellites such as AO-10 and Phase 3D need not be updated nearly as often. This is particularly true if the element set in use has been produced by averaging previous element sets over a long period of time. Other special cases such as the US Space Shuttle SAREX missions can require very frequent updates of the elements sets because the orbit geometry can change significantly and frequently depending on the goals of the mission. Reference element sets are distributed by AMSAT every week by many media including HF and VHF packet radio networks, the packet radio satellites such as AO-16 and UO-22, as well as commercial information services such as CompuServe's HamNet.

Satellite tracking software is now available for a wide variety of computers from many different sources. However, if you purchase your tracking program from AMSAT-NA, you can be sure that your contribution will help finance the next Amateur Radio satellite project. No matter where you purchase your program, you should be sure that it has the features you need and will run correctly on your computer system.

Circular Polarization

In the HF bands, polarization differences between antennas are not really noticeable because of the nonlinearities of ionospheric reflections. On the VHF and UHF bands, however, there is little ionospheric reflection. Cross-polarized stations (one using a vertical antenna, the other a horizontal antenna) often find considerable difficulty, with upwards of 20-dB loss. Such linearly polarized antennas are "horizontal" or "vertical" in terms of the antenna's position relative to the surface of the Earth, a reference that loses its meaning in space.

The need to use circularly polarized (CP) antennas for space communications is well established. If spacecraft antennas used linear polarization, ground stations would not be able to maintain polarization alignment with the spacecraft because of changing orientation. Ground stations using CP antennas are not as sensitive to the polarization motions of the spacecraft antenna, and therefore will maintain a better communications link.

All AO-10 gain antennas (for 2 m, 70 cm, 24 cm and 13 cm) are configured for RHCP operation along their maximum gain direction. See **Table 23.11** and **Fig 23.49.** Since this direction is also the main antenna lobe along the spacecraft +Z axis, the best communications with AO-10 will also be along that direction. Since the AO-10 radiations are RHCP, ground stations should also be RHCP for optimum communications.

There are times, however, when LHCP provides a better satellite link. AO-13 was designed so that the main antenna lobe was oriented toward the center of the Earth when the satellite was at apogee. AO-10 is not under active orientation control due to a failure of the flight computer memory. Thus, the AO-10 main-lobe orientation is a matter of chance.

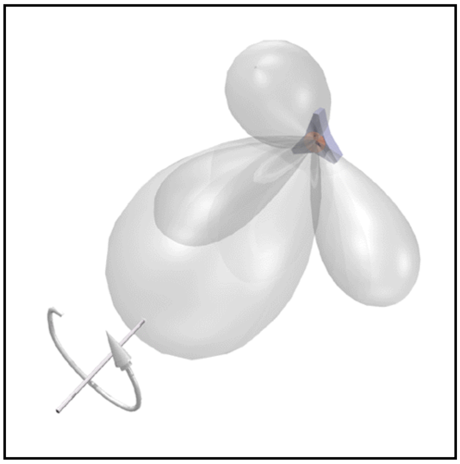

Fig 23.49 — This diagram shows the far-field radiation pattern (undeformed) for the 2-m high-gain antenna on AO-10 and AO-13. (Adapted from *The AMSAT-Phase III Satellite Operations Manual*, prepared by AMSAT and Project OSCAR.)

Table 23.11
Polarization and Gain of AO-10 Antennas

	High Gain Antennas		*Omni Antennas*	
Frequency (MHz)	*Polarization*	*Gain (dBi)*	*Polarization*	*Gain (dBi)*
146	RHCP	9.0	Linear	0.0
436	RHCP	9.5	Linear	2.1
1269	RHCP	12.0	RHCP	0.0

Independently switchable RHCP/LHCP antenna circularity is necessary, especially for 70 cm. It is not required for 24 cm operation as Mode L operations are only conducted on the main lobe. Switchable RHCP/LHCP on 2 m is very convenient and useful for Mode B operations.

Spin Modulation

A characteristic of the AO-10 design is that the 2-m and 70-cm high-gain array patterns have three side lobes located along the spin axis that are only about 3 dB weaker than the primary axial lobe. The effective radiation pattern intended for this antenna is shown in Fig 23.49. Lobes in the off-axis antenna patterns produce amplitude modulation of signal strength as the spacecraft spins about its axis. Off-axis operations of AO-10 are an established fact of life, creating spin modulation frequencies of about 0.5 Hz from a 10 r/min spin rate.

Stations using CP antennas are much less prone to be affected by spin modulation than those using linearly polarized antennas. Good signals are maintainable even far off-axis from the main lobe, if the ground station is using switchable CP.

In free space, a station located at a distance from an RF source will receive an average power flow from that source that is inversely proportional to the square of the distance. Doubling the range will reduce the signal by 6 dB. Since Phase 3 satellites have substantially elliptical orbits, the changes in path length (slant range) and path loss is correspondingly sizable. **Fig 23.50** illustrates the changes in path length of AO-10/P3D signals for all conditions from apogee to perigee and for direct overhead passes (subsatellite point location) to the far-limb viewing at AOS or LOS.

Other physical processes introduce additional losses in signals traveling to and from a Phase 3 spacecraft through the troposphere and ionosphere. While many of these effects are frequency dependent, the additional path losses are small compared to the slant range path losses. **Table 23.12** summarizes the path losses for the 2-m, 70-cm and 24-cm bands.

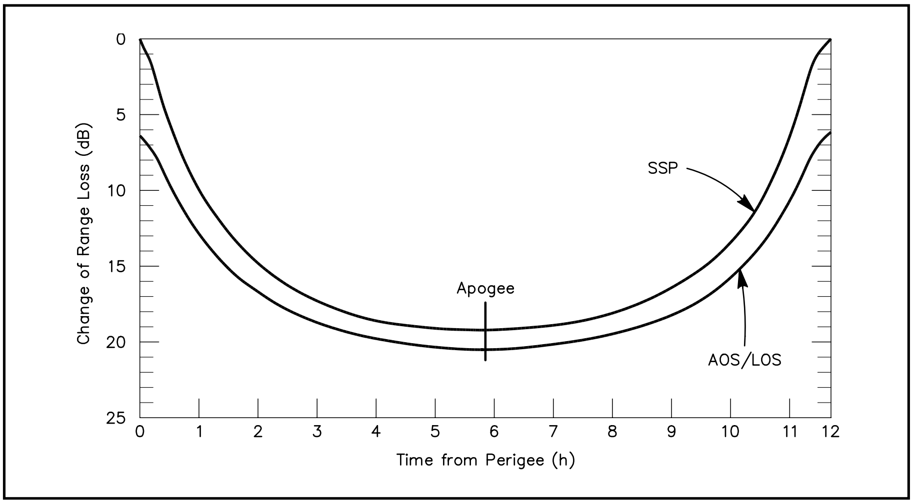

Fig 23.50 — Change of range loss of signal strength during the 11.7-hour elliptical orbit of AO-10. (Adapted from *The AMSAT-Phase III Satellite Operations Manual*, prepared by AMSAT and Project OSCAR.)

Table 23.12
Summary of One-Way Transmission Losses for Communications Paths Between Earth and Phase 3 Spacecraft at Apogee in an 11.7-Hour Elliptical Orbit, as Viewed Near AOS-LOS Range

	Attenuation (dB)		
Loss Mechanism	*2 m*	*70 cm*	*24 cm*
Path Loss	168.07	177.57	186.86
Tropo/Ionospheric Refraction	0.002	0.0003	0.0002
Tropo Absorption	0.1	0.7	1.65
Ionospheric Absorption (by category)			
D Layer	0.12	0.013	0.002
F-Layer	0.12	0.013	0.002
Aurora	0.13	0.014	0.002
Polar Cap Absorption (a rare D-layer event)	0.47	0.053	0.006
Field-Aligned Irregularities	†	†	†

†Little data available; characterized by rapid amplitude and phase fluctuations. (Adapted from *The AMSAT-Phase III Satellite Operations Manual* prepared by AMSAT and Project OSCAR)

Link Budget

Link budget computations can be deceiving to the unwary observer. The problems arise from the application of wide-bandwidth spacecraft transponders to handle a wide variety of complex, time-averaged, narrow-bandwidth QSOs. The analysis presented in **Table 23.13** employs a somewhat lower signal-to-noise ratio than the source information. Actual on-the-air experience has shown these lower

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Table 23.13

Link Budget Computations for Mode-B and Mode-L Transponders on OSCAR 10 at Apogee and AOS-LOS Range

Ground Station Uplink

Symbol	*Parameter*	*Mode B (70-cm uplink)*	*Mode L (24-cm uplink)*
N_f	Sat Receiver Noise Floor	–136.7 dBm	–137.4 dBm
SNR	Avg Signal-to-Noise Ratio	15.0 dB	15.0 dB
P_s	Signal at Satellite	–121.7 dBm	–122.4 dBm
G_r	Satellite Antenna Gain	9.0 dBi	12.0 dBi
P_a	Signal at Sat Antenna	–130.7 dBm	–134.4 dBm
P_L	Path Loss	177.57 dB	186.86 dB
$L_{i,t}$	Iono/Tropo Loss	0.73 dB	1.65 dB
$L_{p,p}$	Pointing/Polarization Loss	1.5 dB	1.5 dB
P_t+G_t	Reqd Gnd Stn avg ERP	19.10 dBW	25.61 dBW
	or:	81.3 W	363.9 W
	Gnd Stn PEP ERP	25.10 dBW	31.51 dBW
	or:	323.6 W	1448.8 W
G_t	Gnd Station Antenna Gain	16.0 dBi	19.0 dBi
P_t	Gnd Stn PEP Power Output	9.1 dBW	13.6 dBW
	or:	8.1 W	18.2 W

Satellite Downlink

Symbol	*Parameter*	*Mode B (2-m downlink)*	*Mode L (70-cm downlink)*
P_t	Satellite Max. PEP Output	16.99 dBW	16.99 dBW
	Average Output	10.99 dBW	10.99 dBW
L_m	Multi-user Load Share	–15.0 dB	–20.0 dB
G_s	Satellite AGC Compression	0.0 dB	0.0 dB
G_t	Satellite Antenna Gain	9.0 dBi	9.5 dBi
P_u	Average User ERP Output	34.99 dBm	30.49 dBm
P_L	Path Loss	168.07 dB	177.57 dB
$L_{i,t}$	Iono/Tropo Loss	0.33 dB	0.73 dB
$L_{p,p}$	Pointing/Polarization Loss	1.5 dB	1.5 dB
G_r	Receiving Antenna Gain	12.0 dBi	16.0 dBi
P_s	Received Signal Level	–122.91 dBi	–133.31 dBm
P_n	Noise in Rcv Bandwidth	–137.76 dBm	–146.67 dBm
SNR	Avg Signal-to-Noise Ratio	14.8 dB	13.4 dB

Link computations are based on the following parameters:
  11.7 hour elliptical orbit
  Eccentricity = 0.6
  Slant range = 41.395 km at AOS/LOS
  2.4 kHz SSB Signal
  6 dB peak (PEP) to average signal ratio
Ground Station Receiving Noise Characteristics
  at 2 m: T = 505 K, NF = 4.4 dB
  at 70 cm: T = 65 K, NF = 0.9 dB
(Adapted from *The AMSAT Phase III Satellite Operations Manual*, prepared by AMSAT and Project OSCAR)

values to be workable. The computation is also performed on the basis of averaged RF power levels. The conversion to PEP is done at the end, assuming a 6-dB relationship between PEP and average.

In the link computations, no allowances have been made for ground station transmission line attenuation. Information for attenuation of a variety of popular feed lines is shown in the **Transmission Lines** chapter. If you measure RF power near the antenna and have a tower-mounted, low-noise preamp, the link computations can be used as presented. The computation is based on two possible worst-case conditions: with the maximum slant range values at AOS/LOS, and with the spacecraft at apogee. An important assumption is that the spacecraft antenna pattern is on-axis to the communications path, a highly unusual spacecraft orientation condition. Of course, an infinite number of cases could be presented in such a tabular assessment.

Another highly variable parameter that must be taken into account is pointing and polarization loss. With the wide variety of AO-10 offset pointing situations that are seen in typical operation, the pointing and polarization losses can easily achieve values of 10 dB or more. Nevertheless, the presentation of Table 23.12 is in the ballpark for Mode B operations for those power levels and received signal conditions seen in practice.

THE 4 × 3 × 5 MHz FILTER FOR MODE J

If your 435-MHz receive system is sensitive enough to experience desense from your 2-m uplink, the filter shown in **Fig 23.51** should solve the problem. Most Mode J OSCAR users have experienced some difficulty getting satisfactory results on this mode. Being able to receive well is the secret. Adding this filter should narrow the passband enough to allow rejection of unwanted noise and birdies. Insert it before any preamp or converter in the antenna feed line. If the third-harmonic level is high, it may be necessary to use a similar filter built for the 144-MHz band after your uplink 144-MHz rig.

Most plumbing-supply outlets can supply you with the material for the 3/4- and 3-inch copper pipe. The only other item of cost is the type of coax receptacle you want to use. Make it adaptable to your system, without sacrificing loss. The filter should cost less than $10.

Be careful when you solder double-sided PC board. Direct the heat of your torch at the pipe and enough heat will transfer to the board to allow the solder to flow. It is not necessary to use PC board, as copper or brass that is thick enough to support the unit will do. If copper or brass is not available, a soup can you can solder to works well. The more stable the structure, the better.

The filter has a narrow passband, but with a good high-gain, low-noise system you should be able to peak up the noise with no signal. A low-power 145.050-MHz signal into a dummy load should give you a test signal to peak the filter.

The insertion loss measured in the ARRL Lab was around 0.4 to 0.5 dB. If you want to improve this

Parts List

Piece No.		
1	Pipe, copper 3″ diam, 5″ long	Cut ends square. Drill or punch for connectors 3 3/4″ from bottom.
2	Pipe, copper 3/4″ diam, 4″ long	AgSn (plumbing alloy) solder to center of 10.
3	Disk, copper 3/4″ diam 1/16″-1/8″ thick	Drill through center. Solder solid hook-up wire between disk and connector to space disk 3/16″ from piece 2.
4	Disk, copper 3/4″ diam 1/16″-1/8″ thick	Drill through center. Solder solid hook-up wire between disk and connector to space disk 3/16″ from piece 2.
5	Connector, coax	BNC, SMA or N type. Solder to prevent turning. For large connector, use chassis punch.
6	Same as 5	
7	Nut, brass 1/4″-20 hex	
8	Nut, brass 1/4″-20 hex	
9	PC board, double-sided. Top 4″ × 4″.	Drill hole in center to clear 1/4-20 bolt. Solder 7 and 8 each side of hole. (Use bolt 11 to hold nuts in place when soldering.)
10	PC board, double-sided. Bottom 4″ × 4″.	Solder 2 in center.
11	Bolt, brass 1/4-20 × 3″	Insert through 12, then through 7 and 8.
12	Locking nut, brass, 1/4-20 hex	To hold piece 11 after resonance adjustment.

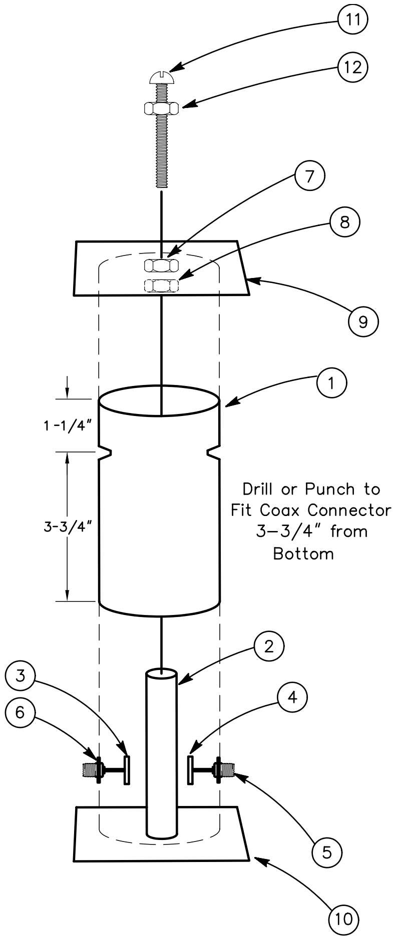


Fig 23.51—Parts list for the 4 × 3 × 5 MHz filter.

figure, use silver braze and silver plating. This filter was fashioned after a design by Joe Reisert, W1JR, and was built by Jay Rusgrove, W1VD.

A similar filter is available as a kit from the Microwave Filter Co, Inc (see the **References** chapter). MFC developed their model 9397 filter specially as a kit for amateur Mode-J satellite operators. Dick Jansson, WD4FAB, describes the kit fully in September 1992 *QEX*.

PARABOLIC REFLECTOR AND HELICAL ANTENNAS FOR MODE S

The Mode S transponder has become very popular for a variety of reasons. Among the reasons are: good performance can be realized with a physically small downlink antenna and good quality downconverters and preamps are available at reasonable prices. Increased operation on Mode S has long been advocated by a number of people including Bill McCaa, K0RZ, who led the team that designed and built the Mode S transponder[14] and James Miller, G3RUH, who operated one of the AO-13 command stations.[15] Ed Krome, K9EK, and James Miller have published many articles detailing the construction of preamps, downconverters, and antennas for Mode S.[16-22] The following is a condensation of several articles written by G3RUH describing two types of antennas that can be easily built and used for reception of the Phase 3 Mode S downlink.

Parabolic Reflector

There are three parts to the dish antenna — the parabolic reflector, the boom, and the feed. There are as many ways to accomplish the construction as there are constructors. It is not necessary to slavishly replicate every nuance of the design. The only critical dimensions occur in the feed system. When the construction is complete, you will have a 60-cm diameter S-band dish antenna with a gain of about 20 dBi with RHCP and a 3 dB beamwidth of 18°. Coupled with the proper down-converter, performance will be more than adequate for Mode S.

The parabolic reflector used for the original antenna was intended to be a lampshade. Several of these aluminum reflectors were located in department store surplus. The dish is 585 mm in diameter and 110 mm deep corresponding to an f/d ratio of 585/110/16 = 0.33 and a focal length of 0.33 × 585 = 194 mm. The f/d of 0.33 is a bit too concave for a simple feed to give optimal performance but the price was right, and the under-illumination keeps ground noise pickup to a minimum. The reflector already had a 40-mm hole in the center with three 4-mm holes around it in a 1-inch radius circle.

The boom passes through the center of the reflector and is made from 12.5 mm square aluminum tube. The boom must be long enough to provide for mounting to the rotator boom on the back side of the dish. The part of the boom extending through to the front of the dish must be long enough to mount the feed at the focus. If you choose to mount the down-converter or a preamp near the feed, some additional length will be necessary. Carefully check the requirements for your particular equipment.

A 3 mm thick piece of aluminum, 65 mm in diameter is used to support the boom at the center of the reflector. Once the center mounting plate is installed, the center boom is attached using four small angle brackets — two on each side of the reflector. See **Fig 23.52** for details of reflector and boom assembly.

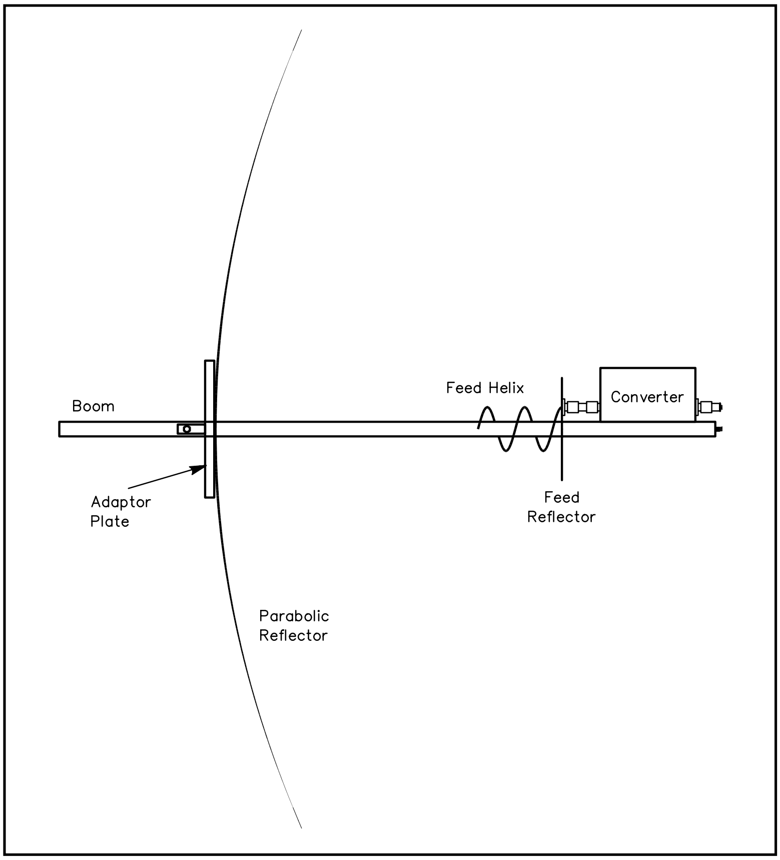


Fig 23.52 — Detail of 60-cm Mode-S dish and feed.

A small helix is used for the S-band antenna feed. The reflector for the helix is made from a 125 mm square piece of 1.6 mm thick aluminum. The center of the reflector has a 13-mm hole to accommodate the square center boom described above. The type N connector is mounted to the reflector about 21.25 mm from the middle. This distance from the middle is, of course, the radius of a helical antenna for S band. Mount the N connector with spacers so that the back of the connector is flush with the reflector surface. The helix feed assembly is shown in **Fig 23.53.**

Copper wire about 3.3 mm in diameter is used to wind the helix. Wind four turns around a 40-mm diameter form. The turns are wound counterclockwise. This is because the polarization sense is reversed from RHCP when reflected from the dish surface. The wire helix will spring out slightly when winding is complete.

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

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

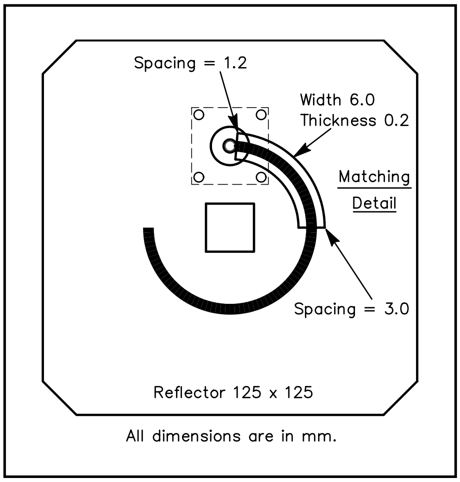


Fig 23.53 — Helix side of 60-cm Mode-S dish feed. The N-type connector is fixed with three screws, and is mounted on a 1.6-mm spacer to bring the PTFE molding flush with the reflector. Dimensions are in mm; 1 in. = 25.4 mm.

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

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

16-Turn Helix

The 16-turn helix described in this section was designed to be as physically small as possible and still allow reception of Mode S downlink signals.[21] The results of tests using the antenna while AO-13 was at apogee of 43,000 km can be found in Reference 22. When coupled with an adequate preamp/downconverter system, the 15.5 dBic gain of the 16-turn helix is adequate for CW operation, and under good conditions, may be adequate for SSB operation as well.

The 16-turn helix is shown in **Fig 23.54**. The helix and reflector plate are constructed as described for the parabolic dish above, except that the helix is wound right handed (clockwise). The matching section spacing from the reflector is 2 mm at the start and 8 mm at the end. The helix is supported at every fifth turn, starting with turn 3/4, using PTFE (Teflon) spacers screwed to the boom.

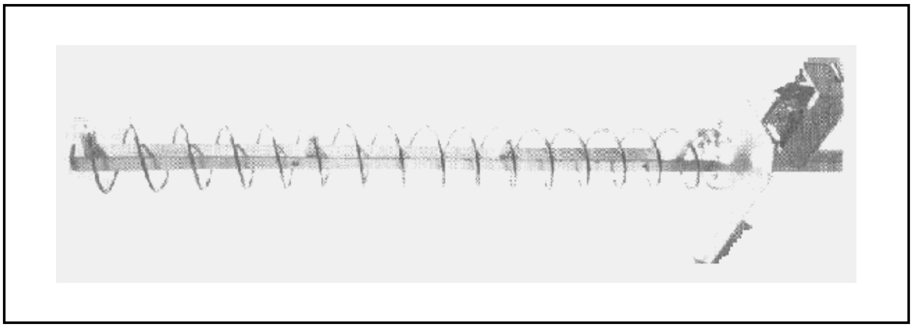


Fig 23.54 — 16-turn helix antenna for Mode S.

For additional information on constructing antennas for use at microwave frequencies, see *The ARRL UHF/Microwave Experimenter's Manual*.

MODE-S RECEIVE CONVERTER

This project, designed by Zack Lau, W1VT, in the ARRL Lab, was first published in July 1994 *QEX*, pp 25-30. Its goal is a simple yet high-performance 13-cm receive converter optimized for 2401-MHz OSCAR Mode-S reception. The design takes advantage of recent advances in PHEMT technology to simplify the circuitry while also improving performance. See **Fig 23.55**. A template package is available.[23] The finished unit checks out with a 0.33-dB NF and 31 dB of conversion gain, according to the ARRL Lab's HP 346A/8970 noise-figure meter. This low noise figure, combined with a 15-turn helix antenna, achieves a gain-to-noise-temperature ratio of around 1. The converter also is small enough to be mounted at the focus of a dish with minimal blockage.

The biggest design simplification comes from the use of Hewlett-Packard PHEMT GaAs MGA-86576 MMICs, which are almost ideal in this application. The MGA-86576 has a relatively low noise figure of 1.5 dB, just the right output power of + dBm, a low current draw of 16 mA, and a gain of 23 dB that peaks in-band. The major disadvantage of the device is that it requires very good grounding for stability. Hewlett-Packard suggests four plated-through holes under each lead. Since this design is for amateurs to duplicate, rather than for commercial manufacturers, very thin circuit board, 15-mil 5880 Rogers Duroid, was used. Microwave Components of Michigan has been selling this material for many years. Excellent stability can be obtained with this thin board by bending the leads sharply and running them through the board. Unlike those of some surface-mount devices, the leads of these MMICs are long enough to go through and bend back against the board for a good mechanical attachment.

An advantage to PHEMT MMICs is their significant power efficiency. The 564 to 2256-MHz multiplier draws only 23 mA, even when an inefficient LM317L linear regulator is used. See **Table 23.14**.

The mixer is a Mini-Circuits SYM-11, a surface mount device with a reasonable RF port impedance. Its 50-Ω input SWR is roughly 2:1.

Since the two MMICs and PHEMT draw only about 50 mA, the local oscillator board was redesigned. See **Fig 23.56**. Size and current consumption were both cut in half. A major part of the size reduction was obtained by using smaller filters. This was done by capacitively loading the hairpin loops of the filter with 4.7-pF chip capacitors. This adds an interesting variable to no-tune de-

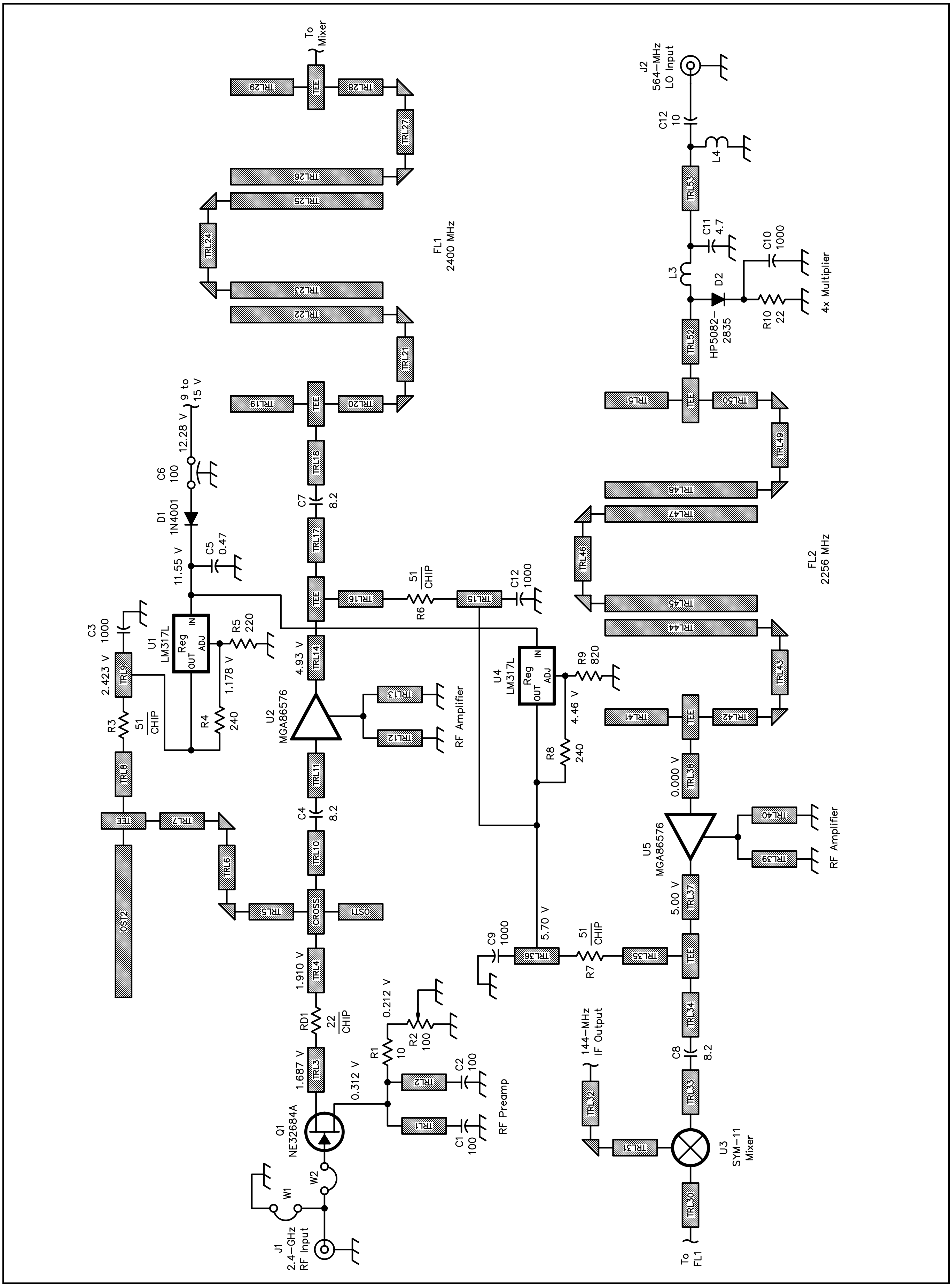
Table 23.14
Measured Performance of the 564 to 2256-MHz Multiplier

Input (dBm)	*Output (dBm)*
7.0	3.3
7.9	5.0
8.8	6.0
10.0	6.8
10.7	7.0
13.0	7.3

Fig 23.55—Schematic of the S-band converter.

C1, C2—100-pF ATC 100A chip capacitors (substitution not recommended).
C3, C9, C10—1000-pF chip capacitors.
C4, C7, C8—8.2-pF, 50-mil chip capacitors.
C5—0.1-µF or larger capacitor.
C6—100-pF feedthrough capacitor (any value from 10 pF to 0.1 µF should work fine).
C11—4.7-pF chip capacitor.
C12—10-pF chip capacitor.
D1—1N4001 rectifier diode.
D2—Hewlett-Packard 5082-2835 Schottky diode (or another Schottky switching diode).
L3, L4—4 turns #28 enameled wire, $^1/_{16}$-inch ID.
RD1—22-Ω, $^1/_{10}$-W chip resistor, 50 × 80 mils.
R3, R6, R7—51-Ω, $^1/_{10}$-W chip resistor.
U1, U4—LM317L adjustable voltage regulator.
U2, U5—Hewlett-Packard MGA 86576 PHEMT MMIC.
U3—Mini-Circuits SYM-11 mixer.
W1—#32 silver-plated wire taken from 20-gauge Teflon stranded wire (8-mil diameter). This is a loop whose ends are 200 mils apart using 250 mils of wire (plus more for the connections). One end is 55 mils above ground; the other end is grounded.
W2—#32 silver-plated wire. This loop is between the center pin of the coax and the transistor gate. The gate lead is 20 mils long. Not counting connections, the length is 310 mils. The ends of the loop are 182 mils apart.

[Schematic on next page.]


J1
2.4-GHz
RF Input
W1
W2
Q1
NE32684A
TRL1
C1
100
TRL2
C2
100
RF Preamp
0.312 V
R1
10
R2
100
0.212 V
TRL3
1.687 V
RD1
22
CHIP
TRL4
1.910 V
CROSS
OST1
TRL5
TRL6
TRL7
TEE
OST2
TRL8
R3
51
CHIP
TRL9
2.423 V
C3
1000
U1
LM317L
Reg
OUT
ADJ
IN
R4
240
1.178 V
R5
220
11.55 V
C5
0.47
D1
1N4001
C6
100
12.28 V
9 to
15 V
TRL10
C4
8.2
TRL11
U2
MGA86576
TRL12
TRL13
RF Amplifier
TRL14
4.93 V
TEE
TRL16
R6
51
CHIP
TRL15
C12
1000
TRL17
C7
8.2
TRL18
TEE
TRL19
TRL20
TRL21
TRL22
TRL23
TRL24
TRL25
TRL26
TRL27
TRL28
TEE
TRL29
To
Mixer
FL1
2400 MHz
U4
LM317L
Reg
OUT
ADJ
IN
R9
820
4.46 V
R8
240
5.70 V
C9
1000
TRL36
R7
51
CHIP
TRL35
TEE
TRL34
C8
8.2
TRL33
144-MHz
IF Output
TRL32
TRL31
U3
SYM-11
Mixer
TRL30
To
FL1
TRL37
5.00 V
U5
MGA86576
TRL39
TRL40
RF Amplifier
TRL38
0.000 V
TEE
TRL41
TRL42
TRL43
TRL44
TRL45
TRL46
TRL47
TRL48
TRL49
TRL50
TEE
TRL51
FL2
2256 MHz
TRL52
HP5082-
2835
D2
R10
22
C10
1000
4x Multiplier
L3
C11
4.7
TRL53
L4
C12
10
J2
564-MHz
LO Input

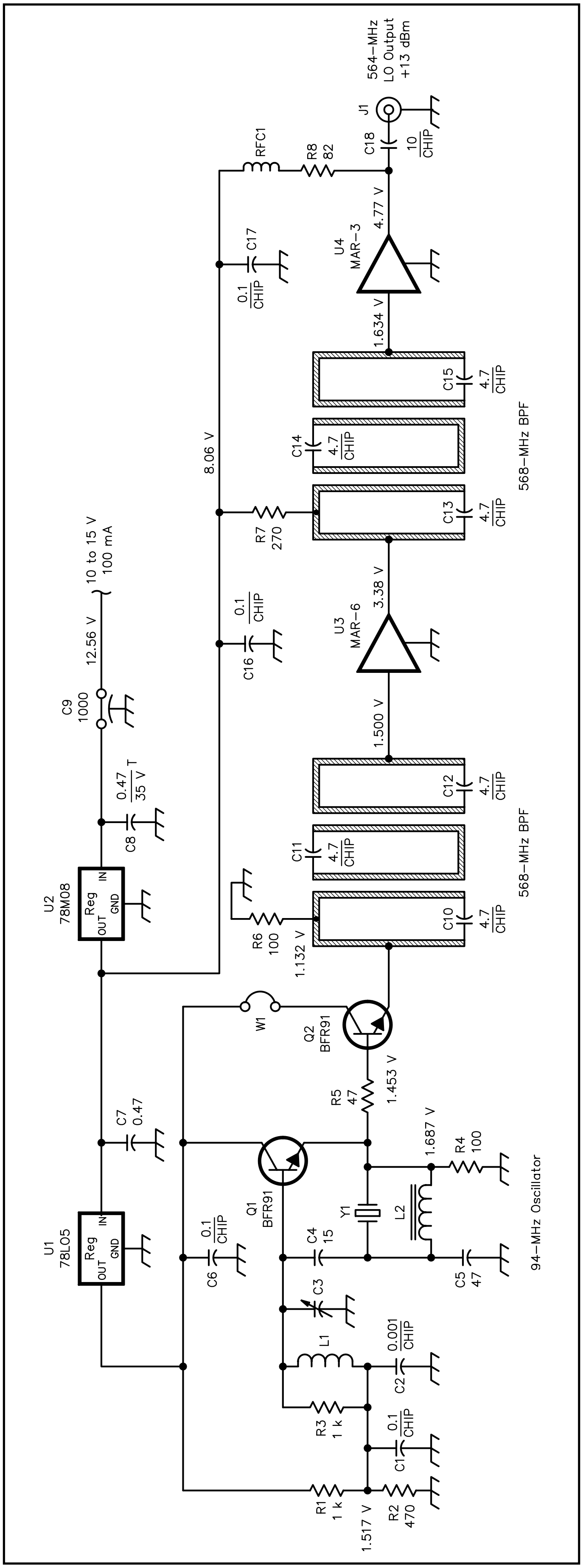


Fig 23.56—Schematic of the 564-MHz local oscillator.

C3—2 to 10-pF trimmer capacitor.

C4—15-pF NP0 capacitor.

C5—47-pF N1500 capacitor. A commonly available NP0 could be used, but the temperature compensation improves stability. (See text.)

C8—0.33-µF or larger capacitor to prevent U2 from oscillating.

C9—1000-pF feedthrough capacitor. Any value from 100 pF to 0.1 µF should work well.

J1—SMA panel jack. At 564 MHz connectors are optional.

L1—7 turns #28 enameled wire, 0.1-inch diameter, closewound. 8 turns may work if C3 tunes low enough.

L2—14 turns #26 enameled wire on a T-25-10 core. As many as 17 turns may be needed on a T-25-6 core, though 10 turns are usually specified. It depends on the crystal's shunt capacitance.

R7—270-Ω resistor. Replace with a 470-Ω resistor to run the MMIC from +12 V (no 8-V regulator).

R8—82-Ω resistor. Replace with a 220-Ω, $^{1}/_{2}$-W resistor to run the MMIC from +12 V.

RFC1—8 turns #26 enameled wire, 0.10-inch ID, closewound.

U1—78L05 5-V regulator.

U2—78M08 8-V regulator.

U3—MAR-6, MSA-0685 MMIC.

U4—MAR-3, MSA-0385 MMIC.

W1—Wire jumper.

Y1—94-MHz crystal. International Crystal Manufacturing part number 473390. For better temperature stability, mount the crystal on the ground-plane side of the board and cover it with antistatic foam.

signs. A disadvantage is that capacitor tolerances can skew the center frequency of the filter, perhaps unacceptably. On the other hand, it also can compensate for variations in board material. Thus, a bad batch of boards might well be salvaged merely by changing the value of the chip capacitors. This circuit might also be used for a 561.6 or 568-MHz LO. Multiply the former frequency by 10 for a 5616-MHz, 6-cm LO and the latter by 18 for a 10,224-MHz, 3-cm LO.

A major variable in dealing with G-10 or FR-4 glass-epoxy board is the board thickness. Variations can be as large as 14%—significant in determining the resonant frequency of a microstrip filter. Rogers advertises an available thickness tolerance of ±1.5%.

The local oscillator is the circuit used in the no-tune transverters.[24] This circuit is not recommended if you wish to set the oscillator to a precise frequency, however. Like many overtone circuits, this one may be difficult to get running properly, since there are at least three things that can go wrong. The most insidious is a parallel resonance in the tank bypass circuit at around 100 MHz. This may prevent the circuit from oscillating properly. This problem can be prevented by changing the value of the bypass capacitors or by changing the spacing between them so the stray inductance changes. The next possibility is that the tank circuit may not resonate at the desired frequency. The easiest solution is to install a 47-Ω resistor in place of the crystal and resonating inductor to see what the tuning range of the tank circuit is. Be sure to verify that the oscillator is operating at 94 MHz. It is entirely possible that the output is near 564 MHz but the oscillator is operating at some other frequency, such as 80.6 MHz. Finally, the parallel resonating inductor must resonate near the desired overtone. Since the shunt capacitance across the crystal seems to vary, the inductance value also must vary. This shunt capacitance can be measured with a 1-kHz capacitance meter that reads a few picofarads accurately.

With a temperature compensating capacitor for C5, a home-built 561-MHz local oscillator drifted 368 Hz over a temperature variation of 41° (0 to 41°C). Unfortunately, temperature compensating capacitors of specific values are not readily available in small quantities, although they can be found in “bargain assortments” at Radio Shack.

CONSTRUCTION

After etching the Teflon board, cut slots in the board for ground foils and transistor source leads. These are marked with thin pads. Use a no. 10 X-acto knife with a sharp blade. The slot should just touch the outside of the pad, so the transistor will cover the copper pads. In addition to the four slots for the transistors, there are seven slots to ground pads with thin copper foil (roughly 1 mil thick). Next, cut the “U” for the RF preamplifier. This allows a piece of unetched circuit board to be soldered in place for the ground plane. Finally, three holes are needed for the IF and dc power connections. Coax can be run between the IF connection and a panel-mount connector. Copper can be cleared away from the holes with a hand-held drill bit. This takes a bit of practice with such thin board material.

A disadvantage of 15-mil board is poor mechanical rigidity. Thus, the board should be mounted in a brass frame. 0.025×1-inch brass strip can be used. Attach the connectors to the brass strips with screws, then solder the strips to the circuit board. The strips without connectors are then soldered to the circuit board. An extra brass strip was added at the center of the enclosure near the mixer for extra stiffness.

The preamplifier construction is almost identical to the design published in Nov 1993 *QEX*.[25] Instead of an SMA connector, however, a nonstandard N connector was used—one with a panel-mount flange similar in size to a BNC connector.

R2 is set so the voltage across R1 is 0.10 V, making the bias current of Q1 10 mA. W1 and W2 may have to be tweaked for best noise figure. It is easy to damage Q1 via electrostatic discharge while doing this, so take proper precautions.

OPERATING HINTS

If this converter will be used with a typical transceiver, the mixer must be protected from the transmitter. When turned off, many modern transceivers transmit momentarily. Installation of a postamplifier and attenuator is recommended if you wish to connect this converter to the antenna port of a transceiver. This unit was really meant to be hooked up at the antenna, much like a mast-mounted preamplifier. There is little benefit to using an expensive GaAs FET preamplifier if it is fed with many feet of lossy coax. However, you can separate the preamp/MMIC amplifier and the rest of the converter, mounting the RF amplifiers at the antenna and having the converter in the station. Doing the calculations to determine the noise figure of the new system is recommended.

A SIMPLE JUNKBOX SATELLITE RECEIVER

This project, by John Reed, W6IOJ, appeared first in April 1994 *QEX*. Single-conversion receivers—including direct-conversion designs—have received a good deal of attention, primarily because of the article by Rick Campbell, KK7B, in August 1992 *QST*. The receiver described here has been configured for monitoring the 70-cm polar-orbiting PACSATs, and has demonstrated very good performance in spite of the limitations of single-conversion designs. In addition, it has retained the simplicity, compactness and versatility of single conversion. The receiver can operate in any part of the 70-cm band. The output is an IF signal having a 250-Hz to 2-MHz passband.

Fig 23.57 is a block diagram of the receiver. This diagram shows one particular PACSAT configuration—the receiver is being used with a 50-kHz IF filter/amplifier/FM discriminator, a 9600-baud modem and a TNC/computer.

GENERAL DESCRIPTION

The receiver's $3\times5^{1}/_{4}\times5^{7}/_{8}$-inch metal cabinet contains two $4^{3}/_{4}\times5$-inch circuit boards. One is the UHF circuit board that has a 70-cm input filter, low-noise monolithic preamplifier, double-balanced mixer and IF preamplifier. See **Fig 23.58**. There is also an LO driver consisting of a tripler/filter arrangement operating from a 145-MHz, 6-mW source. The VFO circuit board has a 24-MHz varactor-tuned VFO and a 145-MHz frequency multiplier followed by a two-stage monolithic amplifier. This amplifier output is the LO driver input. The VFO circuit board includes a 10-V regulator operating from a 12 to 20-V external source.

On the front panel there is a 12-position band selector switch covering 3.6 MHz of the 70-cm band in 300-kHz steps. Fine tuning within these steps is accomplished with a potentiometer covering a 500-kHz spread. The selector range can be placed in any part of the 70-cm band by trimmer adjustments located on the circuit boards. The back panel contains a BNC connector for the 70-cm input and jacks for the receiver output and the AFC input.

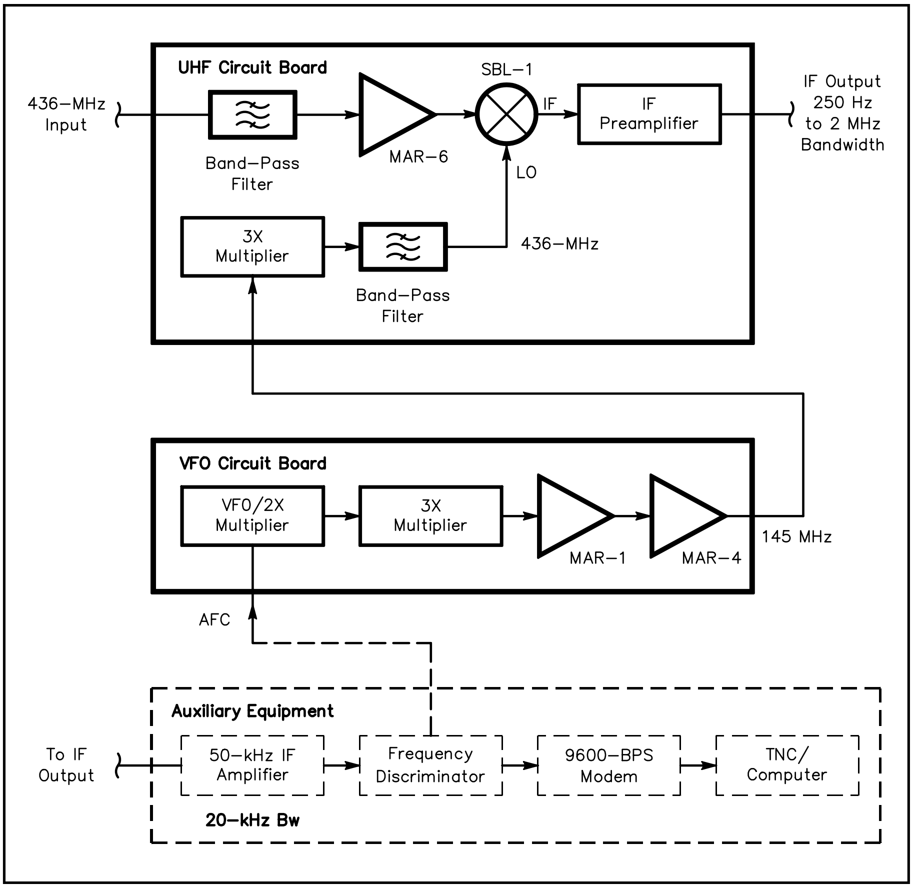


Fig 23.57—Block diagram of the receiver. The dashed-line section indicates a particular configuration for monitoring 9600-baud PACSATs.

LIMITATIONS

Single-conversion receivers lack discrimination of the unused sideband. For example, in a PACSAT application with a 50-kHz IF there will be an image frequency 100 kHz from the received signal. In actual operation, there has been no interference from a signal at this

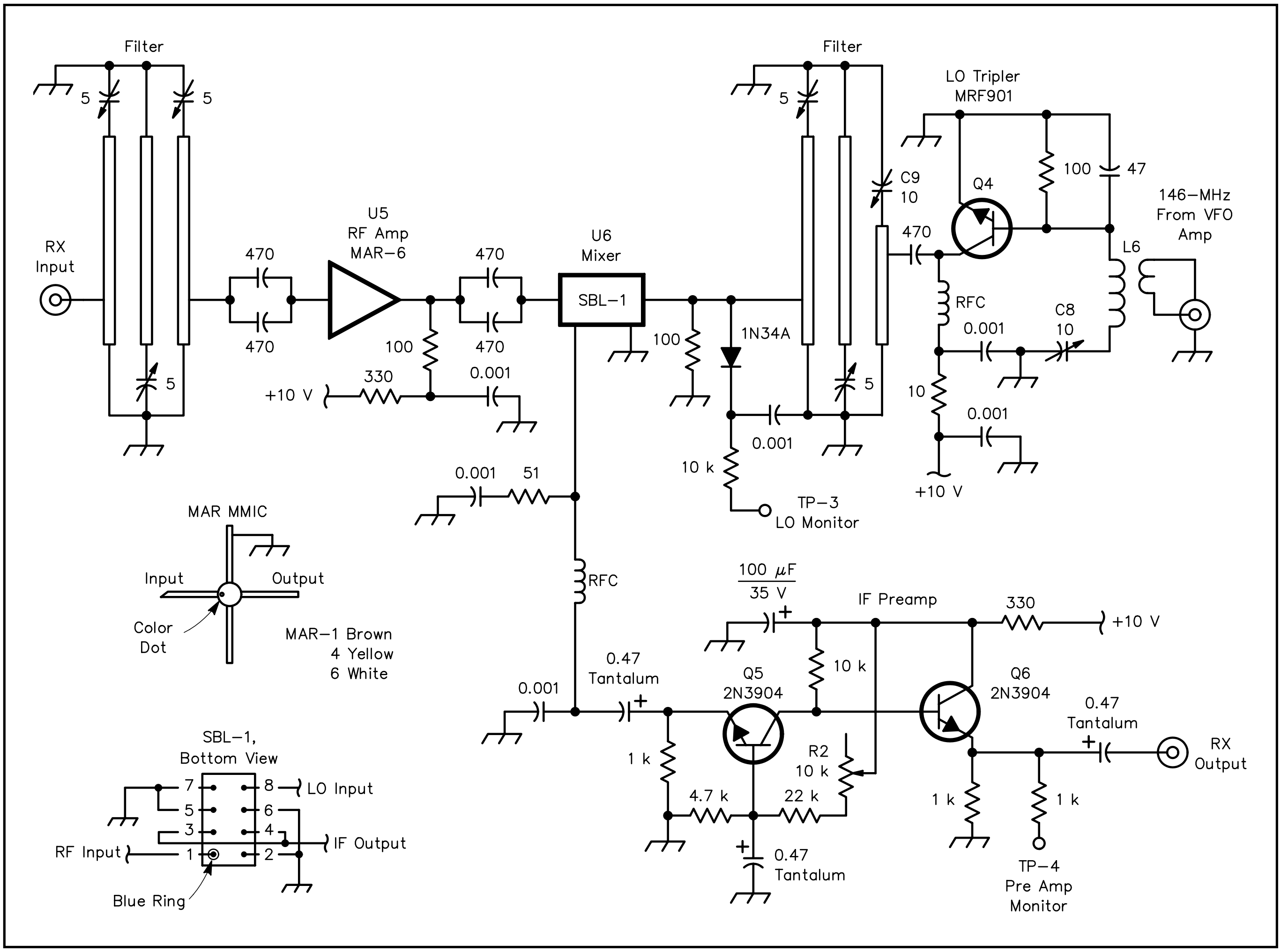


Fig 23.58—Schematic of the UHF circuit board. See Fig 23.59 for detail of the UHF filters. All capacitors are 50-V disc ceramics unless otherwise noted. All RFCs are 20 turns of #26 wire having an ID of $^1/_{16}$ inch. C8 and C9 are 10-pF FILMTRIMS (Sprague-Goodman part #GYA10000). L6 is 7 turns of #18 wire, $^1/_4$-inch ID, $^3/_8$ inch long with a 1-turn link coupling coil connected to the VFO amplifier output coupling cable.

image frequency while monitoring PACSATs. In the rare case where there may be interference, you can tune to the opposite sideband, placing the image at a different frequency.

Probably of more importance is that unattenuated noise at the image frequency causes a 3-dB S/N degradation. Although this is clearly not optimal, typical signal variations of polar-orbiting satellites are so large that this loss does not represent a major compromise. A second possible limitation is 1/f noise originating from the diode mixer. But practically all 1/f noise is below 10 kHz. Therefore, PACSAT application, with its 50-kHz IF, is not affected. Even in applications requiring the use of lower frequencies, the receiver's RF amplifier will largely override the 1/f noise.

The IF preamplifier has been left wideband simply as a versatility feature. Although the dynamic ranges of both the mixer and IF preamplifier start to roll over at about the same input levels, a filter between the mixer and preamplifier will help avoid possible overloading effects of unwanted signals that pass through the input filter but are outside the useful passband. For example, a 50-kHz filter (20-kHz bandwidth) will improve the performance of the PACSAT configuration during some interference conditions.

Frequency stability is a major consideration of simple 70-cm local-oscillator design. One influencing factor in this case is that polar-orbiting satellites have total Doppler shifts of up to 20 kHz. This alone requires automatic frequency control—unless you are willing to keep one hand on the tuner! Of course, if AFC can compensate for Doppler, it can also compensate for some drift in the local oscillator.

CIRCUIT BOARDS

The circuit boards are assembled using a glue-down stripline technique that holds the components and acts as conducting RF links. Using this method, the printed-circuit board foil remains a solid ground-plane, making it appropriate to use a single-sided board. A second feature is that the glued-down pads can be easily removed to accommodate layout changes. The component striplines are about 1/8-inch wide, and the lengths are determined by how many connections are desirable in a single line. The connecting pads are separated by foil notches made with a hacksaw, about 3/16-inch apart or longer, depending upon layout convenience.

The 50-Ω RF conducting lines are made 3/32-inch wide, assuming the use of standard glass-epoxy 0.059-inch material. The width is different from conventional etched striplines due to the raised glue-down stripline edge effect. In this particular application, the critical RF lines are so short that the type of PC board material is of little consequence. Elmer's Clear Household Cement can be used for fastening the striplines. The cement sets up enough to use the pad in a few minutes. Removal of a pad becomes difficult after setting-up for several weeks or more.

UHF CIRCUIT BOARD

The possibility of overloading of the preamplifier by off-frequency interference is minimized by first passing the input signals through a three-section stripline filter. It has an insertion loss of 0.7 dB. As shown in **Fig 23.59**, the filter is easy to build from readily available materials. Although the diagram

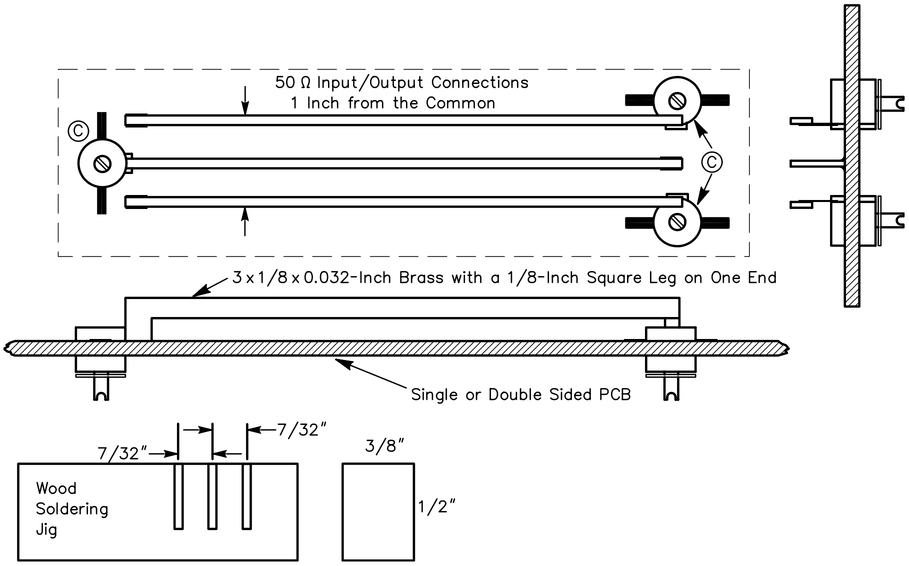


Fig 23.59—Detail of the UHF filter. The filter is easily assembled using the wood soldering jig to hold the striplines at the proper spacing while soldering. Use a 1/8-inch drill placed between the striplines and PC board to ensure proper height above the mounting surface while assembling. The jig slots are made with a hacksaw, which makes the desired 0.032-inch slot width. The devices marked C are 1.6 to 6-pF FILMTRIMs, a Sprague-Goodman plastic-dielectric capacitor (part #GYA5R000). Surplus 2.4 to 9-pF ceramic trimmers also worked well. The local oscillator filter is the same except the input stripline is 1.5 inches long rather than 3 inches long, and the related capacitor, C9, is increased to 10 pF (#GYA10000).

specifies a Sprague capacitor, which is available from many sources (Digi-Key, for example), there are inexpensive surplus miniature ceramic trimmers that will work fine as long as the minimum capacitance is 2.5 pF or less.

The MAR-6 preamplifier MMIC has a typical gain of 18 dB with a noise figure of 3.0 dB. The critical operating characteristic is the 3.5-V bias voltage (measured at the MMIC output terminal). A 10-V V_{CC}, together with 430-D series resistors, sets the proper bias to allow the MMIC to operate near its nominal 16-mA current specification. Although chip coupling capacitors are recommended, standard disc ceramics offer little performance compromise. People with poor eyesight will find disc ceramics much easier to use. Two capacitors in parallel reduce possible compromising inductance. The two MMIC ground leads are raised above the board surface using strips of $^{1}/_{16}$-inch thick brass to make them level with the input and output leads, which connect to the glue-down striplines.

The SBL 1 mixer is mounted in the conventional manner. Use of a drill to slightly ream each of the eight pin holes to avoid pin contact with the foil allows proper connection to the glue-down striplines. Grounded pins are soldered to the PC board with a small piece of soldering braid over the pin. This permits a relatively easy desoldering procedure if for some reason it becomes necessary to remove the mixer. The LO level into the mixer is monitored by a diode peak-reading detector. The nominal level is 5 mW, or about 0.8 V at TP3.

The LO driver filter is like the input filter except the input stripline is made shorter and used with a larger value capacitor. This optimizes loading of Q4, the MRF 901 tripler. The LO driver has a maximum output of 20 mW. The output is reduced to the desired level by the drive control, R1, located on the VFO circuit board.

The IF preamplifier is similar to the one described in Campbell's *QST* article. The grounded-base stage, Q5, provides a 50-Ω load to the mixer and approximately 40 dB of gain. It is followed by an emitter follower to supply a low output impedance.

VFO CIRCUIT BOARD

See **Fig 23.60**. The VFO, Q1, is a 24-MHz JFET Colpitts oscillator. It is tuned by a 12-V Zener diode connected to operate like a varactor. It produces approximately a 10-pF capacitance change that provides the desired 436-MHz LO shift of 4 MHz (222-kHz shift at the VFO). The output is taken from the FET drain with a 48-MHz tuned circuit. This doubles the frequency while providing reasonable isolation from the VFO.

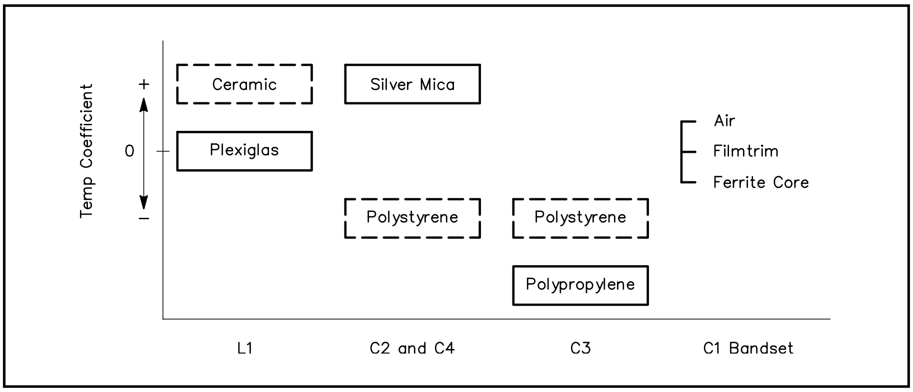


Fig 23.61—Relative temperature coefficients of the VFO components as observed during circuit operation. The solid lines indicate a configuration using a solid Plexiglas coil form and the dashed lines a thin-wall ceramic form. Both configurations will operate continuously for six hours together with a 10° F ambient temperature change with less than a 20-kHz shift in frequency. There is little performance difference between the three types of band-set methods as a function of temperature change.

Fig 23.61 shows the results of tests made of various VFO components. Fig 23.61 also describes two acceptable component combinations. The dominant temperature-sensitive components are the inductor (L1) and the tuned circuit capacitors (C2, 3, 4). The band-set trimmers (both the capacitors and the variable ferrite), and the varactor are less sensitive. The two recommended combinations have an initial turn-on frequency shift of about 10 kHz during the first 15 minutes of operation. After

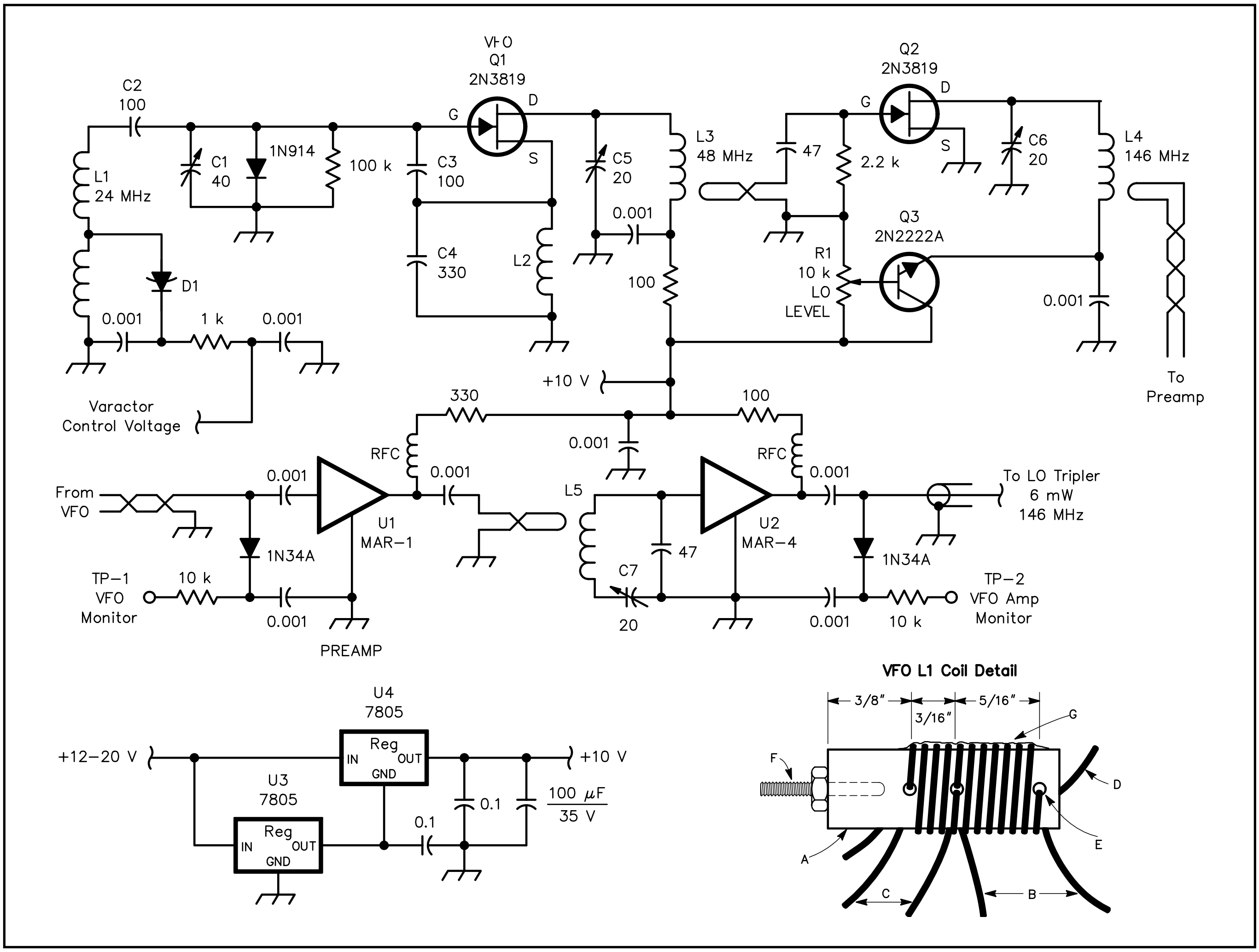


Fig 23.60—Schematic of the VFO circuit board.

C1—40-pF FILMTRIM (Sprague-Goodman #GYC40000).

C2—100-pF silver mica.

C3—100-pF polypropylene (Panasonic #ECQ-P1H101JZ).

C4—330-pF silver mica.

D1—1N4742, 12-V Zener diode (used as a varactor).

L2—10 turns #26 wire wound on a $^1/_4$-inch diam form (wood dowel).

L3—10 turns #26 wire wound on a $^1/_4$-inch diam form with a 2-turn link coupling coil made from #30 wire-wrapping wire. The twisted pair is about 2 inches long.

L4—5 turns #18 wire, $^1/_4$-inch ID, $^5/_{16}$-inch long with a 1-turn link coupling coil made from #22 hookup wire. The twisted pair is about 1 inch long.

L5—7 turns #18 wire, $^1/_4$ inch ID, $^3/_8$ inch long with a 1-turn link coupling coil made from #22 hookup wire. The twisted pair is about 1.5 inches long.

RFC—20 turns #26 wire, $^1/_{16}$ inch ID. Output coupling to the tripler—about 1 ft of miniature microphone cable (RS 278-510).

A—$^3/_8$ inch diam Plexiglas rod.

B—7 turns coil #26 gauge wire.

C—4 turns coil #26 gauge wire.

D—0.010-inch diam carpet thread wound with the coil for uniform turn spacing.

E—$3^1/_{16}$ inch diam holes to hold the coil.

F—#4-40 coil mounting stud. It is cemented or threaded into the Plexiglas form.

G—Place several lines of clear cement along the coil length (Elmer's Clear Household Cement).

that the shift is less than 10 kHz. An uncompensated configuration using all mica capacitors together with a Plexiglas coil form has a frequency shift of about 15 kHz per degree change of ambient temperature.

A resistive divider network, shown in **Fig 23.62**, provides the varactor tuning voltage and an input for the AFC or scanner function. A 12-position switch selects voltage divider resistors having values that compensate for the varactor nonlinearity, resulting in a 300-kHz frequency shift for each position. The voltage for the varactor will vary from 3.7 to 6.6 V or 3.4 to 6.0 V depending on the position of the fine-tuning potentiometer. The AFC/scanner input is nominally biased to 5 V. The frequency can be shifted up to 200 kHz either plus or minus by forcing the bias to 0 or 10 V. The bias resistance is 5 kΩ.

Two 10-turn potentiometers, one for bandset and the other for fine tuning, are an alternative method. Frequency calibration is performed simply by monitoring the varactor input voltage with a meter. This method worked very well. It didn't compensate for the nonlinear varactor, but the tuning was fine enough to make that unimportant.

The VFO is followed by an FET tripler and a two-stage MMIC amplifier. The 145-MHz tripler has a maximum output of about 0.5 mW. This level is controlled by varying the FET drain voltage with the potentiometer R1, and monitored by a diode peak detector (TP1). The first MMIC MAR1 stage has a gain of about 18 dB and an output capability of +7 dBm in the VHF region. Its nominal operating current is 17 mA with a bias of 5 V. Although this output is probably enough to drive the LO tripler, the MAR4 was added as a safety factor to allow for circuit performance variations. It has a gain of about 8 dB with an output of +13 dBm. Its nominal operating current is 50 mA with a bias voltage of 6 V. The bias resistors, 300 and 100 Ω, together with the 10-V source, operate the MMICs close to their nominal values. There is a relatively high-Q tuned circuit used in the interstage coupling between the two MMICs for filtering out unwanted VFO responses. There are three tuned circuits for this purpose, L4/C6, L5/C7 and L6/C8, to ensure a reasonably pure waveform for driving the LO tripler. Output of the VFO amplifier is monitored by a peak voltmeter at TP2. It is also used to initially align L6/C8. At resonance, TP2 will read a minimum value due to lowering of the load impedance. About one foot of miniature microphone cable is used to connect the amplifier RF output to the UHF circuit board. There is a bit of loss in

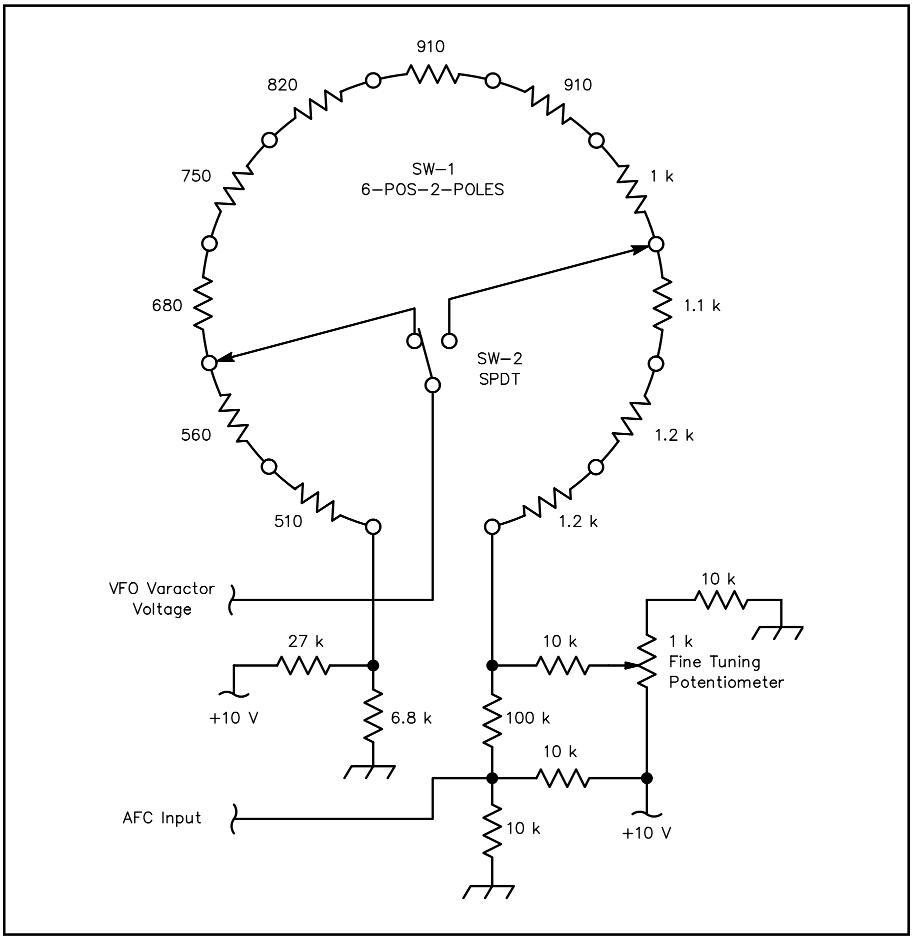


Fig 23.62—Schematic of the varactor voltage controller. There is a 300-kHz frequency shift between each SW-1 position. The fine tuning frequency shift is 500 kHz. The total tuning range is 4 MHz. The AFC input can shift the frequency up to ±200 kHz. It is biased to +5 V by a 5-kΩ resistive divider. Maximum shift occurs when it is forced to 0 or +10 V.

using this cable, but there is power to spare and cable flexibility is an important consideration.

ALIGNMENT

The receiver can be aligned using nothing more than a multimeter and a 2-m transceiver. The 2-m receiver permits initial frequency set of the VFO, and the third harmonic of the 2-m transmitter provides a signal for initial test and alignment of the input filter and RF amplifier. The required alignment steps are detailed in **Table 23.15**.

Performance of the compact stripline filter is far from outstanding. However, it does allow me to monitor PACSATs while transmitting into the adjacent 2-m uplink antenna without interfering with the received signal (for the PACSAT full-duplex mode). The author has concluded that a more complex internal filter would not substantially improve the receiver's performance.

The receiver has been used to copy FM 9600-baud packet from UO-22 and KO-23, and 1200-baud PSK from AO-16. It is a simple assembly that is a pleasure to use.

Table 23.15
Procedures for Final Alignment

1. Adjust all capacitors to minimum capacitance except C1, C5 and C8. Set these three at maximum capacitance. Set R1 for maximum VFO output.
2. Turn the tuner controls for midband response. SW1: pos 6, SW2: low pos. Fine tuning potentiometer: midway point.
3. Set the 2-m transceiver to 145.33 MHz and arrange conditions such that a rubber duck, or some other pick-up device, can be placed near L1.
4. Tune the VFO to 24 MHz by decreasing C1 until the VFO is heard on the receiver.
5. Tune L3/C5 to 48 MHz by decreasing C5 while peaking the 2-m receiver response.
6. Peak the 146-MHz multiplier response by decreasing C6 while monitoring TP1; it should read about 0.3 V.
7. Peak the VFO amp response by increasing C7 while monitoring TP2; it should read greater than 1 V.
8. Peak L6/C8 to 146 MHz by increasing C8 while monitoring TP2; it will null to about 0.8 V.
9. Peak the LO filter by decreasing C9 while monitoring TP3, then trim the remaining two 5-pF capacitors. TP3 should read about 1.2 V.
10. Correct the LO mixer input by adjusting R1 on the VFO circuit board for 0.8 V at TP3.
11. Normalize the IF preamp operation by adjusting R2 to make the dc voltage at TP4 2 V.
12. Peak the three input filter 5-pF capacitors for maximum response to the 2-m transmitter's third harmonic.
13. Optimize the S/N by tuning to a marginal input signal that is about +10 dB S/N (transmitter harmonic, noise, etc) and peaking the three filter 5-pF capacitors. S/N alignment requires the receiver input be terminated with a 50-Ω load.

Parts Suppliers

MMICs—Down East Microwave.

SBL1—Oak Hills Research.

Panasonic P-Series Polypropylene capacitors and Sprague-Goodman FILMTRIMs—Digi-Key Corp.

Silver mica capacitors and ceramic trimmers—All Electronics.

Plexiglas—Check the Yellow Pages under Plastics.

Brass—Hobby shops usually stock small sheets of brass in various thicknesses.

AN INTEGRATED L-BAND SATELLITE ANTENNA AND AMPLIFIER

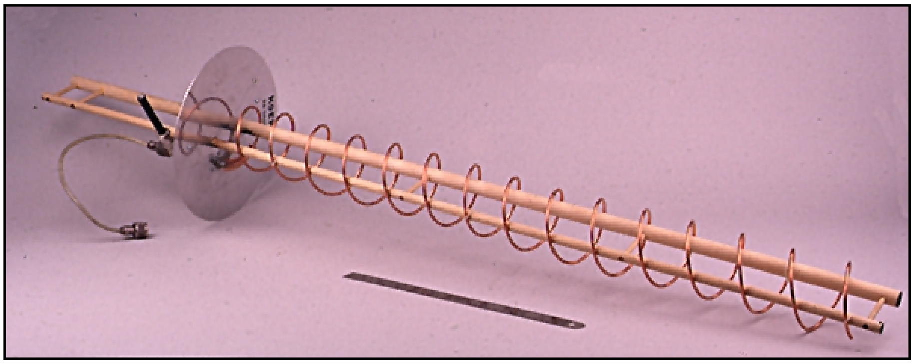


Photo A—This antenna was designed to be home-brewed without any special tools or shop equipment. It is mounted on two 4-foot long hardwood dowel rods. See the text for construction details.

The new Phase 3D satellite offers a variety of bands and modes; literally something for everyone. It will have communications capability on every authorized amateur satellite frequency between 146 MHz and 24 GHz. Uplinks are on 146, 435, 1270, 2400 and 5670 MHz. Downlinks are on 146, 435, 2400 and 10450 MHz, and 24 GHz. All uplink receivers and downlink transmitters share a common intermediate frequency and are switched through a matrix. This allows any uplink to be paired with any downlink; even multiple transmitters and receivers may be paired. Frequency pairings will be selected based on operating considerations. Up and downlinks in the same band (such as on 146, 435 and 2400 MHz) will never be used simultaneously.

To demonstrate what can be done, using a typical commercially available amplifier module, Ed Krome, K9EK (ex-KA9LNV), built an amplifier for the L-band uplink. The amplifier is mounted on a boom, counterbalancing a helical antenna. The antenna design was taken from a program in the *ARRL UHF/Microwave Experimenter's Manual*. All of the work was done in the author's home workshop without any special tools or equipment. This project shows you can still home-brew equipment, even for the latest of the amateur satellites.

The amplifier/antenna combination takes a "system" approach to providing a convenient and practical method of generating a satisfactory Phase 3D uplink, while keeping cable and construction costs to a minimum.

It is likely that the same frequency combinations that have proven historically popular will be used frequently on Phase 3D. Much was learned about communications with AO-13. Mode L (to be termed Mode L/U), with its 1270 MHz uplink and 435 MHz downlink, was very popular and an excellent performer. Mode S (now Mode U/S; 2400 MHz downlink and 435 MHz uplink), was included as an experiment, and proved to be extremely successful. S-band downlinks with 30 inch diameter parabolic dish antennas could provide almost armchair SSB copy. It is expected that Phase 3D will see both of those modes

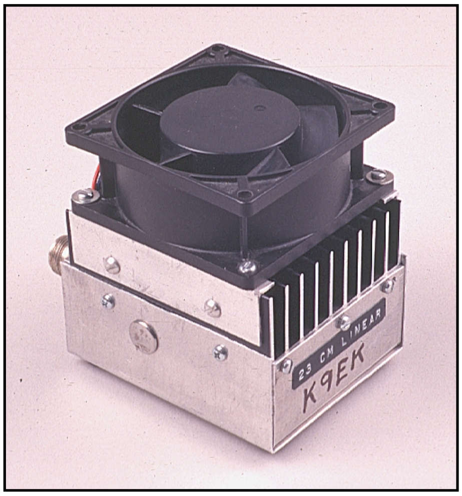


Photo B—The matching brick amplifier can be mounted on the reverse side of the mast to counterbalance the antenna.

Antenna details

Construction parameters for a 1270 MHz, 15 turn helix antenna (from *helix.bas* by KA1GT) (all dimensions are in inches)

Length of wire in each turn = 10.445

Total length of wire required for entire antenna = 156.7

Coil diameter (center of wire) = 3.24

Spacing between turns (center to center) = 2.31

Circumference = 10.186

Total length of antenna coil = 34.7

frequently, as well as a combination that takes the best of both, Mode L/S.

For the 23 cm, or L band, uplink, both kits and commercial equipment are available. Commercial equipment, such as the ICOM IC-1271 series and the 23-cm plug-in module for the popular Yaesu FT-736R, provide about 10-W of output power. Ten watts, coupled to an antenna as small as a 12-turn helix, is predicted to be adequate for satisfactory SSB communications. However, microwave frequencies present different problems from the lower bands. In particular, 10-W in the shack does not necessarily mean you will see those 10 watts at the antenna. Common (and reasonably priced) coaxial feed lines are quite lossy at 1270 MHz. The old standby, RG-8U, loses almost 13 dB per 100 feet, which leaves $^1/_2$-W out from the 10-W input. Hardline is a good solution, but tends to be expensive.

AN INTEGRATED APPROACH

A much better solution may be to integrate the antenna and final amplifier, eliminating the feed-line losses between the two. Fortunately, an elegant solution exists for the “amplifier” part of this integration. This is the M57762 amplifier module, a readily available “hybrid” amplifier (referred to as a *brick*) designed for linear amplifier service on 23 cm. This 50-Ω impedance module requires only the addition of suitable dc power circuitry, input and output connectors and a heat sink to provide a 10 to 20-W, 13 dB gain amplifier.

Many antenna designs are available. One practical design for satellite communications is the helix antenna. Helix antennas are broadbanded, inherently circularly polarized and relatively easy to construct. A suitable helix antenna may be designed using KA1GT’s *helix.bas* computer program from *The ARRL UHF/Microwave Experimenter’s Manual*. The antenna shown uses 15 turns of no. 8 copper wire and provides a calculated gain of 15 dB. This design was selected because it provides slightly more than the minimum required gain and physically fits on a 3-foot long boom.

The L band uplink amplifier and antenna shown carries the integration a step further. The amplifier is mounted on the back end of the helix antenna frame (on the opposite side of the clamp for the crossboom), thereby serving as a counterweight to partially offset the weight of the helix. This is desirable to reduce elevation rotor load.

The amplifier is fed from a shack-mounted 23-cm transmitter, but is rated for less input power than what the common transmitters (as previously noted) produce. To extend our development of an integrated arrangement even further, it may be possible to use the length of cable between the shack-mounted transmitter and the pole-mounted amplifier to attenuate the transmitter’s signal down to the level required by the amplifier. The M57762 is rated at 1-W (+30 dBm) input. First, calculate the attenuation required between the transmitter and the amplifier to prevent damage to the amplifier. Then calculate the amount of your feed line required to provide that attenuation. If the run between the transmitter and amplifier is shorter than the cable required for attenuation, simply use the whole required length of cable and coil the excess up as a drip loop at the bottom of the tower.

ANTENNA CONSTRUCTION

Probably the easiest way to build the helix itself is to stretch out the required length of wire (adding a foot or two to hold on to, which will be cut off later), then mark the wire every “Length of Turn” distance. Calculate the cumulative length and mark from that to prevent errors. Then close wind the marked wire smoothly around a form slightly smaller than the noted diameter. It seems easier to “unwind” the helix while stretching it to size than to “wind” it. Stretch the helix along a rod until the overall length is achieved. Measure and equalize spacing between turns. Finally, cut off the ends to get the desired helix. The helix is effectively fed from its circumference through a matching transformer in the form of a *fin* soldered to the first $^1/_4$ turn of the helix. A $^1/_2$ inch wide strip of 0.015 inch brass stock, cut to match the curve of the helix, works fine. Position the fin back about $^1/_4$ inch from the connector, then solder it to the first quarter turn, parallel to the reflector plate. A usable method of connecting the large helix wire to the N connector center conductor is to flatten the last $^1/_4$ inch of the wire with a hammer and block, then drill a hole in the flattened end to fit over the center conductor. Finally, solder it in place. On the antenna shown, a return loss of 16 dB was attained when the end of the helix was spaced about 0.1 inch from the reflector.

The antenna frame was constructed from 4-foot long hardwood dowel rods. The frame shown uses a $^{3}/_{4}$ inch rod on top and $^{1}/_{2}$ inch rod underneath, jointed together by $^{1}/_{4}$ inch dowel sections slipped into drilled holes and glued into place. Since the inside diameter of the helix is equal to the pitch diameter minus one times the wire diameter, this frame is 3.1 inches outside dimension. The spacers in the 36 inch helix section were installed first, then the free ends of the rods were passed through properly spaced holes drilled in the reflector plate, then the remaining spacers were installed (through holes drilled in the dowels) and glued in place. Varnish the frame before installing the helix. The reflector plate is secured to the frame with homemade angle brackets. The helix was slipped over the frame, stretched to the correct turn-to-turn spacing and held to the frame in several places with small tie-wraps. A homemade clamp plate is used to connect the top dowel rod to the antenna crossboom. Keep the crossboom attachment close to the back of the reflector to aid balance of the finished assembly. Since the amplifier is built with all RF and dc connections on one end, it may be mounted connectors down on the end of the antenna frame and easily weatherproofed with an inverted plastic container. The cables are routed up into the amplifier in such a way as to provide drip loops and prevent water from getting into the amplifier.

A problem with helix antennas is that the helix itself is insulated from dc ground. Therefore, static electricity may build up on the helix until it damages the attached device. One method of preventing such buildup is to add a shorted $^{1}/_{4}$ wavelength stub to the antenna feed. Since a shorted $^{1}/_{4}$ wave stub presents an extremely high impedance at its non-shorted end, it is virtually “invisible” to the RF flowing between the antenna and amplifier at the design frequency but fully grounded for dc. The stub shown is actually $^{3}/_{4}$ wavelength since $^{1}/_{4}$ wavelength is too short to be physically practical. Three-quarter wavelength is measured from the center conductor of the main cable to the shorted end of the stub. With RG-213 cable, the length of the stub from the end of the male N connector to the short is $4^{9}/_{16}$ inches. Attach the stub to the antenna through a “T” fitting. Assembled return loss was measured at 20 dB.

AMPLIFIER CONSTRUCTION

The amplifier (**Fig 23.62A)** is constructed by mounting the module itself on a heat sink, and using an etched circuit board, slipped under the leads on the brick, to provide both RF and dc connections. The only things critical about the board are the width of the 50-Ω input and output lines (0.1 inch wide on 0.062 inch thick, G10 board). Keep all leads from the module to the board traces as short as possible. The connectors (type-N are recommended) should be mounted on the end of the heat sink in such a manner that the center conductors lay on the board traces. Keep everything short! No insulator is required between the module

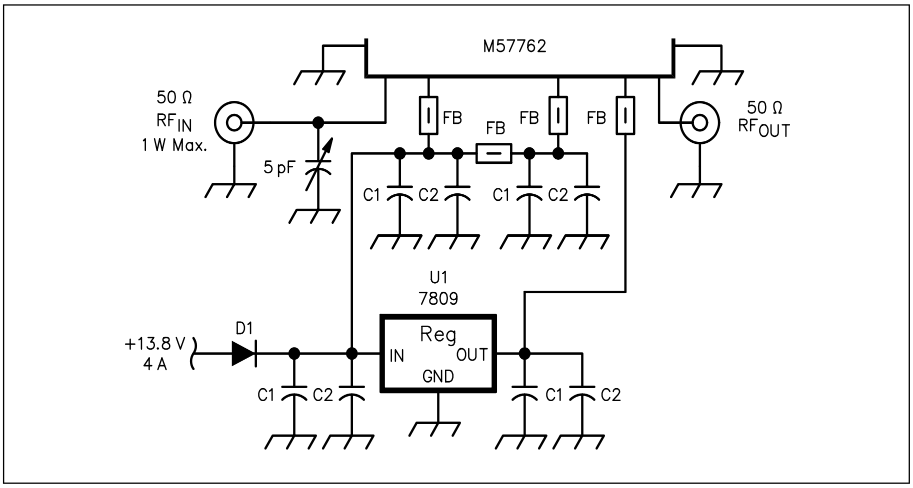


Fig 23.62A—Just a handful of parts are needed to connect the brick amplifier module. All capacitor pairs are 10 µF/35 V chip or tantalum units in parallel with 1000 pF chip capacitors. D1 is a 4-A (minimum), 50-V power rectifier such as Digi-Key GI820CT-ND. It prevents damage due to reverse connection of the power leads. U1 is a 7809 voltage regulator (9-V, 1-A). Check RF Parts and Down East Microwave (see the Chapter 30 Address List) for pricing and availability of the amplifier module.

and the heat sink. Be sure to use thermal conductive grease between the brick and the heat sink. The circuit board also must be grounded to the heat sink. Ensure good grounding of the circuit board to the heat sink by drilling and tapping several holes through the circuit board as shown.

A template, with additional construction details and a PC board layout, is available from the ARRL. See Chapter 30, **References**, for ordering information.

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Earth-Moon-Earth (EME)

EME communication, also known as “moonbounce,” has become a popular form of space communication. The concept is simple: The moon is used as a passive reflector for VHF and UHF signals. With a total path length of nearly 500,000 miles, EME is the ultimate DX. EME is a natural and passive propagation phenomenon, and EME QSOs count toward the WAS, DXCC and VUCC awards. EME opens up the VHF and UHF bands to a new universe of worldwide DX.

The first demonstration of EME capability was done by the US Army Signal Corps just after WW II. In the 1950s, using 400 MW of effective radiated power, the US Navy established a moon relay link between Washington, DC, and Hawaii that could handle four multiplexed Teletype (RTTY) channels. The first successful amateur reception of EME signals occurred in 1953 by W4AO and W3GKP.

It took until 1960 for two-way amateur communications to take place. Using surplus parabolic dish antennas and high-power klystron amplifiers, the Eimac Radio Club, W6HB, and the Rhododendron Swamp VHF Society, W1BU, accomplished this milestone in July 1960 on 1296 MHz. In the 1960s, the first wave of amateur EME enthusiasts established amateur-to-amateur contacts on 144 MHz and 432 MHz. In April 1964, W6DNG and OH1NL made the first 144-MHz EME QSO. 432-MHz EME experimentation was delayed by the 50-W power limit (removed January 2, 1963). Only one month after the first 144-MHz QSO was made, the 1000-ft-diameter dish at Arecibo, Puerto Rico, was used to demonstrate the viability of 432-MHz EME, when a contact was made between KB4BPZ and W1BU. The first amateur-to-amateur 432-MHz EME QSO occurred in July 1964 between W1BU and KH6UK.

The widespread availability of reliable low-noise semiconductor devices along with significant improvements in Yagi arrays ushered in the second wave of amateur activity in the 1970s. Contacts between stations entirely built by amateurs became the norm instead of the exception. In 1970, the first 220- and 2304-MHz EME QSOs were made, followed by the first 50-MHz EME QSO in 1972. 1970s activity was still concentrated on 144 and 432 MHz, although 1296-MHz activity grew.

As the 1980s approached, another quantum leap in receive performance occurred with the use of GaAsFET preamplifiers. This, and improvements in Yagi performance (led by DL6WU’s log-taper design work), and the new US amateur power output limit of 1500 W have put EME in the grasp of most serious VHF and UHF operators. The 1980s saw 144- and 432-MHz WAS and WAC become a reality for a great number of operators. The 1980s also witnessed the first EME QSOs on 3456 MHz and 5760 MHz (1987), followed by EME QSOs on 902 MHz and 10 GHz (1988).

EME is still primarily a CW mode. As stations have improved, SSB is now more popular. Regardless of the transmission mode, successful EME operating requires:

1) As close to the legal power output as possible.

Tommy Henderson, WD5AGO, pursues 144-MHz EME from his Tulsa, Oklahoma, QTH with this array. Local electronics students helped with construction.

2) A fairly large array (compared to OSCAR antennas).
3) Accurate azimuth and elevation rotation.
4) Minimal transmission-line losses.
5) A low system noise figure, preferably with the preamplifier mounted at the array.

The Sounds of Amateur Radio

G3HUL listens to echoes of 70-cm signals reflected off the moon.

Choosing an EME Band

Making EME QSOs is a natural progression for many weak-signal terrestrial operators. Looking at EME path loss vs frequency (**Fig 23.63**), it may seem as if the lowest frequency is best, because of reduced path loss. This is not entirely true. The path-loss graph does not account for the effects of cosmic and man-made noise, nor does it relate the effects of ionospheric scattering and absorption. Both short- and long-term fading effects also must be overcome.

50-MHz EME is quite a challenge, as the required arrays are very large. In addition, sky noise limits receiver sensitivity at this frequency. Because of power and licensing restrictions, it is not likely that many foreign countries will be able to get on 50-MHz EME.

144 MHz is probably the easiest EME band to start on. It supports the largest number of EME operators. Commercial equipment is widely available; a 144-MHz EME station can almost be completely assembled from off-the-shelf equipment. 222 MHz is a good frequency for EME, but there are only a handful of active stations, and 222 MHz is available only in ITU Region 2.

432 MHz is the most active EME band after 144 MHz. Libration fading (see Fig 23.69) is more of a problem than at 144 MHz, but sky noise is more than an order of magnitude less than on 144 MHz. The improved receive signal-to-noise ratio may more than make up for the more rapid fading. However, 432-MHz activity is most concentrated into the one or two weekends a month when conditions are expected to be best.

902 MHz and above should be considered if you primarily enjoy experimenting and building equipment. If you plan to operate at these frequencies, an unobstructed moon window is a must. The antenna used is almost certain to be a dish. 902 MHz has the same problem that 222 MHz has — it's not an international band. Equipment and activity are expected to be limited for many years.

1296 MHz currently has a good amount of activity from all over the world. Recent equipment improvements indicate 1296 MHz should experience a significant growth in activity over the next few years. 2300 MHz has received renewed interest. It suffers from non-aligned international band assignments and restrictions in different parts of the world.

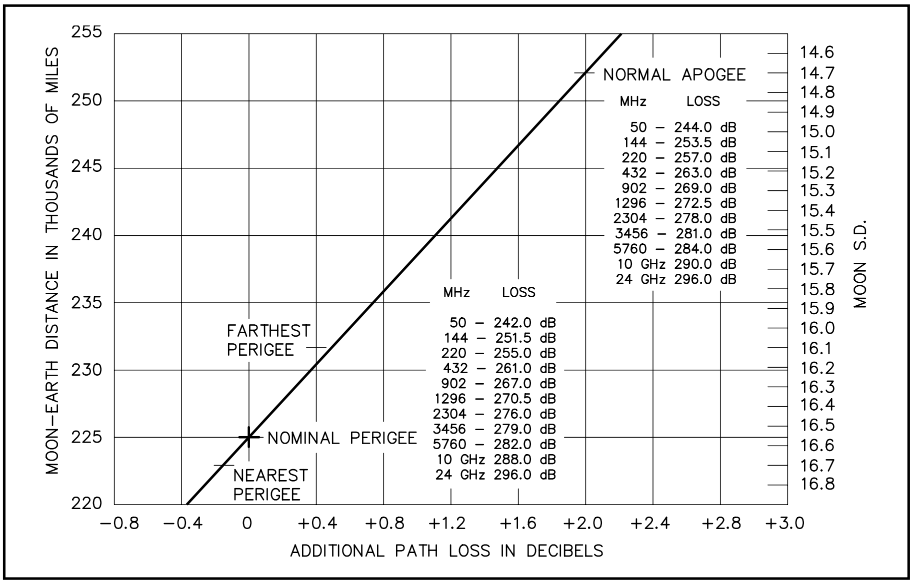


Fig 23.63 — Variations in EME path loss can be determined from this graph. SD refers to semi-diameter of the moon, which is indicated for each day of the year in *The Nautical Almanac*.

Antenna Requirements

The tremendous path loss incurred over the EME circuit requires a high-power transmitter, a low-noise receiver and a high-performance antenna array. Although single-Yagi QSOs are possible, most new EME operators will rapidly become frustrated unless they are able to work many different stations on a regular basis. Because of libration fading and the nature of weak signals, a 1- or 2-dB increase in array gain will often be perceived as being much greater. An important antenna parameter in EME communications is the antenna noise temperature. This refers to the amount of noise received by the array. The noise comes from cosmic noise (noise generated by stars other than the sun), Earth noise (thermal noise radiated by the Earth), and noise generated by man-made sources such as power-line leaks and other broadband RF sources.

Yagi antennas are almost universally used on 144 MHz. Although dish antennas as small as 24 ft in diameter have been successfully used, they offer poor gain-to size trade-offs at 144 MHz. The minimum array gain for reliable operation is about 18 dBd (20.1 dBi). The minimum array gain should also allow a station to hear its own echoes on a regular basis. This is possible by using four 2.2-λ Yagis. The 12-element 2.5-λ Yagi described in the **Antennas and Projects** chapter is an excellent choice. When considering a Yagi design, you should avoid old-technology Yagis, that is, designs that use either constant-width spacings, constant-length directors or a combination of both. These old-design Yagis will have significantly poorer side lobes, a narrower gain bandwidth and a sharper SWR bandwidth than modern log-taper designs. Modern wideband designs will behave much more predictably when stacked in arrays, and, unlike many of the older designs, will deliver close to 3 dB of stacking gain.

222-MHz requirements are similar to those of 144 MHz.

Although dish antennas are somewhat more practical, Yagis still predominate. The 16-element 3.8-λ Yagi described in the **Antennas and Projects** chapter is a good building block for 222-MHz EME. Four of these Yagis are adequate for a minimal 222-MHz EME station, but six or eight will provide a much more substantial signal.

At 432 MHz, parabolic-dish antennas become viable. The minimum gain for reliable 432-MHz EME operation is 24 dBi.

Yagis are also used on 432 MHz. The 22-element Yagi described in the **Antennas and Projects** chapter is an ideal 432-MHz design. Four of the 22-element Yagis meet the 24-dBi-gain criteria, and have been used successfully on EME. If you are going to use a fixed polarization Yagi array, you should plan on building an array with substantially more than 24-dBi gain if you desire reliable contacts with small stations. This extra gain is needed to overcome polarization misalignment.

At 902 MHz and above, the only antenna worthy of consideration is a parabolic dish. While it has been proven that Yagi antennas are capable of making EME QSOs at 1296 MHz, Yagi antennas, whether they use rod or loop elements, are simply not practical.

EME QSOs have been made at 1296 MHz with dishes as small as 6 ft in diameter. For reliable EME operation with similarly equipped stations, a 12-ft diameter dish (31 dBi gain at 1296 MHz) is a practical minimum. TVRO dishes, which are designed to operate at 3 GHz make excellent antennas, provided they have an accurate surface area. The one drawback of TVRO dishes is that they usually have an undesirable F/d ratio. More information on dish construction and feeds can be found in *The ARRL Antenna Book* and *The ARRL UHF/Microwave Experimenter's Manual*.

Polarization Effects

All of the close attention paid to operating at the best time, such as nighttime perigee, with high moon declination and low sky temperatures is of little use if signals are not aligned in polarization between the two stations attempting to make contact. There are two basic polarization effects. The first is called spatial polarization. Simply stated, two stations (using az-el mounts and fixed linear polarization) that are located far apart, will usually not have their arrays aligned in polarization as seen by the moon. Spatial polarization can easily be predicted, given the location of both stations and the position of the moon.

The second effect is Faraday rotation. This is an actual rotation of the radio waves in space, and is caused by the charge level of the Earth's ionosphere. At 1296 MHz and above, Faraday rotation is virtually nonexistent. At 432 MHz, it is believed that up to a 360° rotation is common. At 144 MHz, it is believed that the wavefront can actually rotate seven or more complete 360° revolutions. When Faraday rotation is combined with spatial polarization, there are four possible results:

1) Both stations hear each other and can QSO.
2) Station A hears station B, station B does not hear station A.
3) Station B hears station A, station A does not hear station B.
4) Neither station A not station B hear each other.

At 144 MHz, there are so many revolutions of the signal, and the amount of Faraday rotation changes so fast that, generally, hour-long schedules are arranged. At 432 MHz, Faraday rotation can take hours to change. Because of this, half-hour schedules are used. During the daytime, you can count on 90 to 180° of rotation. If both stations are operating during hours of darkness, there will be little Faraday rotation, and the amount of spatial polarization determines if a schedule should be attempted.

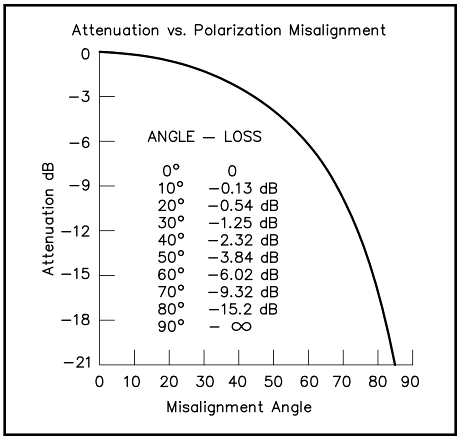
At 1296 MHz and above, circular polarization is standard.

The predominant array is a parabolic reflector, which makes circular polarization easy to obtain. Although the use of circular polarization would make one expect signals to be constant, except for the effect of the moon's distance, long-term fading of 6 to 9 dB is frequently observed.

With improved long-Yagi designs, for years the solution to overcoming polarization misalignment has been to make the array larger. Making your station's system gain 5 or 6 dB greater than required for minimal EME QSOs will allow you to work more stations, simply by moving you farther down the polarization loss curve. After about 60° of misalignment, however, making your station large enough to overcome the added losses quickly becomes a lifetime project! See **Fig 23.64**.

At 432 MHz and lower, Yagis are widely used, making the linear polarization standard. Although circular polarization may seem like a simple solution to polarization problems, when signals are reflected off the moon, the polarization sense of circularly polarized radio wave is reversed, requiring two arrays of opposite polarization sense be used. Initially, crossed Yagis with switchable polarization may also look attractive. Unfortunately, 432-MHz Yagis are physically small enough that the extra feed lines and switching devices become complicated, and usually adversely affect array performance. Keep in mind that even at 144 MHz, Yagis cannot tolerate metal mounting masts and frames in line with the Yagi elements.

When starting out on EME, keep in mind that it is best to use a simple system. You will still be able to work many of the larger fixed-polarization stations and those who have polarization adjustment (only one station needs to have polarization control). Once you gain understanding and confidence in your simple array, a more complex array such as one with polarization rotation can be attempted.



ANGLE	LOSS
0°	0
10°	−0.13 dB
20°	−0.54 dB
30°	−1.25 dB
40°	−2.32 dB
50°	−3.84 dB
60°	−6.02 dB
70°	−9.32 dB
80°	−15.2 dB
90°	− ∞

Fig 23.64 — The graph shows how quickly loss because of polarization misalignment increases after 45°. The curve repeats through 360°, showing no loss at 0° and maximum loss at 90° and 270°.

Receiver Requirements

A low-noise receiving setup is essential for successful EME work. Many EME signals are barely, but not always, out of the noise. To determine actual receiver performance, any phasing line and feed line losses, along with the noise generated in the receiver, must be added to the array noise reception. When all losses are considered, a system noise figure of 0.5 dB (35 K) will deliver about all the performance that can be used at 144 MHz, even when low-loss phasing lines and a quiet array are used.

The sky noise at 432 MHz and above is low enough (cold sky is <15 K (kelvins) at 432 MHz, and 5 K at 1296 MHz) so the lowest possible noise figure is desired. Current high-performance arrays will have array temperatures near 30 K when unwanted noise pickup is added in. Phasing line losses must also be included, along with any relay losses. Even at 432 MHz, it is impossible to make receiver noise insignificant without the use of a liquid-cooled preamplifier. Current technology gives a minimum obtainable GaAsFET preamplifier noise figure, at room temperature, of about 0.35 dB (24 K). See **Fig 23.65**.

GaAsFET preamps have also been standard on 1296 MHz and above for several years. Noise figures range from about 0.4 dB at 1296 MHz (30 K) to about 2 dB (170 K at 10 GHz). HEMT devices are now available to amateurs, but are of little use below 902 MHz because of 1/f noise. At higher frequencies, HEMT devices have already shown impressively low noise figures. Current HEMT devices are capable of noise figures close to 1.2 dB at 10 GHz (93 K) without liquid cooling.

At 1296 MHz, a new noise-limiting factor appears. The physical temperature of the moon is 210 K. This means that just like the Earth, it is a black-body radiator. The additional noise source is the reflection of sun noise off the moon. Just as a full moon reflects sunlight to Earth, the rest of the electromagnetic spectrum is also reflected. On 144 and 432 MHz, the beamwidth of a typical array is wide enough (15° is typical for 144 MHz, 7° for 432 MHz) that the moon, which subtends a 0.5° area is small enough to be insignificant in the array's pattern. At 1296 MHz, beamwidths approach 2°, and moon-noise figures of up to 5 dB are typical at full moon. Stations operating at 2300 MHz and above have such narrow array patterns that many operators actually use moon noise to assure that their arrays are pointed at the moon!

A new weak-signal operator is encouraged to experiment with receivers and filters. A radio with passband tuning or IF-shift capability is desired. These features are used to center the passband and the pitch of the CW signal to the frequency at which the operator's ears perform best. Some operators also use audio filtering. Audio filtering is effective in eliminating high-frequency noise generated in the radio's audio or IF stages. This noise can be very fatiguing during extended weak signal operation. The switched-capacitor audio filter has become popular with many operators.

Transmitter Requirements

Although the maximum legal power (1500 W out) is desirable, the actual power required can be considerably less, depending on the frequency of operation and size of the array. Given the minimum array gain requirements previously discussed, the power levels recommended for reasonable success are shown in Table 23.16.

The amplifier and power supply should be constructed with adequate cooling and safety margins to allow extended slow-speed CW operation without failure. The transmitter must also be free from drift and chirp. The CW note must be pure and properly shaped. Signals that drift and chirp are harder to copy. They are especially annoying to operators who use narrow CW filters. A stable, clean signal will improve your EME success rate.

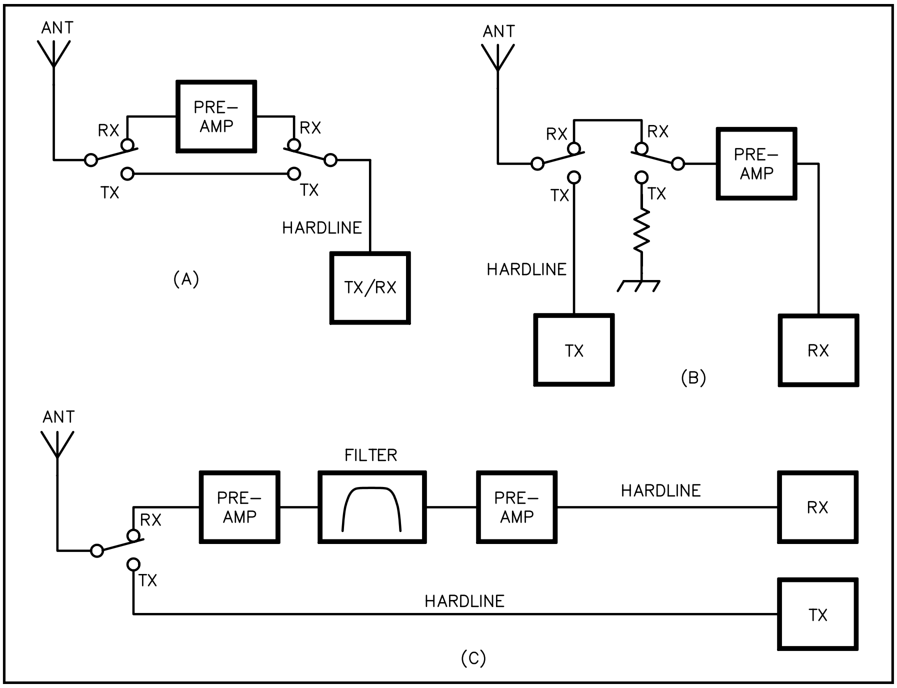


Fig 23.65 — Two systems for switching a preamplifier in and out of the receive line. At A, a single length of cable is used for both the transmit and receive line. At B is a slightly more sophisticated system that uses two separate transmission lines. At C, a high-isolation relay is used for TR switching. The energized position is normally used on receive.

Table 23.16
Transmitter Power Required for EME Success

Power at the array

50 MHz	1500 W
144 MHz	1000 W
222 MHz	750 W
432 MHz	500 W
902 MHz	200 W
1296 MHz	200 W
2300 MHz and above	100 W

Calculating EME Capabilities

Once all station parameters are known, the expected strength of the moon echoes can be calculated given the path loss for the band in use (see Fig 23.61). The formula for the received signal-to-noise ratio is:

$$S/N = P_o - L_t + G_t - P_1 + G_r - P_n \qquad (1)$$

where
P_o = transmitter output power (dBW)
L_t = transmitter feed-line loss (dB)
G_t = transmitting antenna gain (dBi)
P_l = total path loss (dB)
G_r = receiving antenna gain (dBi)
P_n = receiver noise power (dBW).

Receiver noise power, P_n, is determined by the following:

$$P_n = 10 \log_{10} KBT_s \qquad (2)$$

where
$K = 1.38 \times 10^{-23}$ (Boltzmann's constant)
B = bandwidth (Hz)
T_s = receiving system noise temperature (K).

Receiving system noise temperature, T_s, can be found from:

$$T_s = T_a + (L_r - 1)\, T_1 + L_r T_r \qquad (3)$$

where
T_a = antenna temperature (K)
L_r = receiving feed-line loss (ratio)
T_1 = physical temperature of feed line (normally 290 K)
T_r = receiver noise temperature (K).

An example calculation for a typical 432-MHz EME link is:
P_o = +30 dBW (1000 W)
L_t = 1.0 dB
G_t = 26.4 dBi (8 × 6.1-λ 22-el Yagis)
P_1 = 262 dB
G_r = 23.5 dBi (15 ft parabolic)
T_a = 60 K
L_r = 1.02 (0.1-dB preamp at antenna)
T_1 = 290 K
T_r = 35.4 K (NT = 0.5 dB)
T_s = 101.9 K
P_n = –188.5 dB
S/N = + 5.4 dB

It is obvious that EME is no place for a compromise station. Even relatively sophisticated equipment provides less-than optimum results.

Fig 23.66 gives parabolic dish gain for a perfect dish. The best Yagi antennas will not exceed the gain curve shown in the **Antennas and Projects** chapter. If you are using modern, log-taper Yagis, properly spaced, figure about 2.8 to 2.9 dB of stacking gain. For old-technology Yagis, 2.5 dB may be closer to reality. Any phasing line and power divider losses must also be subtracted from the array gain.

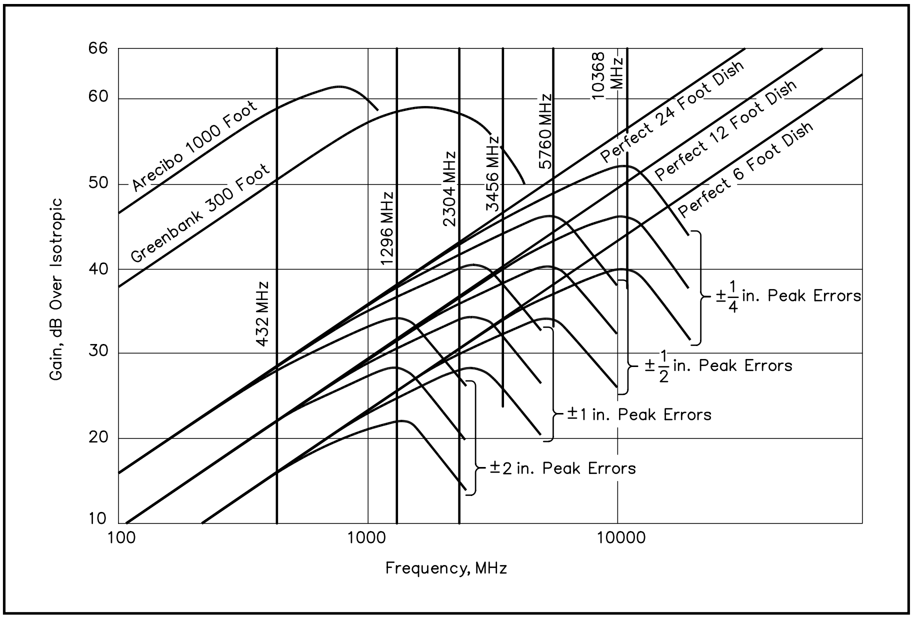


Fig 23.66— Parabolic-antenna gain vs size, frequency and surface errors. All curves assumed 60% aperture efficiency and 10-dB power taper. Reference: J. Ruze, British IEEE.

Locating the Moon

The moon orbits the Earth once in approximately 28 days, a lunar month. Because the plane of the moon's orbit is tilted from the Earth's equatorial plane by approximately 23.5°, the moon swings in a sine-wave pattern both north and south of the equator. The angle of departure of the moon's position at a given time from the equatorial plane is termed declination (abbreviated decl). Declination angles of the moon, which are continually changing (a few degrees a day), indicate the latitude on the Earth's surface where the moon will be at zenith. For this presentation, positive declination angles are used when the moon is north of the equator, and negative angles when south.

The longitude on the Earth's surface where the moon will be at zenith is related to the moon's Greenwich Hour Angle, abbreviated G.H.A. or GHA. "Hour angle" is defined as the angle in degrees to the west of the meridian. If the GHA of the moon were 0°, it would be directly over the Greenwich meridian. If the moon's GHA were 15°, the moon would be directly over the meridian designated as 15° W longitude on a globe. As one can readily understand, the GHA of the moon is continually changing, too, because of both the orbital velocity of the moon and the Earth's rotation inside the moon's orbit. The moon's GHA changes at the rate of approximately 347° per day.

GHA and declination are terms that may be applied to any celestial body. *The Astronomical Almanac* (available from the Superintendent of Documents, US Government Printing Office) and other publications list the GHA and decl of the sun and moon (as well as for other celestial bodies that may be used for navigation) for every hour of the year. This information may be used to point an antenna when the moon is not visible. *Almanac* tables for the sun may be useful for calibrating remote-readout systems.

Using the Almanac

The Astronomical Almanac and other almanacs show the GHA and declination of the sun or moon at hourly intervals for every day of the period covered by the book. Instructions are included in such books for interpolating the positions of the sun or moon for any time on a given date. The orbital velocity of the moon is not constant, and therefore precise interpolations are not linear.

Fortunately, linear interpolations from one hour to the next, or even from one day to the next, will result in data that is entirely adequate for Amateur Radio purposes. If linear interpolations are made from

0000 UTC on one day to 0000 UTC on the next, worse-case conditions exist when apogee or perigee occurs near midday on the next date in question. Under such conditions, the total angular error in the position of the moon may be as much as a sixth of a degree. Because it takes a full year for the Earth to orbit the sun, the similar error for determining the position of the sun will be no more than a few hundredths of a degree.

If a polar mount (a system having one axis parallel to the Earth's axis) is used, information from the *Almanac* may be used directly to point the antenna array. The local hour angle (LHA) is simply the GHA plus or minus the observer's longitude (plus if east longitude, minus if west). The LHA is the angle west of the observer's meridian at which the celestial body is located. LHA and declination information may be translated to an EME window by taking local obstructions and any other constraints into account.

Azimuth and Elevation

An antenna system that is positioned in azimuth (compass direction) and elevation (angle above the horizon) is called an *az-el* system. For such a system, some additional work will be necessary to convert the almanac data into useful information. The GHA and decl information may be converted into azimuth and elevation angles with the mathematical equations that follow. A calculator or computer that treats trigonometric functions may be used. *CAUTION:* Most almanacs list data in degrees, minutes, and either decimal minutes or seconds. Computer programs generally require this information in degrees and decimal fractions, so a conversion may be necessary before the almanac data is entered.

Determining az-el data from equations follows a procedure similar to calculating great-circle bearings and distances for two points on the Earth's surface. There is one additional factor, however. Visualize two observers on opposite sides of the Earth who are pointing their antennas at the moon. Imaginary lines representing the boresights of the two antennas will converge at the moon at an angle of approximately 2°. Now assume both observers aim their antennas at some distant star. The boresight lines now may be considered to be parallel, each observer having raised his antenna in elevation by approximately 1°. The reason for the necessary change in elevation is that the Earth's diameter in comparison to its distance from the moon is significant. The same is not true for distant stars, or for the sun.

Equations for az-el calculations are:

$$\sin E = \sin L \sin D + \cos L \cos D \cos LHA \qquad (4)$$

$$\tan F = \frac{\sin E - K}{\cos E} \qquad (5)$$

$$\cos C = \frac{\sin D - \sin E \sin L}{\cos E \cos L} \qquad (6)$$

where

E = elevation angle for the sun
L = your latitude (negative if south)
D = declination of the celestial body
LHA = local hour angle = GHA plus or minus your longitude (plus if east longitude, minus if west longitude)
F = elevation angle for the moon
K = 0.01657, a constant (see text that follows)
C = true azimuth from north if sin LHA is negative; if sin LHA is positive, then the azimuth = 360 – C.

Assume our location is 50° N latitude, 100° W longitude. Further assume that the GHA of the moon is 140× and its declination is 10°. To determine the az-el information we first find the LHA, which is 140 minus 100 or 40°. Then we solve equation 4:

$$\sin E = \sin 50 \sin 10 + \cos 50 \cos 10 \cos 40$$

$$\sin E = 0.61795 \text{ and } E = 38.2°$$

Solving equation 5 for F, we proceed. (The value for sin E has already been determined in equation 4.)

$$\tan F = \frac{0.61795 - 0.06175}{\cos 38.2} = 0.76489$$

From this, F, the moon’s elevation angle, is 37.4°.

We continue by solving equation 6 for C. (The value of sin E has already been determined.)

$$\cos C = \frac{\sin 10 - 0.61795 \sin 50}{\cos 38.2 \cos 50} = 0.59308$$

C therefore equals 126.4°. To determine if C is the actual azimuth, we find the polarity for sin LHA, which is sin 40° and has a positive value. The actual azimuth then is 360 – C = 233.6°.

If az-el data is being determined for the sun, omit equation 5; equation 5 takes into account the nearness of the moon. The solar elevation angle may be determined from equation 4 alone. In the above example, this angle is 38.2°.

The mathematical procedure is the same for any location on the Earth’s surface. Remember to use negative values for southerly latitudes. If solving equation 4 or 5 yields a negative value for E or F, this indicates the celestial body below the horizon.

These equations may also be used to determine az-el data for man-made satellites, but a different value for the constant, K, must be used. K is defined as the ratio of the Earth’s radius to the distance from the Earth’s center to the satellite.

The value for K as given above, 0.01657 is based on an average Earth-moon distance of 239,000 miles. The actual Earth-moon distance varies from approximately 225,000 to 253,000 mi. When this change in distance is taken into account, it yields a change in elevation angle of approximately 0.1° when the moon is near the horizon. For greater precision in determining the correct elevation angle for the moon, the moon’s distance from the Earth may be taken as:

$$D = -15{,}074.5 \times SD + 474{,}332$$

where

D = moon’s distance in miles

SD = moon’s semi-diameter, from the almanac.

Computer Programs

As has been mentioned, a computer may be used in solving the equations for azimuth and elevation. For EME work, it is convenient to calculate az-el data at 30-minute intervals or so, and to keep the results of all calculations handy during the EME window. Necessary antenna-position corrections can then be made periodically.

A BASIC language program for the IBM PC is available from the ARRL Technical Secretary. Request the ’95 *Handbook* EME template. This program provides azimuth and elevation information for half-hour intervals during a UTC day when the celestial body is above the horizon. The program makes a linear interpolation of GHA and declination values (discussed earlier) during the period of the UTC day.

Commercial, shareware and public-domain tracking programs are also available. See the **References** chapter for a list of some available programs. *RealTrak* prints out antenna azimuth and elevation headings for nearly any celestial object. It can be used with the Kansas City Tracker program described in the satellite section to track celestial objects automatically. *VHF PAK* provides real-time moon and celestial object position information. Two other real-time tracking programs are *EME Tracker* and the *VK3UM EME Planner*.

Libration Fading of EME Signals

One of the most troublesome aspects of receiving a moonbounce signal, besides the enormous path loss and Faraday rotation fading, is libration fading. This section will deal with libration (pronounced *lie-brayshun*) fading, its cause and effects, and possible measures to minimize it.

Libration fading of an EME signal is characterized in general as fluttery, rapid, irregular fading not unlike that observed in tropospheric scatter propagation. Fading can be very deep, 20 dB or more, and the maximum fading will depend on the operating frequency. At 1296 MHz the maximum fading rate is about 10 Hz, and scales directly with frequency.

On a weak CW EME signal, libration fading gives the impression of a randomly keyed signal. In fact on very slow CW telegraphy the effect is as though the keying is being done at a much faster speed. On very weak signals only the peaks of libration fading are heard in the form of occasional short bursts or "pings."

Fig 23.67 shows samples of a typical EME echo signal at 1296 MHz. These recordings, made at W2NFA, show the wild fading characteristics with sufficient S/N ratio to record the deep fades. Circular polarization was used to eliminate Faraday fading; thus these recordings are of libration fading only. The recording bandwidth was limited to about 40 Hz to minimize the higher sideband-frequency components of libration fading that exist but are much smaller in amplitude. For those who would like a better statistical description, libration fading is Raleigh distributed. In the recordings shown in Fig 23.63, the average signal-return level computed from path loss and mean reflection coefficient of the moon is at about the +15 dB S/N level.

It is clear that enhancement of echoes far in excess of this average level is observed. This point should be kept clearly in mind when attempting to obtain echoes or receive EME signals with marginal equipment. The probability of hearing an occasional peak is quite good since random enhancement as much as 10 dB is possible. Under these conditions, however, the amount of useful information that can be copied will be near zero. Enthusiastic newcomers to EME communications will be stymied by this effect

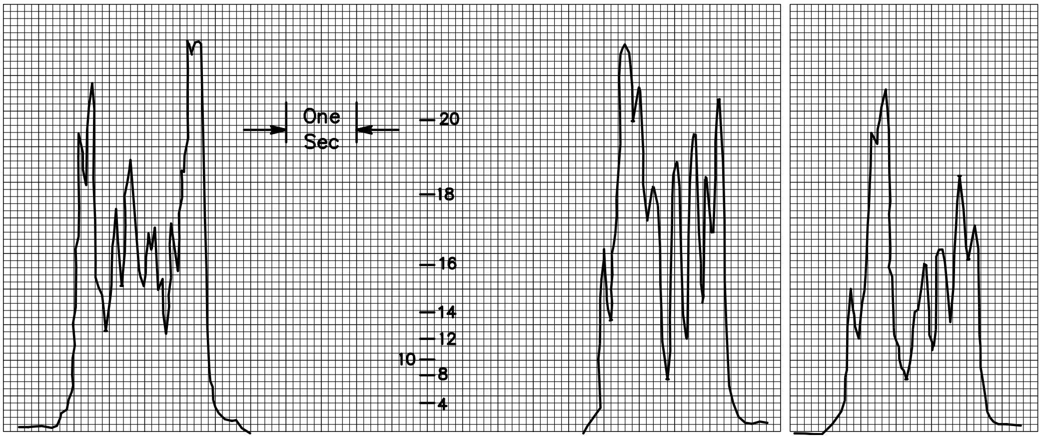


Fig 23.67 — Chart recording of moon echoes received at W2FNA on July 26, 1973, at 1630 UTC. Antenna gain 44 dBi, transmitting power 400 W and system temperature 400 K.

since they know they can hear the signal strong enough on peaks to copy but can’t make any sense out of what they try to copy.

What causes libration fading? Very simply, multipath scattering of the radio waves from the very large (2000-mile diameter) and rough moon surface combined with the relative motion between Earth and moon called librations.

To understand these effects, assume first that the Earth and moon are stationary (no libration) and that a plane wave front arrives at the moon from your Earthbound station as shown in **Fig 23.68A**.

The reflected wave shown n Fig 23.68B consists of many scattered contributions from the rough moon surface. It is perhaps easier to visualize the process as if the scattering were from many small individual flat mirrors on the moon that reflect small portions (amplitudes) of the incident wave energy in different directions (paths) and with different path lengths (phase). Those paths directed toward the moon arrive at your antenna as a collection of small wave fronts (field vectors) of various amplitudes and phases. The vector summation of all these coherent (same frequency) returned waves (and there is a near-infinite array of them) takes place at the feed-point of your antenna (the collecting point in your antenna system). The level of the final summation as measured by a receiver can, of course, have any value from zero to some maximum. Remember that we assumed the Earth and moon were stationary, which means that the final summation of these multipath signal returns from the moon will be one fixed value. The condition of zero relative motion between Earth and moon is a rare event that will be discussed later in this section.

Consider now that the Earth and moon are moving relative to each other (as they are in nature), so the incident radio wave “sees” a slightly different surface of the moon from moment to moment. Since the lunar surface is very irregular, the reflected wave will be equally irregular, changing in amplitude and phase from moment to moment. The resultant continuous summation of the varying multipath signals at your antenna feed-point produces the effect called libration fading of the moon-reflected signal.

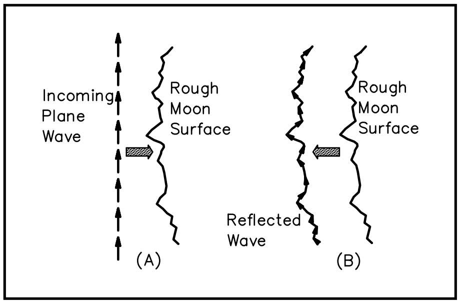


Fig 23.68 — How the rough surface of the moon reflects a plane wave as one having many field vectors.

The term *libration* is used to describe small perturbations in the movement of celestial bodies. Each libration consists mainly of its diurnal rotation; moon libration consists mainly of its 28-day rotation which appears as a very slight rocking motion with respect to an observer on Earth. This rocking motion can be visualized as follows: Place a marker on the surface of the moon at the center of the moon disc, which is the point closest to the observer, as shown in **Fig 23.69**. Over time, we will observe that this marker wanders around within a small area. This means the surface of the moon as seen from the Earth is not quite fixed but changes slightly as different areas of the periphery are exposed because of this rocking motion. Moon libration is very slow (on the order of 10^{-7} radians per second) and can be determined with some difficulty from published moon ephemeris tables.

Although the libration motions are very small and slow, the larger surface area of the moon has nearly an infinite number of scattering points (small area). This means that even slight geometric movements can alter the total summation of the returned multipath echo by a significant amount. Since the librations of the Earth and moon are calculable, it is only logical to ask if there ever occurs a time when the total libration is zero or near zero. The answer is yes, and it has been observed and verified experimentally on radar echoes that minimum fading rate (not depth of fade)

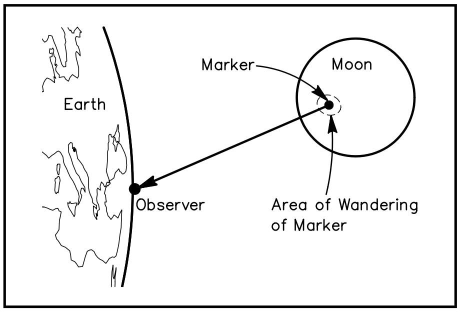


Fig 23.69 — The moon appears to “wander” in its orbit about the Earth. Thus a fixed marker on the moon’s surface will appear to move about in a circular area.

is coincident with minimum total libration. Calculation of minimum total libration is at best tedious and can only be done successfully by means of a computer. It is a problem in extrapolation of rates of change in coordinate motion and in small differences of large numbers.

EME OPERATING TECHNIQUES

Many EME signals are near the threshold of readability, a condition caused by a combination of path loss, Faraday rotation and libration fading. This weakness and unpredictability of the signals has led to the development of techniques for the exchange of EME information that differ from those used for normal terrestrial work. The fading of EME signals chops dashes into pieces and renders strings of dots incomplete. This led to the use of the "T M O R" reporting system. Different, but similar, systems are used on the low bands (50 and 144 MHz) and the high bands (432 MHz and above). **Tables 23.17** and **23.18** summarize the differences between the two systems.

As equipment and techniques have improved, the use of normal RST signal reports has become more common. It is now quite common for two stations working for the first time to go straight to RST reports if signals are strong enough. These normal reports let stations compare signals from one night to the next. EME QSOs are often made during the ARRL VHF contests. These contacts require the exchange of 4-digit grid locators. On 432 MHz and above, the sending of GGGG has come to mean "Please send me your grid square," or conversely, "I am now going to send my grid square."

The length of transmit and receive periods is also different between the bands. On 50 and 144 MHz, 2-minute sequences are used. That is, stations transmit for two full minutes, and then receive for two full minutes. One-hour schedules are used, with the eastern-most station (referenced to the international date line) transmitting first. **Table 23.19** gives the 2-minute sequence procedure. On 222 MHz, both the 144 and 432-MHz systems are used.

On 432 MHz and above, $2^{1}/_{2}$-minute sequences are standard.

The longer period is used to let stations with variable polarization have adequate time to peak the signal. The last 30 seconds is reserved for signal reports only. **Table 23.20** provides more information on the 432-MHz EME QSO sequence. The western-most station usually transmits first. However, if one of the stations has variable polarization, it may elect to transmit second, to take the opportunity to use the first sequence to peak the signal. If both stations have variable polarization, the station that transmits first should leave its polarization fixed on transmit, to avoid "polarization chasing."

CW sending speed is usually in the 10 to 13-wpm range. It is often best to use greater-than-normal spacing between individual

Table 23.17

Signal Reports Used on 144-MHz EME

T — Signal just detectable
M — Portions of call copied
O — Complete call set has been received
R — Both "O" report and call sets have been received
$\overline{\text{SK}}$ — End of contact

Table 23.18

Signal Reports Used on 432-MHz EME

T — Portions of call copied
M — Complete calls copied
O — Good signal—solid copy (possibly enough for SSB work)
R — Calls and reports copied
$\overline{\text{SK}}$ — End of contact

Table 23.19

144-MHz Procedure — 2-Minute Sequence

Period	*$1^{1}/_{2}$ minutes*	*30 seconds*
1	Calls (W6XXX DE W1XXX)	
2	W1XXX DE WE6XXX	TTTT
3	W6XXX DE W1XXX	OOOO
4	RO RO RO RO	DE W1XXX K
5	R R R R R R	DE W6XXX K
6	QRZ? EME	DE W1XXX K

Table 23.20

432-MHz Procedure—$2^{1}/_{2}$-Minute Sequence

Period	*2 minutes*	*30 seconds*
1	VE7BBG DE K2UYH	
2	K2UYH DE VE7BBG	
3	VE7BBG DE K2UYH	TTT
4	K2UYH DE VE7BBG	MMM
5	RM RM RM RM	DE K2UYH K
6	R R R R R	DE VE7BBG $\overline{\text{SK}}$

dits and dahs, as well as between complete letters. This helps to overcome libration fading effects. The libration fading rate will be different from one band to another. This makes the optimum CW speed for one band different from another. Keep in mind that characters sent too slowly will be chopped up by typical EME fading. Morse code sent too fast will simply be jumbled. Pay attention to the sending practices of the more successful stations, and try to emulate them.

Doppler shift must also be understood. As the moon rises or sets it is moving toward or away from objects on Earth. This leads to a frequency shift in the moon echoes. The amount of Doppler shift is directly proportional to frequency. At 144 MHz, about 500 Hz is the maximum shift. On 432 MHz, the maximum shift is 1.5 kHz. The shift is upward on moonrise and downward on moonset. When the moon is due south, your own echoes will have no Doppler shift, but stations located far away will still be affected. For scheduling, the accepted practice is to transmit zero beat on the schedule frequency, and tune to compensate for the Doppler shift. Be careful—most transmitters and transceivers have a built-in CW offset. Some radios read this offset when transmitting, and others don't. Find out how your transmitter operates and compensate as required.

Random operation has become popular in recent years. In the ARRL EME contest, many of the big guns will not even accept schedules during the contest periods, because they can slow down the pace of their contest contacts.

The Sounds of Amateur Radio

W2RS works W5UN by bouncing a 2-meter CW signal off the moon.

EME Operating Times

Obviously, the first requirement for EME operation is to have the moon visible by both EME stations. This requirement not only consists of times when the moon is above the horizon, but when it is actually clear of obstructions such as trees and buildings. It helps to know your exact EME operating window, specified in the form of beginning and ending GHAs (Greenwich Hour Angle) for different moon declinations. This information allows two different stations to quickly determine if they can simultaneously see the moon.

Once your moon window is determined, the next step is to decide on the best times during that window to schedule or operate. Operating at perigee is preferable because of the reduced path loss. Fig 23.61 shows that not all perigees are equal. There is about a 0.6-dB difference between the closest and farthest perigee points. The next concern is operating when the moon is in a quiet spot of the sky. Usually, northern declinations are preferred, as the sky is quietest at high declinations. If the moon is too close to the sun, your array will pick up sun noise and reduce the sensitivity of your receiver. Finally, choosing days with minimal libration fading is also desirable.

Perigee and apogee days can be determined from the *Astronomical Almanac* by inspecting the tables headed "S.D." (semi-diameter of the moon in minutes of arc). These semi-diameter numbers can be compared to Fig 23.63 to obtain the approximate moon distance. Many computer programs for locating the moon now give the moon's distance. The expected best weekends to operate on 432 MHz and the higher bands are normally printed well in advance in various EME newsletters.

When the moon passes through the galactic plane, sky temperature is at its maximum. Even on the higher bands this is one of the least desirable times to operate. The areas of the sky to avoid are the constellations of Orion and Gemini (during northern declinations), and Sagittarius and Scorpios (during southern declinations). The position of the moon relative to these constellations can be checked with information supplied in the *Astronomical Almanac* or *Sky and Telescope* magazine.

Frequencies and Scheduling

According to the ARRL-sponsored band plan, the lower edge of most bands is reserved for EME operation. On 144 MHz, EME frequencies are primarily between 144.000 and 144.080 MHz for CW, and 144.100 and 144.120 MHz for SSB. Random CW activity is usually between 144.000 and 144.020 MHz. In the US, 144.000 to 144.100 MHz is a CW sub-band, so SSB QSOs often take place by QSYing up 100 kHz after a CW contact has been established. Because of the large number of active 144-MHz stations, coordinating schedules in the small EME window is not simple. The more active stations usually have assigned frequencies for their schedules.

On 432 MHz, the international EME CW calling frequency is 432.010 MHz. Random SSB calling is done on 432.015 MHz. Random activity primarily takes place between 432.000 and 432.020 MHz. The greater Doppler shift on 432 MHz requires greater separation between schedule frequencies than on 144 MHz. Normally 432.000 MHz, 432.020 MHz and each 5-kHz increment up to 432.070 MHz are used for schedules.

Activity on 1296 MHz is centered between 1296.000 and 1296.040 MHz. The random calling frequency is 1296.010 MHz. Operation on the other bands requires more specific coordination. Activity on 33 cm is split between 902 and 903 MHz. Activity on 2300 MHz has to accommodate split-band procedures because of the different band assignments around the world.

EME Net Information

An EME net meets on 14.345 MHz on weekends for the purpose of arranging schedules and exchanging EME information. The net meets at 1600 UTC. OSCAR satellites are becoming more popular for EME information exchange. When Mode B is available, a downlink frequency of 145.950 MHz is where the EME group gathers. On Mode L and Mode JL, the downlink frequency is 435.975 MHz.

Other Modes

Most EME contacts are still made on CW, although SSB has gained in popularity and it is now common to hear SSB QSOs on any activity weekend. The ability to work SSB can easily be calculated from Eq 1. The proper receiver bandwidth (2.3 kHz) is substituted. SSB usually requires a +3-dB signal-to-noise ratio, whereas slow-speed CW contacts can be made with a 0-dB signal-to-noise ratio. Slow-scan television and packet communication has been attempted between some of the larger stations. Success has been limited because of the greater signal-to-noise ratios required for these modes, and severe signal distortion from libration fading.

Radio Direction Finding

Far more than simply finding the direction of an incoming radio signal, radio direction finding (RDF) encompasses a variety of techniques for determining the exact location of a signal source. The process involves both art and science. RDF adds fun to ham radio, but has serious purposes, too.

This section was written by Joe Moell, K0OV.

RDF is almost as old as radio communication. It gained prominence when the British Navy used it to track the movement of enemy ships in World War I. Since then, governments and the military have developed sophisticated and complex RDF systems. Fortunately, simple equipment, purchased or built at home, is quite effective in Amateur Radio RDF.

In European and Asian countries, direction finding contests are foot races. The object is to be first to find four or five transmitters in a large wooded park. Young athletes have the best chance of capturing the prizes. This sport is known as *foxhunting* (after the British hill-and-dale horseback events) or *ARDF* (Amateur Radio direction finding).

In North America and England, most RDF contests involve mobiles—cars, trucks, vans, even motorcycles. It may be possible to drive all the way to the transmitter, or there may be a short hike at the end, called a *sniff*. These competitions are also called foxhunting by some, while others use *bunny hunting*, *T-hunting* or the classic term *hidden transmitter hunting*.

In the 1950s, 3.5 and 28 MHz were the most popular bands for hidden transmitter hunts. Today, most competitive hunts worldwide are for 144-MHz FM signals, though other VHF bands are also used. Some international foxhunts include 3.5-MHz events.

Even without participating in RDF contests, you will find a knowledge of the techniques useful. They simplify the search for a neighborhood source of power- line interference or TV cable leakage. RDF must be used to track down emergency radio beacons, which signal the location of pilots and boaters in distress. Amateur Radio enthusiasts skilled in transmitter hunting are in demand by agencies such as the Civil Air Patrol and the US Coast Guard Auxiliary for search and rescue support.

The FCC's Field Operations Bureau has created an Amateur Auxiliary, administered by the ARRL Section Managers, to deal with interference matters. In many areas of the country, there are standing agreements between Local Interference Committees and district FCC offices, permitting volunteers to provide evidence leading to prosecution in serious cases of malicious amateur-to-amateur interference. RDF is an important part of the evidence-gathering process.

The most basic RDF system consists of a directional antenna and a method of detecting and measuring the level of the radio signal, such as a receiver with signal strength indicator. RDF antennas range from a simple tuned loop of wire to an acre of antenna elements with an electronic beam-forming network. Other sophisticated techniques for RDF use the Doppler effect, or measure the time of arrival difference of the signal at multiple antennas.

All of these methods have been used from 2 to 500 MHz and above. However, RDF practices vary greatly between the HF and VHF/UHF portions of the spectrum. For practical reasons, high gain beams, Dopplers and switched dual antennas find favor on VHF/UHF, while loops and phased arrays are the most popular choices on 6 m and below. Signal propagation differences between HF and VHF also affect RDF practices. But many basic transmitter hunting techniques, discussed later in this chapter, apply to all bands and all types of portable RDF equipment.

RDF ANTENNAS FOR HF BANDS

Below 50 MHz, gain antennas such as Yagis and quads are of limited value for RDF. The typical installation of a tribander on a 70-ft tower yields only a general direction of the incoming signal, due to ground effects and the antenna's broad forward lobe. Long monoband beams at greater heights work better, but still cannot achieve the bearing accuracy and repeatability of simpler antennas designed specifically for RDF.

RDF Loops

An effective directional HF antenna can be as uncomplicated as a small loop of wire or tubing, tuned to resonance with a capacitor. When immersed in an electromagnetic field, the loop acts much the same as the secondary winding of a transformer. The voltage at the output is proportional to the amount of flux passing through it and the number of turns. If the loop is oriented such that the greatest amount of area is presented to the magnetic field, the induced voltage will be the highest. If it is rotated so that little or no area is cut by the field lines, the voltage induced in the loop is zero and a null occurs.

To achieve this transformer effect, the loop must be small compared with the signal wavelength. In a single-turn loop, the conductor should be less than 0.08 λ long. For example, a 28-MHz loop should be less than 34 inches in circumference, giving a diameter of approximately 10 inches. The loop may be smaller, but that will reduce its voltage output. Maximum output from a small loop antenna is in directions corresponding to the plane of the loop; these lobes are very broad. Sharp nulls, obtained at right angles to that plane, are more useful for RDF.

For a perfect bidirectional pattern, the loop must be balanced electrostatically with respect to ground. Otherwise, it will exhibit two modes of operation, the mode of a perfect loop and that of a nondirectional vertical antenna of small dimensions. This dual-mode condition results in mild to severe inaccuracy, depending on the degree of imbalance, because the outputs of the two modes are not in phase.

The theoretical true loop pattern is illustrated in **Fig 23.70A**. When properly balanced, there are two nulls exactly 180° apart. When the unwanted antenna effect is appreciable and the loop is tuned to resonance, the loop may exhibit little directivity, as shown in Fig 23.70B. By detuning the loop to shift the phasing, you may obtain a useful pattern similar to Fig 23.70C. While not symmetrical, and not necessarily at right angles to the plane of the loop, this pattern does exhibit a pair of nulls.

By careful detuning and amplitude balancing, you can approach the unidirectional pattern of Fig 23.70D. Even though there may not be a complete null in the pattern, it resolves the 180° ambiguity of Fig 23.70A. Korean War era military loop antennas, sometimes available on today's surplus market, use this controlled-antenna-effect principle.

An easy way to achieve good electrostatic balance is to shield the loop, as shown in **Fig 23.71**. The shield, represented by the dashed lines in the drawing, eliminates the antenna effect. The response of a well-constructed shielded loop is quite close to the ideal pattern of Fig 23.70A.

For 160 through 30 m, single-turn loops that are small enough for portability are usually unsatisfactory for RDF work. Multiturn loops are generally used instead. They are easier to resonate with practical capacitor values and give

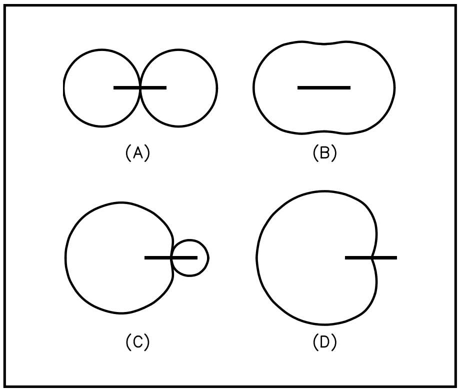


Fig 23.70 — Small loop field patterns with varying amounts of antenna effect — the undesired response of a loop acting merely as a mass of metal connected to the receiver antenna terminals. The horizontal lines show the plane of the loop turns.

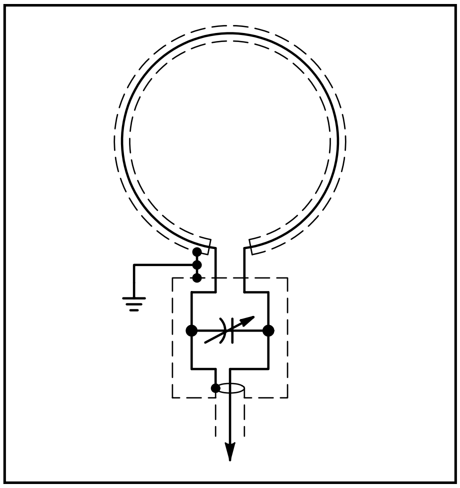


Fig 23.71 — Electrostatically shielded loop for RDF. To prevent shielding of the loop from magnetic fields, leave the shield unconnected at one end.

higher output voltages. This type of loop may also be shielded. If the total conductor length remains below 0.08 λ, the directional pattern is that of Fig 23.70A.

Ferrite Rod Antennas

Another way to get higher loop output is to increase the permeability of the medium in the vicinity of the loop. By winding a coil of wire around a form made of high-permeability material, such as ferrite rod, much greater flux is obtained in the coil without increasing the cross-sectional area.

Modern magnetic core materials make compact directional receiving antennas practical. Most portable AM broadcast receivers use this type of antenna, commonly called a *loopstick*. The loopstick is the most popular RDF antenna for portable/mobile work on 160 and 80 m.

As does the shielded loop discussed earlier, the loopstick responds to the magnetic field of the incoming radio wave, and not to the electrical field. For a given size of loop, the output voltage increases with increasing flux density, which is obtained by choosing a ferrite core of high permeability and low loss at the frequency of interest. For increased output, the turns may be wound over two rods taped together. A practical loopstick antenna is described later in this chapter.

A loop on a ferrite core has maximum signal response in the plane of the turns, just as an air core loop. This means that maximum response of a loopstick is broadside to the axis of the rod, as shown in **Fig 23.72**. The loopstick may be shielded to eliminate the antenna effect; a U-shaped or C-shaped channel of aluminum or other form of "trough" is best. The shield must not be closed, and its length should equal or slightly exceed the length of the rod.

Sense Antennas

Because there are two nulls 180° apart in the directional pattern of a small loop or loopstick, there is ambiguity as to which null indicates the true direction of the target station. For example, if the line of bearing runs east and west from your position, you have no way of knowing from this single bearing whether the transmitter is east of you or west of you.

If bearings can be taken from two or more positions at suitable direction and distance from the transmitter, the ambiguity can be resolved and distance can be estimated by triangulation, as discussed later in this chapter. However, it is almost always desirable to be able to resolve the ambiguity immediately by having a unidirectional antenna pattern available.

You can modify a loop or loopstick antenna pattern to have a single null by adding a second antenna element. This element is called a sense antenna, because it senses the phase of the signal wavefront for comparison with the phase of the loop output signal. The sense element must be omnidirectional, such as a short vertical. When signals from the loop and the sense antenna are combined with 90° phase shift between the two, a heart-shaped (cardioid) pattern results, as shown in **Fig 23.73A**.

Fig 23.73B shows a circuit for adding a sense antenna to a loop or loopstick. For the best null in the composite pattern, signals from the loop and sense antennas must be of equal amplitude. R1 adjusts the level of the signal from the sense antenna.

In a practical system, the cardioid pattern null is not as sharp as the bidirectional null of the loop alone. The usual procedure when

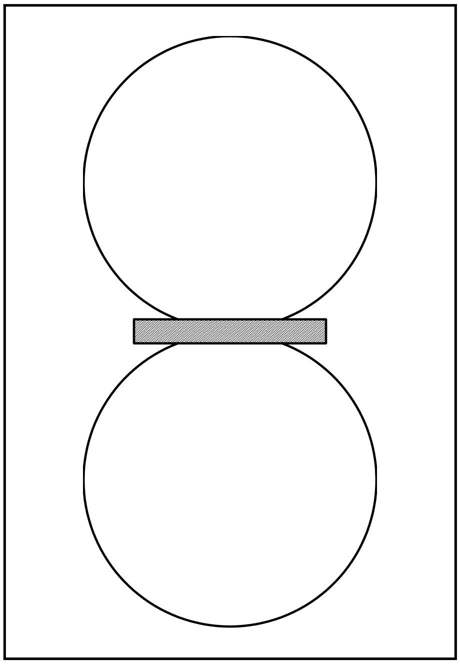


Fig 23.72 — Field pattern for a ferrite rod antenna. The dark bar represents the rod on which the loop turns are wound.

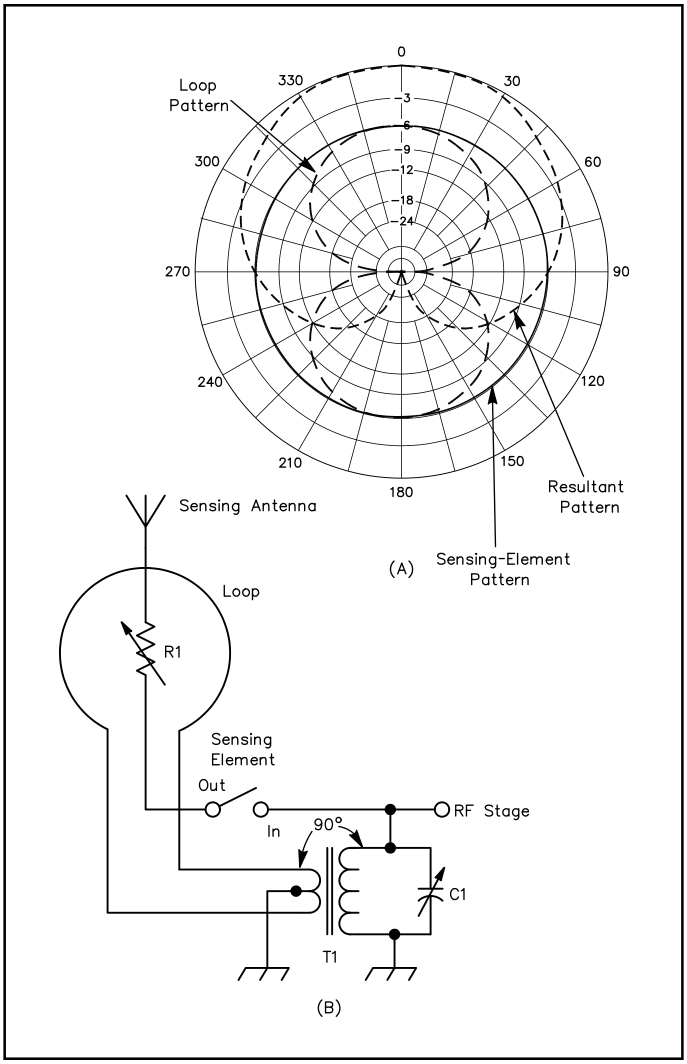


Fig 23.73 — At A, the directivity pattern of a loop antenna with sensing element. At B is a circuit for combining the signals from the two elements. Adjust C1 for resonance with T1 at the operating frequency.

transmitter hunting is to use the loop alone to obtain a precise line of bearing, then switch in the sense antenna and take another reading to resolve the ambiguity.

Phased Arrays and Adcocks

Two-element phased arrays are popular for amateur HF RDF base station installations. Many directional patterns are possible, depending on the spacing and phasing of the elements. A useful example is two $^{1}/_{2}$-λ elements spaced $^{1}/_{4}$ λ apart and fed 90° out of phase. The resultant pattern is a cardioid, with a null off one end of the axis of the two antennas and a broad peak in the opposite direction. The directional frequency range of this antenna is limited to one band, because of the critical length of the phasing lines.

The best-known phased array for RDF is the Adcock, named after the man who invented it in 1919. It consists of two vertical elements fed 180° apart, mounted so the array may be rotated. Element spacing is not critical, and may be in the range from $^{1}/_{10}$ to $^{3}/_{4}$ λ. The two elements must be of identical lengths, but need not be self-resonant; shorter elements are commonly used. Because neither the element spacing nor length is critical in terms of wavelengths, an Adcock array may operate over more than one amateur band.

Fig 23.74 is a schematic of a typical Adcock configuration, called the H-Adcock because of its shape. Response to a vertically polarized wave is very similar to a conventional loop. The passing wave induces currents I1 and I2 into the vertical members. The output current in the transmission line is equal to their difference. Consequently, the directional pattern has two broad peaks and two sharp nulls, like the loop. The magnitude of the difference current is proportional to the spacing (d) and length (l) of the elements. You will get somewhat higher gain with larger dimensions. The Adcock of Fig 23.75, designed for 40 m, has element lengths of 12 ft and spacing of 21 ft (approximately 0.15 λ).

Fig 23.76 shows the radiation pattern of the Adcock. The nulls are broadside to the axis of the array, becoming sharper with increased element spacings. When element spacing exceeds $^{3}/_{4}$ λ, however, the antenna begins to take on additional unwanted nulls off the ends of the array axis.

The Adcock is a vertically polarized antenna. The vertical elements do not respond to horizontally polarized waves, and the currents induced in the horizontal members by a horizontally polarized wave (dotted arrows in Fig 23.74) tend to balance out regardless of the orientation of the antenna.

Since the Adcock uses a balanced feed system, a coupler is required to match the unbalanced input of the receiver. T1 is an air-wound coil with a two-turn link wrapped around the middle. The combination

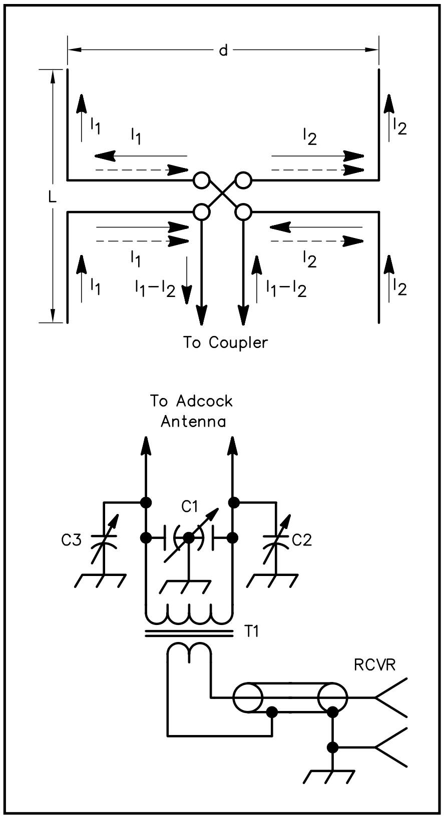


Fig 23.74 — A simple Adcock antenna and its coupler.

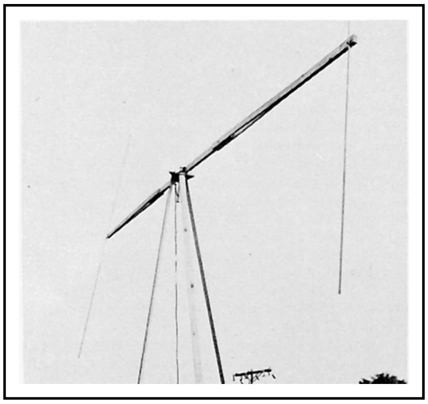


Fig 23.75 — An experimental Adcock antenna on a wooden frame.

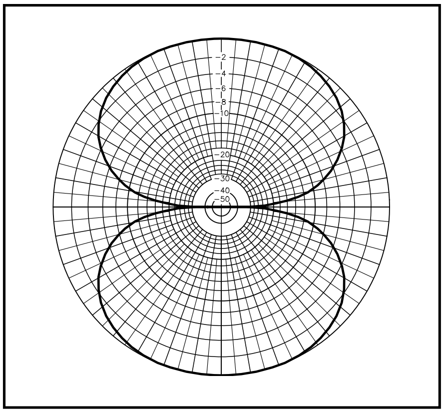


Fig 23.76 — The pattern of an Adcock array with element spacing of $^1/_2$ wavelength. The elements are aligned with the vertical axis.

is resonated with C1 to the operating frequency. C2 and C3 are null-clearing capacitors. Adjust them by placing a low-power signal source some distance from the antenna and exactly broadside to it. Adjust C2 and C3 until the deepest null is obtained.

While you can use a metal support for the mast and boom, wood is preferable because of its nonconducting properties. Similarly, a mast of thick-wall PVC pipe gives less distortion of the antenna pattern than a metallic mast. Place the coupler on the ground below the wiring harness junction on the boom and connect it with a short length of 300-Ω twin-lead feed line.

Loops vs Phased Arrays

Loops are much smaller than phased arrays for the same frequency, and are thus the obvious choice for portable/mobile HF RDF. For base stations in a triangulation network, where the 180° ambiguity is not a problem, Adcocks are preferred. In general, they give sharper nulls than loops, but this is in part a function of the care used in constructing and feeding the individual antennas, as well as of the spacing of the elements. The primary construction considerations are the shielding and balancing of the feed line against unwanted signal pickup and the balancing of the antenna for a symmetrical pattern. Users report that Adcocks are somewhat less sensitive to proximity effects, probably because their larger aperture offers some space diversity.

Skywave Considerations

Until now we have considered the directional characteristics of the RDF loop only in the two-dimensional azimuthal plane. In three-dimensional space, the response of a vertically oriented small loop is doughnut-shaped. The bidirectional null (analogous to a line through the doughnut hole) is in the line of bearing in the azimuthal plane and toward the horizon in the vertical plane. Therefore, maximum null depth is achieved only on signals arriving at 0° elevation angle.

Skywave signals usually arrive at nonzero wave angles. As the elevation angle increases, the null in a vertically oriented loop pattern becomes more shallow. It is possible to tilt the loop to seek the null in elevation as well as azimuth. Some amateur RDF enthusiasts report success at estimating distance to the target by measurement of the elevation angle with a tilted loop and computations based on estimated height of the propagating ionospheric layer. This method seldom provides high accuracy with simple loops, however.

Most users prefer Adcocks to loops for skywave work, because the Adcock null is present at all elevation angles. Note, however, that an Adcock has a null in all directions from signals arriving from overhead. Thus for very high angles, such as under-250-mile skip on 80 and 40 m, neither loops nor Adcocks will perform well.

Electronic Antenna Rotation

State-of-the-art fixed RDF stations for government and military work use antenna arrays of stationary elements, rather than mechanically rotatable arrays. The best known type is the Wullenweber antenna. It has a large number of elements arranged in a circle, usually outside of a circular reflecting screen. Depending on the installation, the circle may be anywhere from a few hundred feet to more than a quarter of a mile in diameter. Although the Wullenweber is not practical for most amateurs, some of the techniques it uses may be applied to amateur RDF.

The device which permits rotating the antenna beam without moving the elements has the classic name *radiogoniometer*, or simply *goniometer*. Early goniometers were RF transformers with fixed coils connected to the array elements and a moving pickup coil connected to the receiver input. Both amplitude and phase of the signal coupled into the pickup winding are altered with coil rotation in a way that corresponded to actually rotating the array itself. With sufficient elements and a goniometer, accurate RDF measurements can be taken in all compass directions.

Beam Forming Networks

By properly sampling and combining signals from individual elements in a large array, an antenna beam is electronically rotated or steered. With an appropriate number and arrangement of elements in the system, it is possible to form almost any desired antenna pattern by summing the sampled signals in appropriate amplitude and phase relationships. Delay networks and/or attenuation are added in line with selected elements before summation to create these relationships.

To understand electronic beam forming, first consider just two elements, shown as A and B in **Fig 23.77**. Also shown is the wavefront of a radio signal arriving from a distant transmitter. The wavefront strikes element A first, then travels somewhat farther before it strikes element B. Thus, there is an interval between the times that the wavefront reaches elements A and B.

We can measure the differences in arrival times by delaying the signal received at element A before summing it with that from element B. If two signals are combined directly, the amplitude of the sum will be maximum when the delay for element A exactly equals the propagation delay, giving an in-phase condition at the summation point. On the other hand, if one of the signals is inverted and the two are added, the signals will combine in a 180° out-of-phase relationship when the element A delay equals the propagation delay, creating a null. Either way, once the time delay is determined by the amount of delay required for a peak or null, we can convert it to distance. Then trigonometry calculations provide the direction from which the wave is arriving.

Altering the delay in small increments steers the peak (or null) of the antenna. The system is not frequency sensitive, other than the frequency range limitations of the array elements. Lumped-constant networks are suitable for delay elements if the system is used only for receiving. Delay lines at installations used for trans-

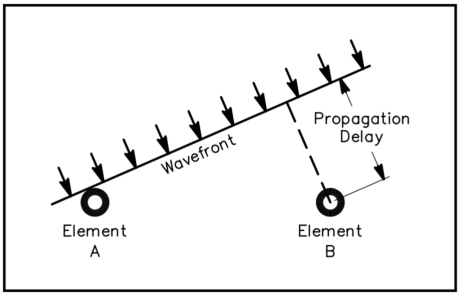


Fig 23.77 — One technique used in electronic beam forming. By delaying the signal from element A by an amount equal to the propagation delay, two signals are summed precisely in phase, even though the signal is not in the broadside direction.

mitting and receiving employ rolls of coaxial cable of various lengths, chosen for the time delay they provide at all frequencies, rather than as simple phasing lines designed for a single frequency.

Combining signals from additional elements narrows the broad beamwidth of the pattern from the two elements and suppress unwanted sidelobes. Electronically switching the delays and attenuations to the various elements causes the formed beam to rotate around the compass. The package of electronics that does this, including delay lines and electronically switched attenuators, is the beam forming network.

METHODS FOR VHF/UHF RDF

Three distinct methods of mobile RDF are commonly in use by amateurs on VHF/UHF bands: directional antennas, switched dual antennas and Dopplers. Each has advantages over the others in certain situations. Many RDF enthusiasts employ more than one method when transmitter hunting.

Directional Antennas

Ordinary mobile transceivers and hand-helds work well for foxhunting on the popular VHF bands. If you have a lightweight beam and your receiver has an easy-to-read S-meter, you are nearly ready to start. All you need is an RF attenuator and some way to mount the setup in your vehicle.

Amateurs seldom use fractional wavelength loops for RDF above 60 MHz because they have bidirectional characteristics and low sensitivity, compared to other practical VHF antennas. Sense circuits for loops are difficult to implement at VHF, and signal reflections tend to fill in the nulls. Typically VHF loops are used only for close-in sniffing where their compactness and sharp nulls are assets, and low gain is of no consequence.

Phased Arrays

The small size and simplicity of 2-element driven arrays make them a common choice of newcomers at VHF RDF. Antennas such as phased ground planes and ZL Specials have modest gain in one direction and a null in the opposite direction. The gain is helpful when the signal is weak, but the broad response peak makes it difficult to take a precise bearing.

As the signal gets stronger, it becomes possible to use the null for a sharper S-meter indication. However, combinations of direct and reflected signals (called *multipath*) will distort the null or perhaps obscure it completely. For best results with this type of antenna, always find clear locations from which to take bearings.

Parasitic Arrays

Parasitic arrays are the most common RDF antennas used by transmitter hunters in high competition areas such as Southern California. Antennas with significant gain are a necessity due to the weak signals often encountered on weekend-long T-hunts, where the transmitter may be over 200 miles distant. Typical 144-MHz installations feature Yagis or quads of three to six elements, sometimes more. Quads are typically home-built, using data from *The ARRL Antenna Book* and *Transmitter Hunting* (see Bibliography).

Two types of mechanical construction are popular for mobile VHF quads. The model of **Fig 23.78** uses thin gauge wire (solid or stranded), suspended on wood dowel or fiberglass rod spreaders. It is lightweight and easy to turn rapidly by hand while the vehicle moves. Many hunters prefer to use larger gauge solid wire (such as AWG 10)

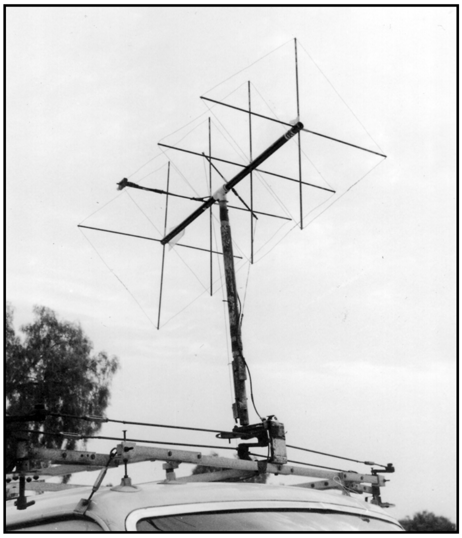


Fig 23.78 — The mobile RDF installation of WB6ADC features a thin wire quad for 144 MHz and a mechanical linkage that permits either the driver or front passenger to rotate the mast by hand.

on a PVC plastic pipe frame (**Fig 23.79**). This quad is more rugged and has somewhat wider frequency range, at the expense of increased weight and wind resistance. It can get mashed going under a willow, but it is easily reshaped and returned to service.

Yagis are a close second to quads in popularity. Commercial models work fine for VHF RDF, provided that the mast is attached at a good balance point. Lightweight and small-diameter elements are desirable for ease of turning at high speeds.

A well-designed mobile Yagi or quad installation includes a method of selecting wave polarization. Although vertical polarization is the norm for VHF-FM communications, horizontal polarization is allowed on many T-hunts. Results will be poor if a VHF RDF antenna is cross-polarized to the transmitting antenna, because multipath and scattered signals (which have indeterminate polarization) are enhanced, relative to the cross-polarized direct signal. The installation of Fig 23.78 features a slip joint at the boom-to-mast junction, with an actuating cord to rotate the boom, changing the polarization. Mechanical stops limit the boom rotation to 90°.

Fig 23.79 — K0OV uses this mobile setup for RDF on several bands, with separate antennas for each band that mate with a common lower mast section, pointer and 360° indicator. Antenna shown is a heavy gauge wire quad for 2 m.

Parasitic Array Performance for RDF

The directional gain of a mobile beam (typically 8 dB or more) makes it unexcelled for both weak signal competitive hunts and for locating interference such as TV cable leakage. With an appropriate receiver, you can get bearings on any signal mode, including FM, SSB, CW, TV, pulses and noise. Because only the response peak is used, the null-fill problems and proximity effects of loops and phased arrays do not exist.

You can observe multiple directions of arrival while rotating the antenna, allowing you to make educated guesses as to which signal peaks are direct and which are from nondirect paths or scattering. Skilled operators can estimate distance to the transmitter from the rate of signal strength increase with distance traveled. The RDF beam is useful for transmitting, if necessary, but use care not to damage an attenuator in the coax line by transmitting through it.

The 3-dB beamwidth of typical mobile-mount VHF beams is on the order of 80°. This is a great improvement over 2-element driven arrays, but it is still not possible to get pinpoint bearing accuracy. You can achieve errors of less than 10° by carefully reading the S-meter. In practice, this is not a major hindrance to successful mobile RDF. Mobile users are not as concerned with precise bearings as fixed station operators, because mobile readings are used primarily to give the general direction of travel to "home in" on the signal. Mobile bearings are continuously updated from new, closer locations.

Amplitude-based RDF may be very difficult when signal level varies rapidly. The transmitter hider may be changing power, or the target antenna may be moving or near a well-traveled road or airport. The resultant rapid S-meter movement makes it hard to take accurate bearings with a quad. The process is slow because the antenna must be carefully rotated by hand to "eyeball average" the meter readings.

Switched Antenna RDF Units

Three popular types of RDF systems are relatively insensitive to variations in signal level. Two of them use a pair of vertical dipole antennas, spaced $^{1}/_{2}$ l or less apart, and alternately switched at a rapid rate to the input of the receiver. In use, the indications of the two systems are similar, but the principles are different.

Switched Pattern Systems

The switched pattern RDF set (**Fig 23.80**) alternately creates two cardioid antenna patterns with lobes to the left and the right. The patterns are generated in much the same way as in the phased arrays described above. PIN RF diodes select the alternating patterns. The combined antenna outputs go to a receiver with AM detection. Processing after the detector output determines the phase or amplitude difference between the patterns' responses to the signal.

Switched pattern RDF sets typically have a zero center meter as an indicator. The meter swings negative when the signal is coming from the user's left, and positive when the signal source is on the right. When the plane of the antenna is exactly perpendicular to the direction of the signal source, the meter reads zero.

The sharpness of the zero crossing indication makes possible more precise bearings than those obtainable with a quad or Yagi. Under ideal conditions with a well-built unit, null direction accuracy is within 1°. Meter deflection tells the user which way to turn to zero the meter. For example, a negative (left) reading requires turning the antenna left. This solves the 180° ambiguity caused by the two zero crossings in each complete rotation of the antenna system.

Because it requires AM detection of the switched pattern signal, this RDF system finds its greatest use in the 120-MHz aircraft band, where AM is the standard mode. Commercial manufacturers make portable RDF sets with switched pattern antennas and built-in receivers for field portable use. These sets can usually be adapted to the amateur 144-MHz band. Other designs are adaptable to any VHF receiver that covers the frequency of interest and has an AM detector built in or added.

Switched pattern units work well for RDF from small aircraft, for which the two vertical antennas are mounted in fixed positions on the outside of the fuselage or simply taped inside the windshield. The left-right indication tells the pilot which way to turn the aircraft to home in. Since street vehicles generally travel only on roads, fixed mounting of the antennas on them is undesirable. Mounting vehicular switched-pattern arrays on a rotatable mast is best.

Time of Arrival Systems

Another kind of switched antenna RDF set uses the difference in arrival times of the signal wavefront at the two antennas. This narrow-aperture Time-Difference-of-Arrival (TDOA) technology is used for many sophisticated military RDF systems. The rudimentary TDOA implementation of **Fig 23.81** is quite effective for amateur use. The signal from transmitter 1 reaches antenna A before antenna B. Conversely, the signal from transmitter 3 reaches antenna B before antenna A. When the plane of the antenna is perpendicular to the signal source (as transmitter 2 is in the figure), the signal arrives at both antennas simultaneously.

If the outputs of the antennas are alternately switched at an

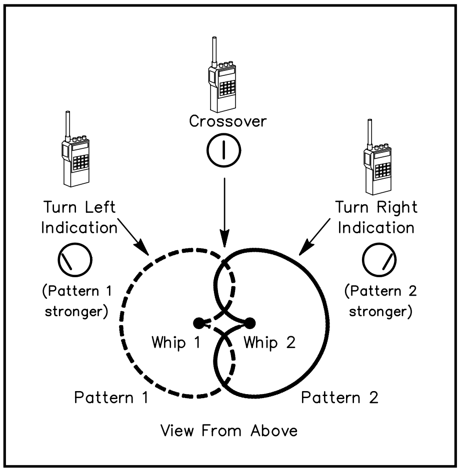


Fig 23.80 — In a switched pattern RDF set, the responses of two cardioid antenna patterns are summed to drive a zero center indicator.

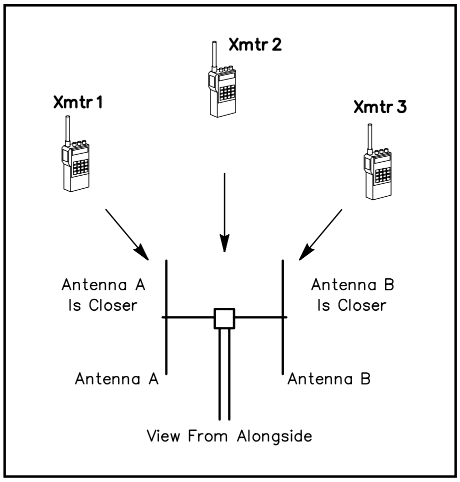


Fig 23.81 — A dual-antenna TDOA RDF system has a similar indicator to a switched pattern unit, but it obtains bearings by determining which of its antennas is closer to the transmitter.

audio rate to the receiver input, the differences in the arrival times of a continuous signal produce phase changes that are detected by an FM discriminator. The resulting short pulses sound like a tone in the receiver output. The tone disappears when the antennas are equidistant from the signal source, giving an audible null.

The polarity of the pulses at the discriminator output is a function of which antenna is closer to the source. Therefore, the pulses can be processed and used to drive a left-right zero center meter in a manner similar to the switched pattern units described above. Left-right LED indicators may replace the meter for economy and visibility at night.

RDF operations with a TDOA dual antenna RDF are done in the same manner as with a switched antenna RDF set. The main difference is the requirement for an FM receiver in the TDOA system and an AM receiver in the switched pattern case. No RF attenuator is needed for close-in work in the TDOA case.

Popular designs for practical do-it-yourself TDOA RDF sets include the Simple Seeker (described elsewhere in this chapter) and the W9DUU design (see article by Bohrer in the Bibliography). Articles with plans for the Handy Tracker, a simple TDOA set with a delay line to resolve the dual-null ambiguity instead of LEDs or a meter, are listed in the Bibliography.

Performance Comparison

Both types of dual antenna RDFs make good on-foot “sniffing” devices and are excellent performers when there are rapid amplitude variations in the incoming signal. They are the units of choice for airborne work. Compared to Yagis and quads, they give good directional performance over a much wider frequency range. Their indications are more precise than those of beams with broad forward lobes.

Dual-antenna RDF sets frequently give inaccurate bearings in multipath situations, because they cannot resolve signals of nearly equal levels from more than one direction. Because multipath signals are a combined pattern of peaks and nulls, they appear to change in amplitude and bearing as you move the RDF antenna along the bearing path or perpendicular to it, whereas a non-multipath signal will have constant strength and bearing.

The best way to overcome this problem is to take large numbers of bearings while moving toward the transmitter. Taking bearings while in motion averages out the effects of multipath, making the direct signal more readily discernible. Some TDOA RDF sets have a slow-response mode that aids the averaging process.

Switched antenna systems generally do not perform well when the incoming signal is horizontally polarized. In such cases, the bearings may be inaccurate or unreadable. TDOA units require a carrier type signal such as FM or CW; they usually cannot yield bearings on noise or pulse signals.

Unless an additional method is employed to measure signal strength, it is easy to “overshoot” the hidden transmitter location with a TDOA set. It is not uncommon to see a TDOA foxhunter walk over the top of a concealed transmitter and walk away, following the opposite 180° null, because there is no display of signal amplitude.

Doppler RDF Sets

RDF sets using the Doppler principle are popular in many areas because of their ease of use. They have an indicator that instantaneously displays direction of the signal source relative to the vehicle heading, either on a circular ring of LEDs or a digital readout in degrees. A ring of four, eight or more antennas picks up the signal. Quarter-wavelength monopoles on a ground plane are popular for vehicle use, but half-wavelength vertical dipoles, where practical, perform better.

Radio signals received on a rapidly moving antenna experience a frequency shift due to the Doppler effect, a phenomenon well known to anyone who has observed a moving car with its horn sounding. The horn’s pitch appears higher than normal as the car approaches, and lower as the car recedes. Similarly, the received radio frequency increases as the antenna moves toward the transmitter and vice versa. An FM receiver will detect this frequency change.

Fig 23.82 shows a $^{1}/_{4}$-λ vertical antenna being moved on a circular track around point P, with constant angular velocity. As the antenna approaches the transmitter on its track, the received frequency is shifted higher. The highest instantaneous frequency occurs when the antenna is at point A, because tangential velocity toward the transmitter is maximum at that point. Conversely, the lowest frequency occurs when the antenna reaches point C, where velocity is maximum away from the transmitter.

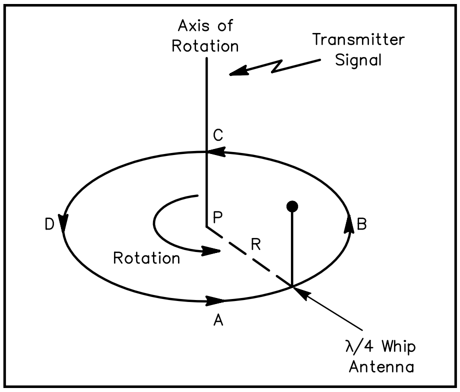


Fig 23.82 — A theoretical Doppler antenna circles around point P, continuously moving toward and away from the source at an audio rate.

Fig 23.83 shows a plot of the component of the tangential velocity that is in the direction of the transmitter as the antenna moves around the circle. Comparing Figs 23.82 and 23.83, notice that at B in Fig 23.83, the tangential velocity is crossing zero from the positive to the negative and the antenna is closest to the transmitter. The Doppler shift and resulting audio output from the receiver discriminator follow the same plot, so that a negative-slope zero-crossing detector, synchronized with the antenna rotation, senses the incoming direction of the signal.

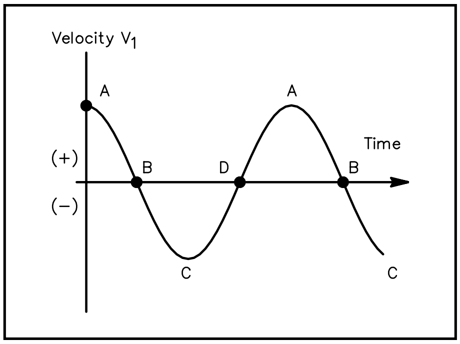


Fig 23.83 — Frequency shift versus time produced by the rotating antenna movement toward and away from the signal source.

The amount of frequency shift due to the Doppler effect is proportional to the RF frequency and the tangential antenna velocity. The velocity is a function of the radius of rotation and the angular velocity (rotation rate). The radius of rotation must be less than $^{1}/_{4}$ λ to avoid errors. To get a usable amount of FM deviation (comparable to typical voice modulation) with this radius, the antenna must rotate at approximately 30,000 RPM (500 Hz). This puts the Doppler tone in the audio range for easy processing.

Mechanically rotating a whip antenna at this rate is impractical, but a ring of whips, switched to the receiver in succession with RF PIN diodes, can simulate a rapidly rotating antenna. Doppler RDF sets must be used with receivers having FM detectors. The DoppleScAnt and Roanoke Doppler (see Bibliography) are mobile Doppler RDF sets designed for inexpensive home construction.

Doppler Advantages and Disadvantages

Ring-antenna Doppler sets are the ultimate in simplicity of operation for mobile RDF. There are no moving parts and no manual antenna pointing. Rapid direction indications are displayed on very short signal bursts.

Many units lock in the displayed direction after the signal leaves the air. Power variations in the source signal cause no difficulties, as long as the signal remains above the RDF detection threshold. A Doppler antenna goes on top of any car quickly, with no holes to drill. Many Local Interference Committee members choose Dopplers for tracking malicious interference, because they are inconspicuous (compared to beams) and effective at tracking the strong vertically polarized signals that repeater jammers usually emit.

A Doppler does not provide superior performance in all VHF RDF situations. If the signal is too weak for detection by the Doppler unit, the hunt advantage goes to teams with beams. Doppler installations are not suitable for on-foot sniffing. The limitations of other switched antenna RDFs also apply: (1) poor results with horizontally polarized signals, (2) no indication of distance, (3) carrier type signals only and (4) inadvisability of transmitting through the antenna.

Readout to the nearest degree is provided on some commercial Doppler units. This does not guarantee that level of accuracy, however. A well-designed four-monopole set is typically capable of ±5° accuracy on 2 m, if the target signal is vertically polarized and there are no multipath effects.

The rapid antenna switching can introduce cross modulation products when the user is near strong off-channel RF sources. This self-generated interference can temporarily render the system unusable. While not a common problem with mobile Dopplers, it makes the Doppler a poor choice for use in remote RDF installations at fixed sites with high power VHF transmitters nearby.

Mobile RDF System Installation

Of these mobile VHF RDF systems, the Doppler type is clearly the simplest from a mechanical installation standpoint. A four-whip Doppler RDF array is easy to implement with magnetic mount antennas. Alternately, you can mount all the whips on a frame that attaches to the vehicle roof with suction cups. In either case, setup is rapid and requires no holes in the vehicle.

You can turn small VHF beams and dual-antenna arrays readily by extending the mast through a window. Installation on each model vehicle is different, but usually the mast can be held in place with some sort of cup in the arm rest and a plastic tie at the top of the window, as in **Fig 23.84**. This technique works best on cars with frames around the windows, which allow the door to be opened with the antenna in place. Check local vehicle codes, which limit how far your antenna may protrude beyond the line of the fenders. Larger antennas may have to be put on the passenger side of the vehicle, where greater overhang is generally permissible.

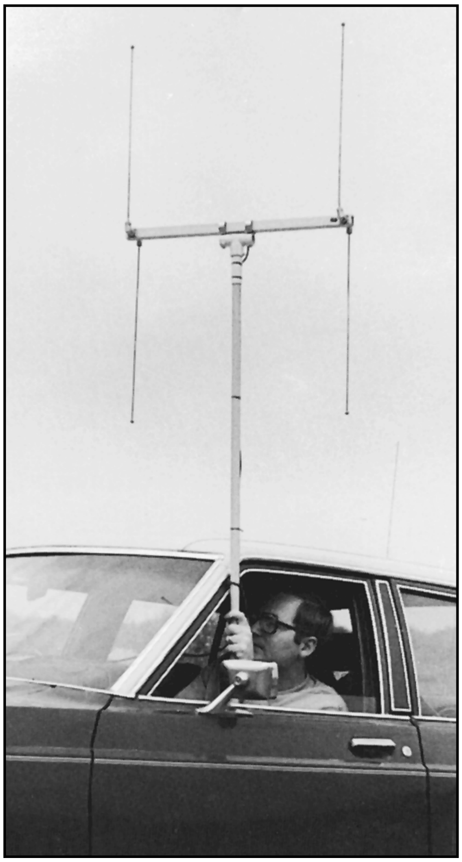


Fig 23.84 — A set of TDOA RDF antennas is light weight and mounts readily through a sedan window without excessive overhang.

The window box (**Fig 23.85**) is an improvement over through-the-window mounts. It provides a solid, easy-turning mount for the mast. The plastic panel keeps out bad weather. You will need to custom-design the box for your vehicle model. Vehicle codes may limit the use of a window box to the passenger side.

For the ultimate in convenience and versatility, cast your fears aside, drill a hole through the center of the roof and install a waterproof bushing. A roof-hole mount permits the use of large antennas without overhang violations. The driver, front passenger and even a rear passenger can turn the mast when required. The installation in Fig 23.79 uses a roof-hole bushing made from mating threaded PVC pipe adapters and reducers. When it is not in use for RDF, a PVC pipe cap provides a watertight cover. There is a pointer and 360° indicator at the bottom of the mast for precise bearings.

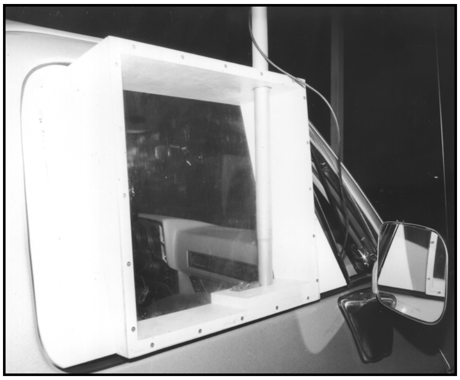


Fig 23.85 — A window box allows the navigator to turn a mast mounted antenna with ease while remaining dry and warm. No holes in the vehicle are needed with a properly designed window box.

DIRECTION-FINDING TECHNIQUES AND PROJECTS

The ability to locate a transmitter quickly with RDF techniques is a skill you will acquire only with practice. It is very important to become familiar with your equipment and its limitations. You must also understand how radio signals behave in different types of terrain at the frequency of the hunt. Experience is the best teacher, but reading and hearing the stories of others who are active in RDF will help you get started.

Verify proper performance of your portable RDF system before you attempt to track signals in unknown locations. Of primary concern is the accuracy and symmetry of the antenna pattern. For instance, a lopsided figure-8 pattern with a loop, Adcock, or TDOA set leads to large bearing errors. Nulls should be exactly 180° apart and exactly at right angles to the loop plane or the array boom. Similarly, if feed-line pickup causes an off-axis main lobe in your VHF RDF beam, your route to the target will be a spiral instead of a straight line.

Perform initial checkout with a low-powered test transmitter at a distance of a few hundred feet. Compare the RDF bearing indication with the visual path to the transmitter. Try to "find" the transmitter with the RDF equipment as if its position were not known. Be sure to check all nulls on antennas that have more than one.

If imbalance or off-axis response is found in the antennas, there are two options available. One is to correct it, insofar as possible. A second option is to accept it and use some kind of indicator or correction procedure to show the true directions of signals. Sometimes the end result of the calibration procedure is a compromise between these two options, as a perfect pattern may be difficult or impossible to attain.

The same calibration suggestions apply for fixed RDF installations, such as a base station HF Adcock or VHF beam. Of course it does no good to move it to an open field. Instead, calibrate the array in its intended operating position, using a portable or mobile transmitter. Because of nearby obstructions or reflecting objects, your antenna may not indicate the precise direction of the transmitter. Check for imbalance and systemic error by taking readings with the test emitter at locations in several different directions.

The test signal should be at a distance of 2 or 3 miles for these measurements, and should be in as clear an area as possible during transmissions. Avoid locations where power lines and other overhead wiring can conduct signal from the transmitter to the RDF site. Once antenna adjustments are optimized, make a table of bearing errors noted in all compass directions. Apply these error values as corrections when actual measurements are made.

Preparing to Hunt

Successfully tracking down a hidden transmitter involves detective work — examining all the clues, weighing the evidence and using good judgment. Before setting out to locate the source of a signal, note its general characteristics. Is the frequency constant, or does it drift? Is the signal continuous, and if not, how long are transmissions? Do transmissions occur at regular intervals, or are they sporadic? Irregular, intermittent signals are the most difficult to locate, requiring patience and quick action to get bearings when the transmitter comes on.

Refraction, Reflections and the Night Effect

You will get best accuracy in tracking ground wave signals when the propagation path is over homogeneous terrain. If there is a land/water boundary in the path, the different conductivities of the two media can cause bending (refraction) of the wave front, as in **Fig 23.86A**. Even the most sophisticated RDF equipment will not indicate the correct bearing in this situation, as the equipment can only show the direction from which the signal is arriving. RDFers have observed this phenomenon on both HF and VHF bands.

Signal reflections also cause misleading bearings. This effect becomes more pronounced as frequency increases. T-hunt hiders regularly achieve strong signal bounces from distant mountain ranges on the 144-MHz band.

Tall buildings also reflect VHF/UHF signals, making midcity RDF difficult. Hunting on the 440-MHz and higher amateur bands is even more arduous because of the plethora of reflecting objects.

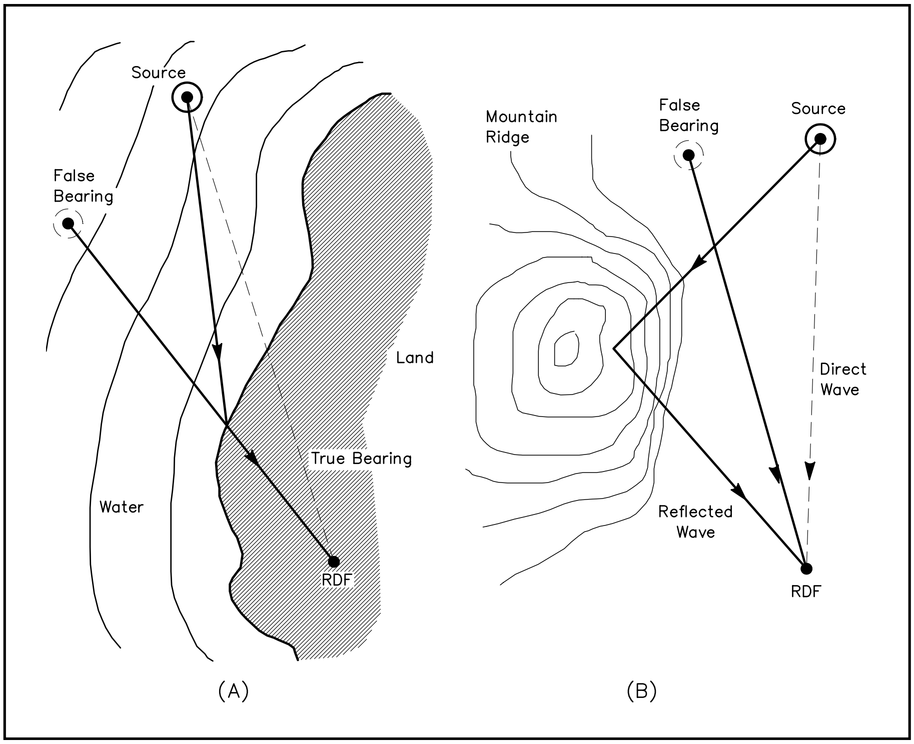


Fig 23.86 — RDF errors caused by refraction (A) and reflection (B). The reading at A is false because the signal actually arrives from a direction that is different from that to the source. At B, a direct signal from the source combines with a reflected signal from the mountain ridge. The RDF set may average the signals as shown, or indicate two lines of bearing.

In areas of signal reflection and multipath, some RDF gear may indicate that the signal is coming from an intermediate point, as in Fig 23.86B. High gain VHF/UHF RDF beams will show direct and reflected signals as separate S-meter peaks, leaving it to the operator to determine which is which. Null-based RDF antennas, such as phased arrays and loops, have the most difficulty with multipath, because the multiple signals tend to make the nulls very shallow or fill them in entirely, resulting in no bearing indication at all.

If the direct path to the transmitter is masked by intervening terrain, a signal reflection from a higher mountain, building, water tower, or the like may be much stronger than the direct signal. In extreme cases, triangulation from several locations will appear to “confirm” that the transmitter is at the location of the reflecting object. The direct signal may not be detectable until you arrive at the reflecting point or another high location.

Objects near the observer such as concrete/steel buildings, power lines and chain-link fences will distort the incoming wavefront and give bearing errors. Even a dense grove of trees can sometimes have an adverse effect. It is always best to take readings in locations that are as open and clear as possible, and to take bearings from numerous positions for confirmation. Testing of RDF gear should also be done in clear locations.

Locating local signal sources on frequencies below 10 MHz is much easier during daylight hours, particularly with loop antennas. In the daytime, D-layer absorption minimizes skywave propagation on these frequencies. When the D layer disappears after sundown, you may hear the signal by a combination of ground wave and high-angle skywave, making it difficult or impossible to obtain a bearing. RDFers call this phenomenon the *night effect*.

While some mobile T-hunters prefer to go it alone, most have more success by teaming up and assigning tasks. The driver concentrates on handling the vehicle, while the assistant (called the “navigator” by some teams) turns the beam, reads the meters and calls out bearings. The assistant is also responsible for maps and plotting, unless there is a third team member for that task.

Maps and Bearing-Measurements

Possessing accurate maps and knowing how to use them is very important for successful RDF. Even in difficult situations where precise bearings cannot be obtained, a town or city map will help in plotting points where signal levels are high and low. For example, power line noise tends to propagate along the power line and radiates as it does so. Instead of a single source, the noise appears to come from a multitude of sources. This renders many ordinary RDF techniques ineffective. Mapping locations where signal amplitudes are highest will help pinpoint the source.

Several types of area-wide maps are suitable for navigation and triangulation. Street and highway maps work well for mobile work. Large detailed maps are preferable to thick map books. Contour maps are ideal for open country. Aeronautical charts are also suitable. Good sources of maps include auto clubs, stores catering to camping/hunting enthusiasts and city/county engineering departments.

A *heading* is a reading in degrees relative to some external reference, such as your house or vehicle; a *bearing* is the target signal's direction relative to your position. Plotting a bearing on a hidden transmitter from your vehicle requires that you know the vehicle location, transmitter heading with respect to the vehicle and vehicle heading with respect to true north.

First, determine your location, using landmarks or a navigation device such as a loran or GPS receiver. Next, using your RDF equipment, determine the bearing to the hidden transmitter (0 to 359.9°) with respect to the vehicle. Zero degrees heading corresponds to signals coming from directly in front of the vehicle, signals from the right indicate 90°, and so on.

Finally, determine your vehicle's true heading, that is, its heading relative to true north. Compass needles point to magnetic north and yield magnetic headings. Translating a magnetic heading into a true heading requires adding a correction factor, called *magnetic declination*, which is a positive or negative factor that depends on your location.

Declination for your area is given on US Geological Survey (USGS) maps, though it undergoes long-term changes. Add the declination to your magnetic heading to get a true heading.

As an example, assume that the transmitted signal arrives at 30° with respect to the vehicle heading, that the compass indicates that the vehicle's heading is 15°, and the magnetic declination is +15°. Add these values to get a true transmitter bearing (that is, a bearing with respect to true north) of 60°.

Because of the large mass of surrounding metal, it is very difficult to calibrate an in-car compass for high accuracy at all vehicle headings. It is better to use a remotely mounted flux-gate compass sensor, properly corrected, to get vehicle headings, or to stop and use a hand compass to measure the vehicle heading from the outside. If you T-hunt with a mobile VHF beam or quad, you can use your manual compass to sight along the antenna boom for a magnetic bearing, then add the declination for true bearing to the fox.

Triangulation Techniques

If you can obtain accurate bearings from two locations separated by a suitable distance, the technique of *triangulation* will give the expected location of the transmitter. The intersection of the lines of bearing from each location provides a *fix*. Triangulation accuracy is greatest when stations are located such that their bearings intersect at right angles. Accuracy is poor when the angle between bearings approaches 0° or 180°.

There is always uncertainty in the fixes obtained by triangulation due to equipment limitations, propagation effects and measurement errors. Obtaining bearings from three or more locations reduces the uncertainty. A good way to show the probable area of the transmitter on the triangulation map is to draw bearings as a narrow sector instead of as a single line. Sector width represents the amount of bearing uncertainty. **Fig 23.87** shows a portion of a map marked in this manner. Note how the bearing from Site 3 has narrowed down the probable area of the transmitter position.

Computerized Transmitter Hunting

A portable computer is an excellent tool for streamlining the RDF process. Some T-hunters use one

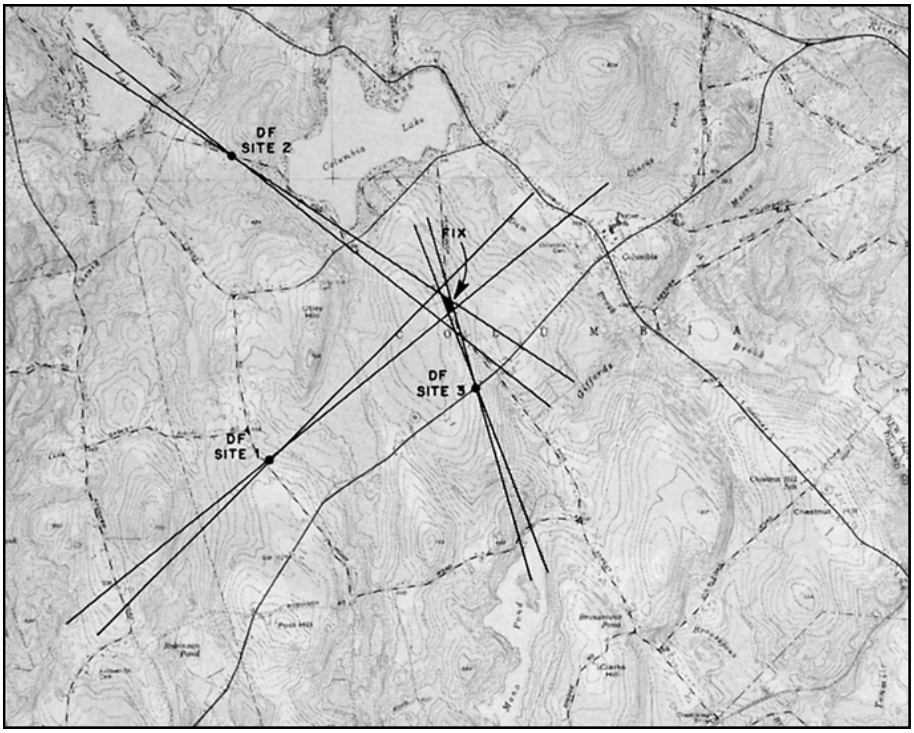
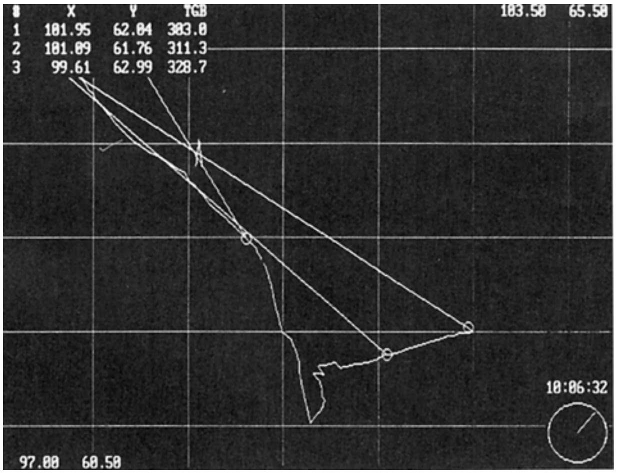


Fig 23.87 — Bearing sectors from three RDF positions drawn on a map for triangulation. In this case, bearings are from loop antennas, which have 180° ambiguity.



```
#      X       Y      TGB                     103.50   65.50
1   101.95   62.04   303.0
2   101.09   61.76   311.3
3    99.61   62.99   328.7
                                              10:06:32
97.00   60.50
```

Fig 23.88 — Screen plot from a computerized RDF system showing three T-hunt bearings (straight lines radiating from small circles) and the vehicle path (jagged trace). The grid squares correspond to areas of standard topographic maps.

to optimize VHF beam bearings, generating a two-dimensional plot of signal strength versus azimuth. Others have automated the bearing-taking process by using a computer to capture signal headings from a Doppler RDF set, vehicle heading from a flux-gate compass, and vehicle location from a GPS receiver (**Fig 23.88**). The computer program can compute averaged headings from a Doppler set to reduce multipath effects.

Provided with perfect position and bearing information, computer triangulation could determine the transmitter location within the limits of its computational accuracy. Two bearings would exactly locate a fox. Of course, there are always uncertainties and inaccuracies in bearing and position data. If these uncertainties can be determined, the program can compute the uncertainty of the triangulated bearings. A "smart" computer program can evaluate bearings, triangulate the bearings of multiple hunters, discard those that appear erroneous, determine which locations have particularly great or small multipath problems and even "grade" the performance of RDF stations.

By adding packet radio connections to a group of computerized base and mobile RDF stations, the processed bearing data from each can be shared. Each station in the network can display the triangulated bearings of all. This requires a common map coordinate set among all stations. The USGS Universal Transverse Mercator (UTM) grid, consisting of 1×1-km grid squares, is a good choice.

The computer is an excellent RDF tool, but it is no substitute for a skilled "navigator." You will probably discover that using a computer on a high-speed T-hunt requires a full-time operator in the vehicle to make full use of its capabilities.

Skywave Bearings and Triangulation

Many factors make it difficult to obtain accuracy in skywave RDF work. Because of Faraday rotation during propagation, skywave signals are received with random polarization. Sometimes the vertical component is stronger, and at other times the horizontal. During periods when the vertical component is weak, the signal may appear to fade on an Adcock RDF system. At these times, determining an accurate signal null direction becomes very hard.

For a variety of reasons, HF bearing accuracy to within 1 or 2° is the exception rather than the rule. Errors of 3 to 5° are common. An error of 3° at a thousand miles represents a distance of 52 miles. Even with every precaution taken in measurement, do not expect cross-country HF triangulation to pinpoint a signal beyond a county, a corner of a state or a large metropolitan area. The best you can expect is to be able to determine where a mobile RDF group should begin making a local search.

Triangulation mapping with skywave signals is more complex than with ground or direct waves because the expected paths are great-circle routes. Commonly available world maps are not suitable, because the triangulation lines on them must be curved, rather than straight. In general, for flat maps, the larger the area encompassed, the greater the error that straight line triangulation procedures will give.

A highway map is suitable for regional triangulation work if it uses some form of conical projection, such as the Lambert conformal conic system. This maintains the accuracy of angular representation, but the distance scale is not constant over the entire map.

One alternative for worldwide areas is the azimuthal-equidistant projection, better known as a great-circle map. True bearings for great-circle paths are shown as straight lines from the center to all points on the Earth. Maps centered on three or more different RDF sites may be compared to gain an idea of the general geographic area for an unknown source.

For worldwide triangulation, the best projection is the *gnomonic*, on which all great circle paths are represented by straight lines and angular measurements with respect to meridians are true. Gnomonic charts are custom maps prepared especially for government and military agencies.

Skywave signals do not always follow the great-circle path in traveling from a transmitter to a receiver. For example, if the signal is refracted in a tilted layer of the ionosphere, it could arrive from a direction that is several degrees away from the true great-circle bearing.

Another cause of signals arriving off the great-circle path is termed *sidescatter*. It is possible that, at a given time, the ionosphere does not support great-circle propagation of the signal from the transmitter to the receiver because the frequency is above the MUF for that path. However, at the same time, propagation may be supported from both ends of the path to some mutually accessible point off the great-circle path. The signal from the source may propagate to that point on the Earth's surface and hop in a sideways direction to continue to the receiver.

For example, signals from Central Europe have propagated to New England by hopping from an area in the Atlantic Ocean off the northwest coast of Africa, whereas the great-circle path puts the reflection point off the southern coast of Greenland. Readings in error by as much as 50° or more may result from sidescatter. The effect of propagation disturbances may be that the bearing seems to wander somewhat over a few minutes of time, or it may be weak and fluttery. At other times, however, there may be no telltale signs to indicate that the readings are erroneous.

Closing In

On a mobile foxhunt, the objective is usually to proceed to the hidden T with minimum time and mileage. Therefore, do not go far out of your way to get off-course bearings just to triangulate. It is usually better to take the shortest route along your initial line of bearing and "home in" on the signal.

With a little experience, you will be able to gauge your distance from the fox by noting the amount of attenuation needed to keep the S-meter on scale.

As you approach the transmitter, the signal will become very strong. To keep the S-meter on scale, you will need to add an RF attenuator in the transmission line from the antenna to the receiver. Simple resistive attenuators are discussed in another chapter.

In the final phases of the hunt, you will probably have to leave your mobile and continue the hunt on foot. Even with an attenuator in the line, in the presence of a strong RF field, some energy will be coupled directly into the receiver circuitry. When this happens, the S-meter reading changes only slightly or perhaps not at all as the RDF antenna rotates, no matter how much attenuation you add. The cure is to shield the receiving equipment. Something as simple as wrapping the receiver in foil or placing it in a bread pan or cake pan, covered with a piece of copper or aluminum screening securely fastened at several points, may reduce direct pickup enough for you to get bearings.

Alternatively, you can replace the receiver with a field-strength meter as you close in, or use a heterodyne-type active attenuator. Plans for these devices are at the end of this chapter.

The Body Fade

A crude way to find the direction of a VHF signal with just a hand-held transceiver is the body fade technique, so named because the blockage of your body causes the signal to fade. Hold your HT close to your chest and turn all the way around slowly. Your body is providing a shield that gives the hand-held a cardioid sensitivity pattern, with a sharp decrease in sensitivity to the rear. This null indicates that the source is behind you (**Fig 23.89**).

If the signal is so strong that you can't find the null, try tuning 5 or 10 kHz off frequency to put the signal into the skirts of the IF passband. If your hand-held is dual-band (144/440 MHz) and you are hunting on 144 MHz, try tuning to the much weaker third harmonic of the signal in the 440-MHz band.

The body fade null, which is rather shallow to begin with, can be obscured by reflections, multipath, nearby objects, etc. Step well away from your vehicle before trying to get a bearing. Avoid large buildings, chain-link fences, metal signs and the like. If you do not get a good null, move to a clearer location and try again.

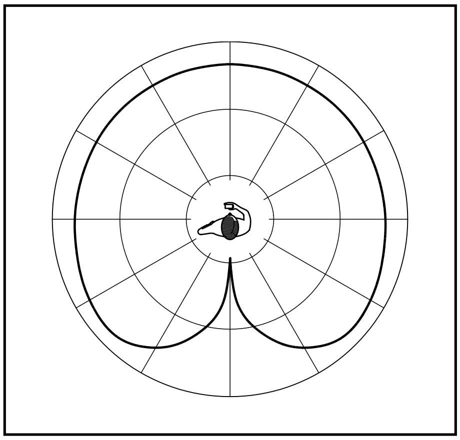


Fig 23.89 — When performing the body fade maneuver, a hand-held transceiver exhibits this directional pattern.

Air Attenuators

In microwave parlance, a signal that is too low in frequency to be propagated in a waveguide (that is, below the *cutoff frequency*) is attenuated at a predictable logarithmic rate. In other words, the farther inside the waveguide, the weaker the signal gets. Devices that use this principle to reduce signal strength are commonly known as *air attenuators*. Plans for a practical model for insertion in a coax line are in *Transmitter Hunting* (see Bibliography).

With this principle, you can reduce the level of strong signals into your hand-held transceiver, making it possible to use the body fade technique at very close range. Glen Rickerd, KC6TNF, documented this technique for *QST*. Start with a pasteboard mailing tube that has sufficient inside diameter to accommodate your hand-held. Cover the outside of the tube completely with aluminum foil. You can seal the bottom end with foil, too, but it probably will not matter if the tube is long enough. For durability and to prevent accidental shorts, wrap the foil in packing tape. You will also need a short, stout cord attached to the hand-held. The wrist strap may work for this, if long enough.

To use this air attenuation scheme for body fade bearings, hold the tube vertically against your chest and lower the hand-held into it until the signal begins to weaken (**Fig 23.90**). Holding the receiver in place, turn around slowly and listen for a sudden decrease in signal strength. If the null is poor, vary the depth of the receiver in the tube and try again. You do not need to watch the S-meter, which will likely be out of sight in the tube. Instead, use noise level to estimate signal strength.

For extremely strong signals, remove the "rubber duck" antenna or extend the wrist strap with a shoelace to get greater depth of suspension in the tube. The depth that works for one person may not work for another. Experiment with known signals to determine what works best for you.

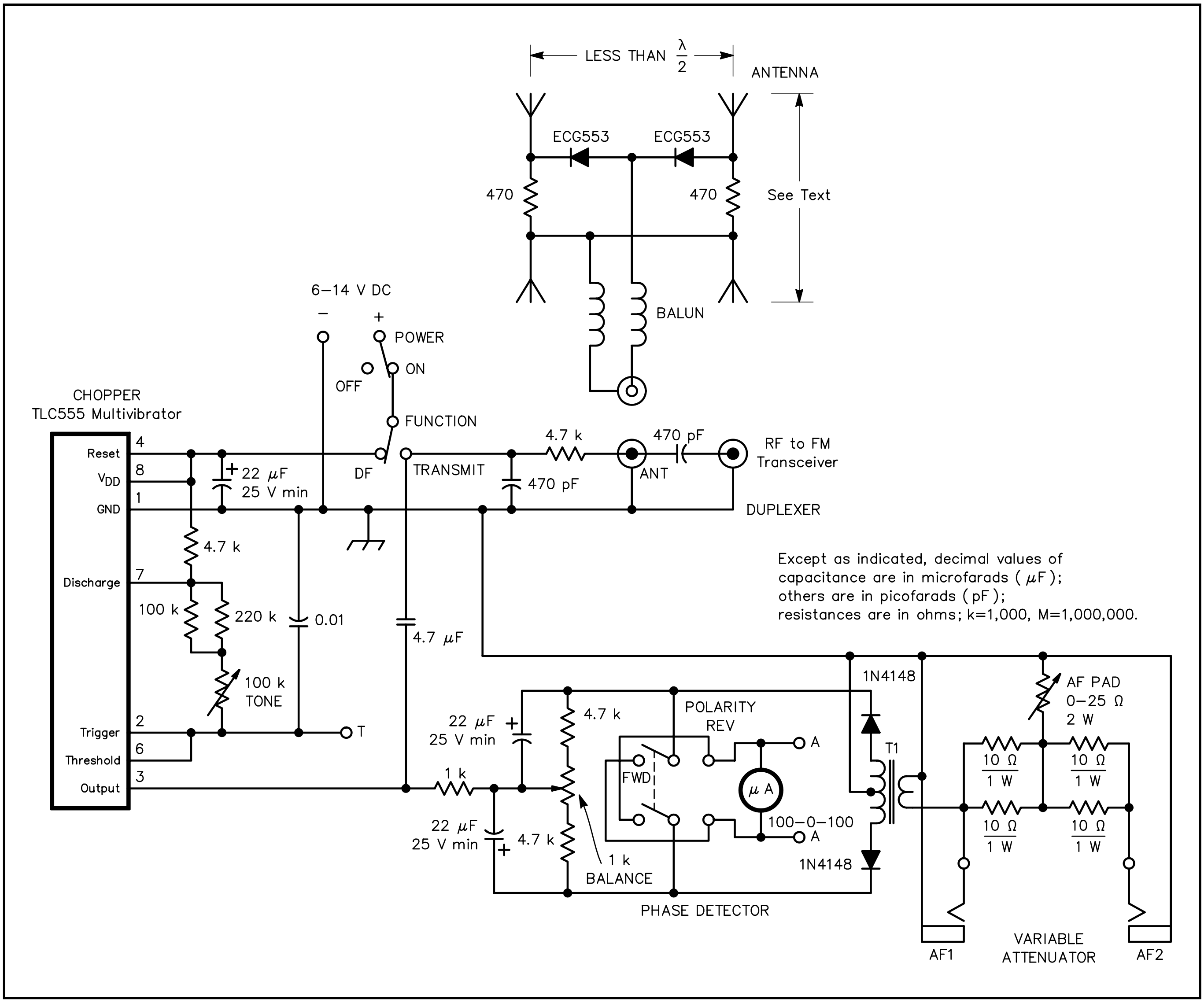
Fig 23.90 — The air attenuator for a VHF hand-held in use. Suspend the radio by the wrist strap or a string inside the tube.

THE SIMPLE SEEKER

The Simple Seeker for 144 MHz is the latest in a series of dual-antenna TDOA projects by Dave Geiser, WA2ANU. Fig 23.79 and accompanying text shows its principle of operation. It is simple to perform rapid antenna switching with diodes, driven by a free-running multivibrator. For best RDF performance, the switching pulses should be square waves, so antennas are alternately connected for equal times. The Simple Seeker uses a CMOS version of the popular 555 timer, which demands very little supply current. A 9-V alkaline battery will give long life. See **Fig 23.95** for the schematic diagram.

PIN diodes are best for this application because they have low capacitance and handle a moderate amount of transmit power. Philips ECG553, NTE-555, Motorola MPN3401 and similar types are suitable. Ordinary 1N4148 switching diodes are acceptable for receive-only use.

Off the null, the polarity of the switching pulses in the receiver output changes (with respect to the switching waveform), depending on which antenna is nearer the source. Thus, comparing the receiver output phase to that of the switching waveform determines which end of the null line points toward the



Except as indicated, decimal values of capacitance are in microfarads (µF); others are in picofarads (pF); resistances are in ohms; k=1,000, M=1,000,000.

Fig 23.95 — Schematic of the Simple Seeker. A capacitor from point T to ground will lower the tone frequency, if desired. A single SPDT center-off toggle switch can replace separate power and function switches.

transmitter. The common name for a circuit to make this comparison is a *phase detector,* achieved in this unit with a simple bridge circuit. A phase detector balance control is included, although it may not be needed. Serious imbalance indicates incorrect receiver tuning, an off-frequency target signal, or misalignment in the receiver IF stages.

Almost any audio transformer with approximately 10:1 voltage step-up to a center-tapped secondary meets the requirements of this phase detector. The output is a positive or negative indication, applied to meter M1 to indicate left or right.

Antenna Choices

Dipole antennas are best for long-distance RDF. They ensure maximum signal pickup and provide the best load for transmitting. **Fig 23.96** shows plans for a pair of dipoles mounted on an H frame of $^1/_2$-inch PVC tubing. Connect the 39-inch elements to the switcher with coaxial cables of *exactly* equal length. Spacing between dipoles is about 20 inches for 2 m, but is not critical. To prevent external currents flowing on the coax shield from disrupting RDF operation, wrap three turns (about 2 inch diameter) of the incoming coax to form a choke balun.

For receive-only work, dipoles are effective over much more than their useful transmit bandwidth. A pair of appropriately spaced 144-MHz dipoles works from 130 to 165 MHz. You will get greater tone amplitude with greater dipole spacing, making it easier to detect the null in the presence of modulation on the signal. But do not make the spacing greater than one-half free-space wavelength on any frequency to be used.

Best bearing accuracy demands that signals reach the receiver only from the switched antenna system. They should not arrive on the receiver wiring directly (through an unshielded case) or enter on wiring other than the antenna coax. The phase detecting system is less amplitude sensitive than systems such as quads and Yagis, but if you use small-aperture antennas such as "rubber duckies," a small signal leak may have a big effect. A wrap of aluminum foil around the receiver case helps block unwanted signal pickup, but tighter shielding may be needed.

Fig 23.97 shows a "sniffer" version of the unit with helix antennas. The added RDF circuits fit in a shielded box, with the switching pulses fed through a low-pass filter (the series 4.7-kΩ resistor and shunt 470-pF capacitor) to the

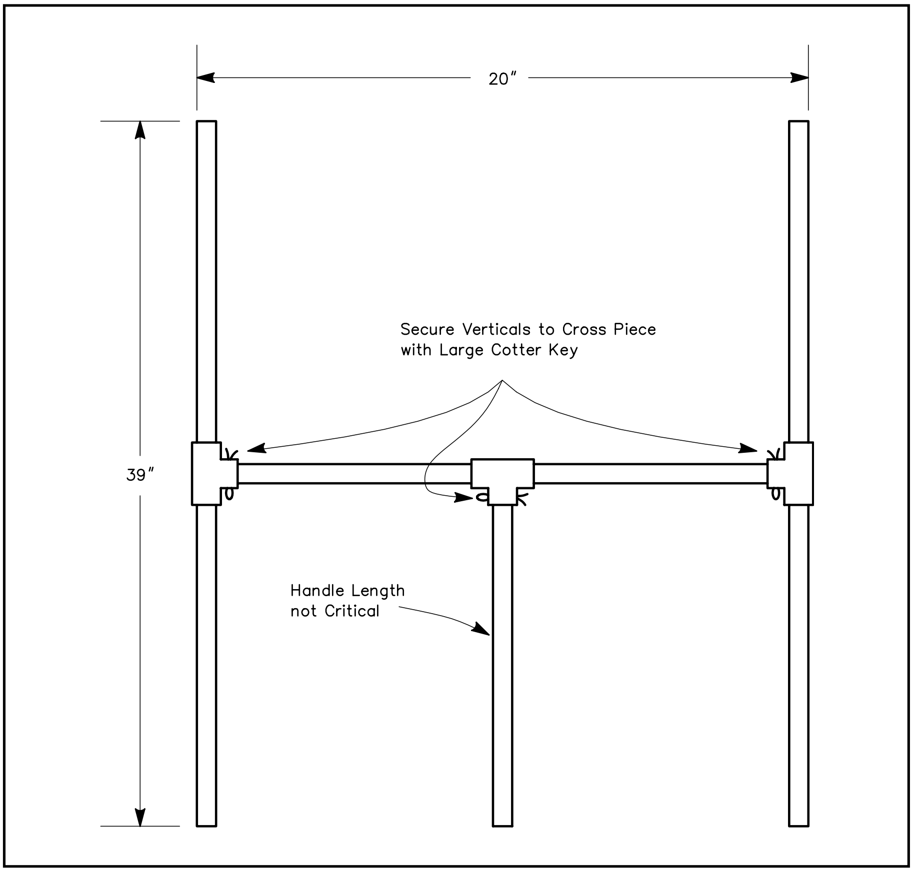


Fig 23.96 — "H" frame for the dual dipole Simple Seeker antenna set, made from $^1/_2$-in. PVC tubing and tees. Glue the vertical dipole supports to the tees. Connect vertical tees and handle to the cross piece by drilling both parts and inserting large cotter pins. Tape the dipole elements to the tubes.

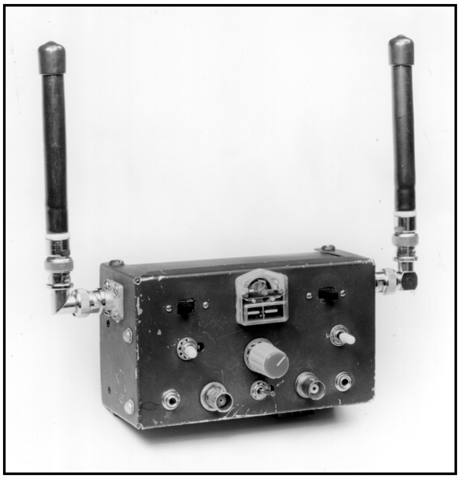


Fig 23.97 — Field version of the Simple Seeker with helix antennas.

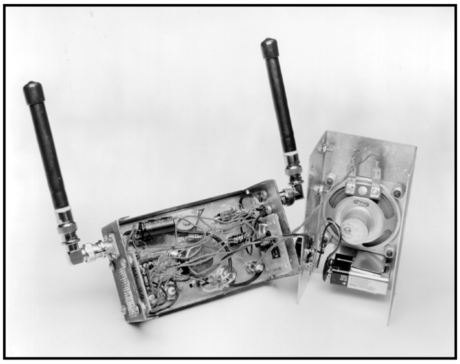


Fig 23.98 — Interior view of the Simple Seeker. The multivibrator and phase detector circuits are mounted at the box ends. This version has a convenient built-in speaker.

receiver. The electronic switch is on a 20-pin DIP pad, with the phase detector on another pad (see **Fig 23.98**).

Because the phase detector may behave differently on weak and strong signals, the Simple Seeker incorporates an audio attenuator to allow either a full-strength audio or a lesser, adjustable received signal to feed the phase detector. You can plug headphones into jack AF2 and connect receiver audio to jack AF1 for no attenuation into the phase detector, or reverse the external connections, using the pad to control level to both the phones and the phase detector.

Convention is that the meter or other indicator deflects left when the signal is to the left. Others prefer that a left meter indication indicates that the antenna is rotated too far to the left. Whichever your choice, you can select it with the DPDT polarity switch. Polarity of audio output varies between receivers, so test the unit and receiver on a known signal source and mark the proper switch position on the unit before going into the field.

PIN diodes, when forward biased, exhibit low RF resistance and can pass up to approximately 1 W of VHF power without damage. The transmit position on the function switch applies steady dc bias to one of the PIN diodes, allowing communications from a hand-held RDF transceiver.

AN ACTIVE ATTENUATOR FOR VHF-FM

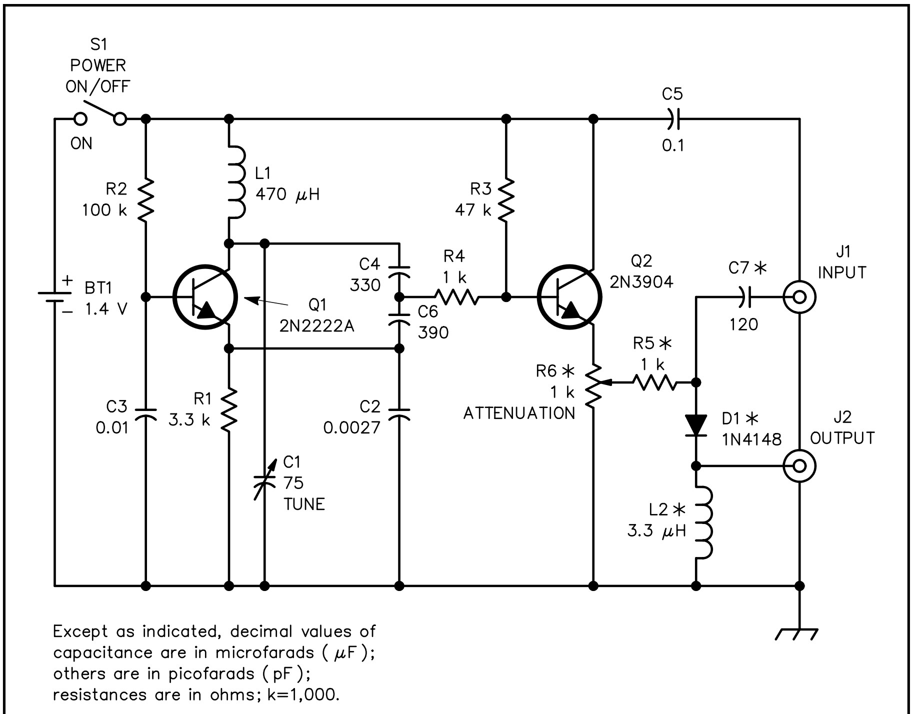
During a VHF transmitter hunt, the strength of the received signal can vary from roughly a microvolt at the starting point to nearly a volt when you are within an inch of the transmitter, a 120-dB range. If you use a beam or other directional array, your receiver must provide accurate signal-strength readings throughout the hunt. Zero to full scale range of S-meters on most hand-held transceivers is only 20 to 30 dB, which is fine for normal operating, but totally inadequate for transmitter hunting. Inserting a passive attenuator between the antenna and the receiver reduces the receiver input signal. However, the usefulness of an external attenuator is limited by how well the receiver can be shielded.

Anjo Eenhoorn, PA0ZR, has designed a simple add-on unit that achieves continuously variable attenuation by mixing the received signal with a signal from a 500-kHz oscillator. This process creates mixing products above and below the input frequency. The spacing of the closest products from the input frequency is equal to the local oscillator (LO) frequency. For example, if the input signal is at 146.52 MHz, the closest mixing products will appear at 147.02 and 146.02 MHz.

The strength of the mixing products varies with increasing or decreasing LO signal level. By DFing on the mixing product frequencies, you can obtain accurate headings even in the presence of a very strong received signal. As a result, any hand-held transceiver, regardless of how poor its shielding may be, is usable for transmitter hunting, up to the point where complete blocking of the receiver front end occurs. At the mixing product frequencies, the attenuator's range is greater than 100 dB.

Varying the level of the oscillator signal provides the extra advantage of controlling the strength of the input signal as it passes through the mixer. So as you close in on the target, you have the choice of monitoring and controlling the level of the input signal or the product signals, whichever provides the best results.

The LO circuit (**Fig 23.99**) uses the easy-to-find 2N2222A transistor. Trimmer capacitor C1 adjusts the oscillator's frequency. Frequency stability is only a minor concern; a few kilohertz of drift is tolerable. Q1's output feeds an emitter-follower buffer using a 2N3904 transistor, Q2. A linear-taper potentiometer (R6) controls the oscillator signal level present at the cathode of the mixing diode, D1. The diode and coupling capacitor C7 are in series with the signal path from antenna input to attenuator output.



Except as indicated, decimal values of capacitance are in microfarads (µF); others are in picofarads (pF); resistances are in ohms; k=1,000.

∗ See text and caption

Fig 23.99 — Schematic of the active attenuator. Resistors are $^1/_4$-W, 5%-tolerance carbon composition or film.

BT1 — Alkaline hearing-aid battery, Duracell SP675 or equivalent.
C1 — 75-pF miniature foil trimmer.
J1, J2 — BNC female connectors.
L1 — 470-µH RF choke.
L2 — 3.3-µH RF choke.
R6 — 1-kΩ, 1-W linear taper (slide or rotary).
S1 — SPST toggle.

This frequency converter design is unorthodox; it does not use the conventional configuration of a doubly balanced mixer, matching pads, filters and so on. Such sophistication is unnecessary here. This approach gives an easy to build circuit that consumes very little power. PA0ZR uses a tiny 1.4-V hearing-aid battery with a homemade battery clip. If your enclosure permits, you can substitute a standard AAA-size battery and holder.

Construction and Tuning

For a template for this project, including the PC board layout and parts overlay, see Chapter 30, References. A circuit board is available from FAR Circuits. The prototype (**Fig 23.100**) uses a plated enclosure with female BNC connectors for RF input and output. C7, D1, L2 and R5 are installed with point-to-point wiring between the BNC connectors and the potentiometer. S1 mounts on the rear wall of the enclosure.

Most hams will find the 500-kHz frequency offset convenient, but the oscillator can be tuned to other frequencies. If VHF/UHF activity is high in your area, choose an oscillator frequency that creates mixing products in clear portions of the band. The attenuator was designed for 144-MHz RDF, but will work elsewhere in the VHF/UHF range.

You can tune the oscillator with a frequency counter or with a strong signal of known frequency. It helps to enlist the aid of a friend with a hand-held transceiver a short distance away for initial tests. Connect a short piece of wire to J1, and cable your hand-held transceiver to J2. Select a simplex receive frequency and have your assistant key the test transmitter at its lowest power setting. (Better yet, attach the transmitter to a dummy antenna.)

With attenuator power on, adjust R6 for mid-scale S-meter reading. Now retune the hand-held to receive one of the mixing products. Carefully tune C1 and R6 until you hear the mixing product. Watch the S-meter and tune C1 for maximum reading.

If your receiver features memory channels, enter the hidden transmitter frequency along with both mixing product frequencies before the hunt starts. This allows you to jump from one to the other at the press of a button.

When the hunt begins, listen to the fox's frequency with the attenuator switched on. Adjust R6 until you get a peak reading. If the signal is too weak, connect your quad or other RDF antenna directly to your transceiver and hunt without the attenuator until the signal becomes stronger.

As you get closer to the fox, the attenuator will not be able to reduce the on-frequency signal enough to get good bearings. At this point, switch to one of the mixing product frequencies, set R6 for on-scale reading and continue. As you make your final approach, stop frequently to adjust R6 and take new bearings. At very close range, remove the RDF antenna altogether and replace it with a short piece of wire. It's a good idea to make up a short length of wire attached to a BNC fitting in advance, so you do not damage J1 by sticking random pieces of wire into the center contact.

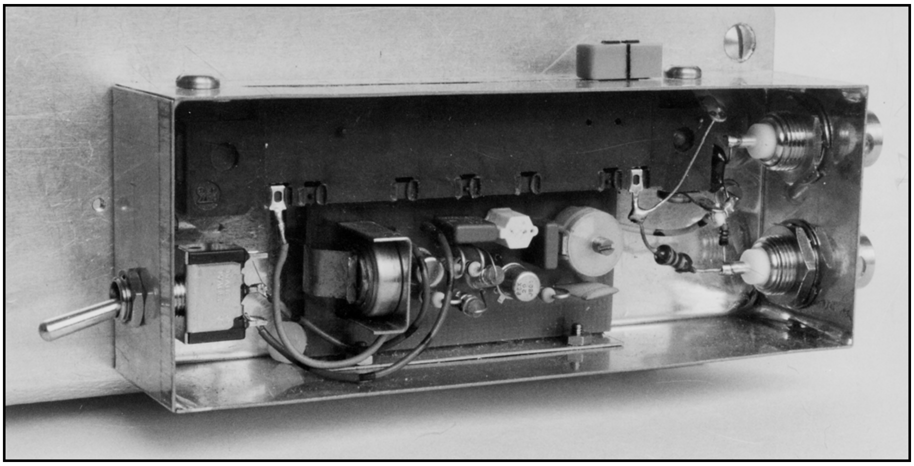


Fig 23.100—Interior view of the active attenuator. Note that C7, D1 and L2 are mounted between the BNC connectors. R5 (not visible in this photograph) is connected to the wiper of slide pot R6.

While it is most convenient to use this system with receivers having S-meters, the meter is not indispensable. The active attenuator will reduce signal level to a point where receiver noise becomes audible. You can then obtain accurate fixes with null-seeking antennas or the “body fade” technique by simply listening for maximum noise at the null.

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