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July 1996

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By Darrel Emerson, AA7FV, G3SYS

The Radio Sky

This article concludes Darrel Emerson's discussion of background noise that began last month in *QST*. As he continues, Darrel refers to Figures 1 through 3. Those figures and Notes 1 through 11 appear in that article.—*Ed.*

Part 2 concludes this series by discussing antenna headings for celestial noise sources; sky-noise variation with frequency; solar and terrestrial noise. Combine these topics to map sky noise at *your* location and apply the results.

Converting Between Sky-Coordinate Systems

Figures 1 and 2 show the distribution of sky background radiation on the RA, dec coordinate system.[12] To estimate the effect on a given communication link, it is usually more convenient to use an azimuth-elevation (az-el) coordinate system at the station. Figure 4 shows the 20° beamwidth data from Figure 2C, plotted at two-hour intervals throughout the day for a station at 40° N latitude. (For beamwidths likely with most amateur antennas, the plots are accurate enough for any latitude within the continental US.) It's easy to compare features on Figures 2C and 4 because the two maps use the same contour levels.

Figure 4 shows plots for one day of *local sidereal time* (LST) at two-hour intervals. Figure 5 shows the mean sidereal time at the Greenwich meridian (GMST) at 0000 hours UTC for each day of the year. (This chart is accurate to within a few minutes for any year.) To find your current approximate LST, use LST ≈ GMST (0000h) + UTC + (longitude/15), where west longitudes are negative. For example, let's calculate the LST for 1500h EDT on June 1 at Newington (72° 45' W). The GMST at 0000h UTC from Figure 5 for June 1 is 1640h. Then add the current UTC (1500 + 0400 = 1900 UTC) in hours to this GMST, and further add (longitude/15 = –72.75/15 = –4.85) hours, where the longitude is that for your location, measured in degrees, with west longitude having negative values. This gives 16.7 + 19.0 + (–4.85) = 30.85 or 3051h. Since this is greater than 2400h, we must subtract 24 hours, to get 0651h LST. Once you have calculated *your* LST, the plot from Figure 4 that is closest to your LST approximates the radio sky above your head. If you want to convert RA, dec coordinates more precisely, get the "Sky Noise" information package from ARRL Headquarters.[13] Two simple BASIC programs are available as well. One program converts between RA, dec and az-el coordinates; the other collects sky-map data from an ICOM R-7100 interfaced to a PC. (See Note 13.)

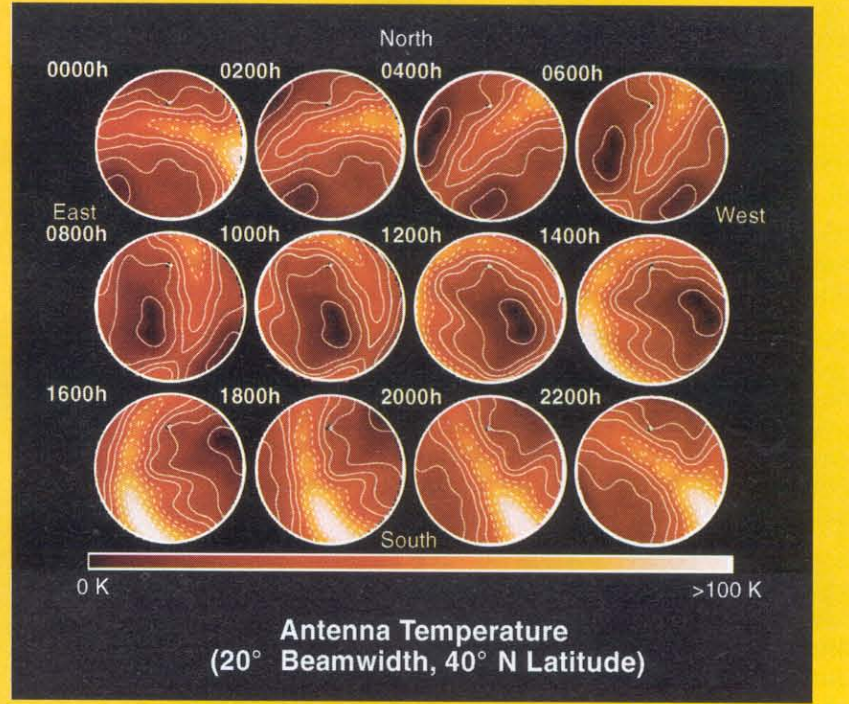

Figure 4—Contours overlaid on false-color plots of the radio sky at 432 MHz for two-hour intervals throughout the local sidereal day. The data from Figure 2C (contours for 15, 20, 25, 30, 40, 50, 75, 100, 125K) have been translated into az-el coordinates, and plotted with the zenith in the center and the horizon around the perimeter of each plot. This gives a fisheye view of the radio sky, as would be seen with radio eyes, lying on your back, with your feet to the south. As in Figure 2, contours for 40 K and greater are dashed. Times are in LST. It's easy to see the galactic plane rotating. At 1400h LST, the galactic plane lies all along the eastern horizon. Reception of terrestrial signals from these directions will be very noisy around 1400h LST. Just before 1800h LST, the bright galactic nucleus reaches its highest elevation, in the south.

Variation with Frequency

The radiation shown in Figures 1 and 2 is very broadband, but its absolute intensity changes gradually with frequency. Every time the frequency is doubled, the sky temperature of the galactic background decreases by a factor ~5 to 7; this factor changes slightly with frequency, too.[14] Figure 6 shows the maximum and minimum antenna temperatures expected with antenna beamwidths of 1°, 5°, 20° and 40°, from 28 MHz up to 2.4 GHz. I derived these temperatures from the smoothed intensities of Figure 2 and then scaled them according to frequency, using factors from the astronomical literature. (See notes 7 and 8 in Part 1.)

Emissions from the Milky Way dominate the radio sky up to UHF, but the 2.7 K cosmic background radiation becomes important above ~600 MHz. Penzias and Wilson received a Nobel prize for discovering this noise in 1965, at 4 GHz. Astrono-

[12]Notes appear on page 31.

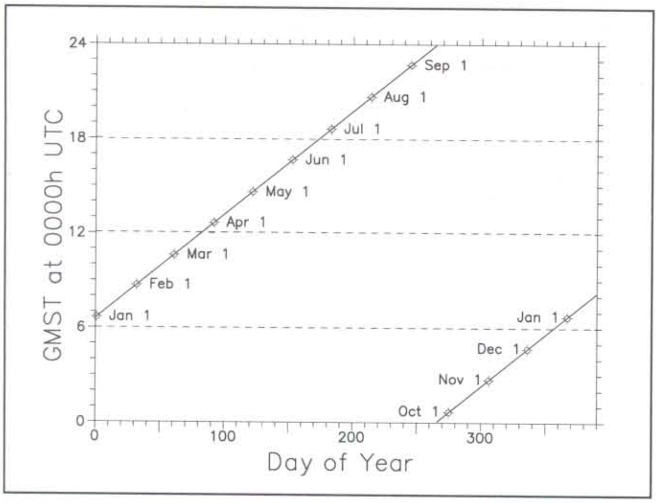

Figure 5—LST: the graph shows GMST, the sidereal time at Greenwich (longitude 0°) at 0000h UTC for every day of the year. Although calculated for 1996, the plot is correct to within a few minutes for any year. The text tells how to find your approximate LST.

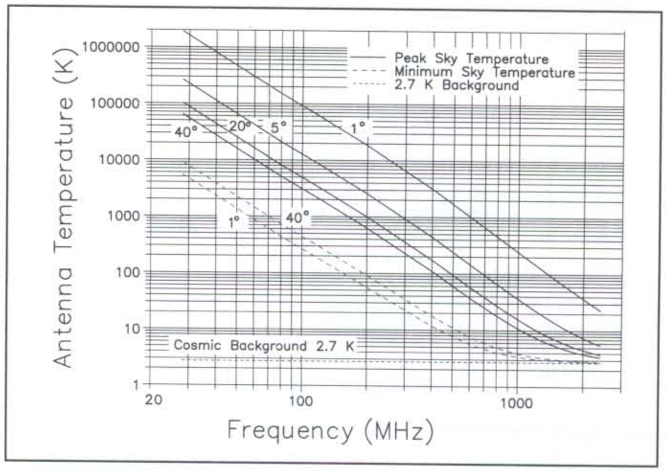

Figure 6—The maximum and minimum sky temperatures for antenna beamwidths of 1°, 5°, 20° and 40°, at frequencies from 28 MHz to 2.4 GHz. Note the logarithmic axes; the peak temperature ranges from about 1,000,000 K at ~30 MHz to only a few kelvins at 2 GHz. Except for the 1° beamwidth, the brightest emission is always the galactic center. Even with the relatively broad 40° beamwidth, there is still a ratio of 6:1 or 7:1 between the maximum and minimum antenna temperatures over most of this frequency range. At about 1 GHz and above, the 2.7 K cosmic background radiation dominates the lowest sky temperature. This plot does not include additional noise from terrestrial sources: atmosphere, ionosphere or ground.

mers consider it to be the cooling relict of the Big Bang. At the 13-cm amateur band and at shorter wavelengths, this cosmic background radiation swamps emission from the Milky Way—at least with common amateur antenna beamwidths. The Sky Noise package (see Note 13) tells how radio-sky intensities were scaled to different frequencies, both to derive expected intensities at 432 MHz (Figures 2 to 4) from the measurements of 408 MHz, and to produce the data plotted in Figure 6. Note that above about 1 GHz, noise from the atmosphere can also begin to become important. It can give a few kelvins of additional noise beyond that plotted in Figure 6.

Solar Radiation

The distribution of emission discussed so far has not included our Sun, often the brightest object in the radio sky. The Sun moves about a degree per day with respect to the sky background, and the strength of solar radiation varies greatly at radio wavelengths.

Figure 7 shows the antenna temperature expected from the Sun (see Note 15) over a wide range of frequencies, for an antenna gain of 10 dBi, such as a typical five-element Yagi. The antenna temperatures are proportional to antenna gain. For an antenna gain of 16 dBi (an increase of 6 dB), the solar signal would be four times greater than that shown in Figure 7.

The two lower solid lines show the range of signal expected from the quiet Sun at different phases of the sunspot cycle, including a component for the slowly varying emission. The upper dashed line shows the amplitude of a typical outburst; at 50 MHz this can be more than 1000 times more intense than the normal solar radiation. A five-element Yagi—or even a single dipole—would easily detect it. A comparison of the solid lines in Figure 7 with Figure 6, however, shows that—with the modest 10 dBi of antenna gain—the radiation from the *quiet* Sun at 50 MHz could be difficult to distinguish from the general galactic radiation.

The radio emission from the Sun can be useful for a rough check that a receiving system is operating correctly.[16,17] The emission can be so variable, however (on time scales ranging from seconds to years), that it is of limited use for absolute calibration of antennas or receivers.

Noise from the Atmosphere

Even at frequencies below 1 GHz, the Earth's atmosphere gives slight attenuation to radio waves. The loss of signal is usually insignificant at these frequencies, but the extra noise radiated from the atmosphere as a result of the attenuation can be very significant.

The source in Note 18 gives the extra antenna temperature expected from oxygen and water vapor in the atmosphere. At the zenith (minimum path length through the atmosphere) the extra noise is ~1.2 K at 500 MHz and ~2.4 K at 2.4 GHz. This noise comes almost entirely from oxygen rather than water vapor, so it is fairly independent of local weather conditions. Extra noise and attenuation from atmospheric water vapor becomes important at even higher frequencies.

The extra noise is approximately proportional to the path length through the atmosphere, and above a few degrees of elevation, the path length is proportional to 1/sin(elevation). Operators must consider the curvature of the Earth at very low elevation angles (see Note 18), but that is beyond the scope of this article. At 30° elevation the atmospheric noise is twice that at the zenith, becoming ~2.4 K and ~4.8 K at 500 MHz and 2.4 GHz, respectively. At 5° elevation the contributions become ~13.5 K and ~25 K.

Atmospheric noise increases quite sharply at even lower elevations, simply because of the extra path length through the atmosphere. The extra noise experienced in practice will be an average of the noise from the range of elevation angles accepted by the antenna. Narrow beams pointing at the horizon see only very long paths through the atmosphere and so collect more atmospheric noise than wider beams. Hence, the S/N improvement for larger antennas (narrower beamwidths) pointing at the horizon can be somewhat less than expected.

Ground Radiation

The Earth's surface effectively glows at radio wavelengths, giving off "black body" radiation corresponding, for 100% absorbing ground, to the local ground temperature in kelvins (~290 K, about 17°C or 63°F). For an antenna pointed at the horizon, half of the main and side lobes will pick up ground radiation, adding ~145 K to the system noise. Thus, the noise temperature for a station might be 35 K (0.5-dB noise figure), yet it would become *at least* 180 K (145 K + 35 K) for terrestrial communications. Any radiation from the Milky Way, the Sun or the Earth's atmosphere will further increase the noise temperature. The system noise decreases when you point the antenna upward, toward your favorite satellite, but many of the side lobes may include ground. Remember, it's not just the

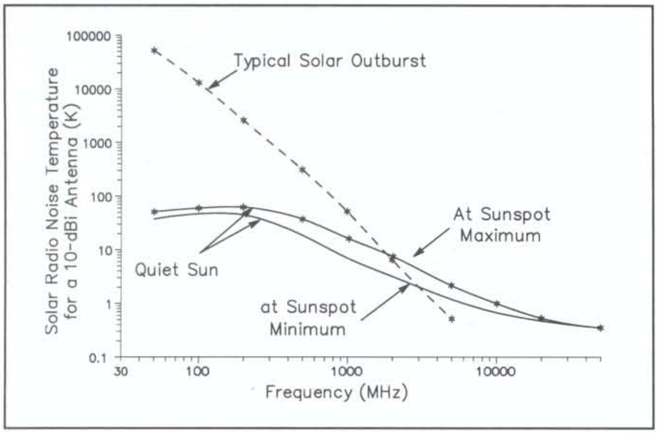

Figure 7—The range of antenna temperatures expected from the Sun, as a function of frequency, using a 10-dBi-gain antenna (derived from the source in Note 15). The lower solid line shows the emission of the quiet Sun at sunspot minimum. The upper solid line shows the quiet Sun near sunspot maximum, including the slowly varying emission and assuming a sunspot number, R, of ~100. The upper, dashed line shows the strength of a typical outburst.

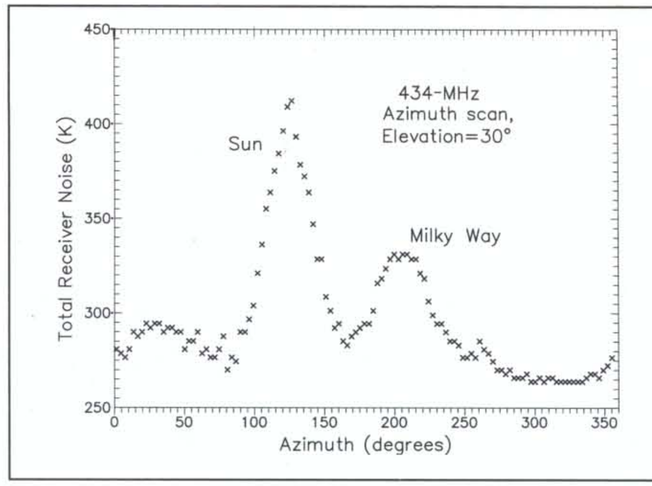

Figure 9—A one-minute record of the receiver AGC response, at 434 MHz, as the antenna rotates 360° in azimuth at 30° elevation. Note the increases in noise temperature as the antenna crosses the Sun at azimuth ~126°, then the galactic plane at azimuth ~205°.

peak side lobe that counts, but the total energy received in *all* sidelobes. The brightness levels plotted in Figure 2 show that ground radiation is likely to be much more serious than the celestial background emission at 430 MHz and higher frequencies, except when the antenna is pointing toward the Sun or at our galactic nucleus, Sagittarius A.

Figure 6 shows that at wavelengths of 2 meters and greater most of the background sky has a radio temperature much higher than that of the ground. At these lower frequencies, the ground looks cold in comparison to the sky; the Earth shields the antenna from some of the noisy sky radiation.

The ground radiation in Figure 8 very clearly dominates the 434-MHz measurements of the sky made at AA7FV. We'll discuss this more later.

How Relevant is All This to the Average Radio Amateur?

Lest it be thought that all this is only important to the EME operators with huge antennas and the very ultimate in receiving equipment, Figures 8 and 9 show results obtained at AA7FV with what would be considered a rather poor amateur 70-cm receiving setup.

The antenna is an eight-element Yagi for 70 cm, barely five feet long. Its specified gain is 14.6 dBi, and 30 feet of coax connect it to a preamp in the shack. The digitized AGC voltage of the receiver, an ICOM R-7100, is available at its standard CI-V interface. A PC recorded the receiver AGC level continuously (~27 samples per second), while the antenna was slewed across the sky. It takes about one minute to slew my antenna through 360° in azimuth; I collected data at 10° elevation intervals from 0 to 90°. It took 10 minutes to make a complete map of the visible sky. The receiver bandwidth was about 200 kHz.

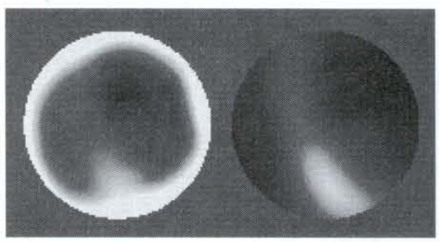

Figure 8—The left image is a gray-scale display of total system noise for the entire visible sky at about 1800h LST from AA7FV (latitude 32.33° N), observed with an eight-element Yagi antenna at 434 MHz. The image orientation is like that of Figure 4. The right image is a simulation based on the 408-MHz data from Figure 1. (See text.)

I carefully calibrated the digitized AGC level from the R-7100, so that the PC logging program could convert the AGC values into receive-system noise level in kelvins. The total receiver noise includes preamp noise, cable and other losses, added to all the ground, atmospheric and celestial radiation entering the antenna beam and its sidelobes. The PC later interpolates the recorded data to a regular az-el grid.

The AGC values are rather coarsely digitized, with about 21 units for a 10-dB change in receiver noise. Fortunately, receiver noise contributes a certain amount of "dithering," to produce a much finer resolution of very small changes in the total receiver noise level.

The most difficult problem was overcoming man-made noise. At 70 cm, the worst interference encountered was from my own data-logging PC. It was helpful to use the slowest PC available (a 12-MHz 286 laptop) with all computer cables filtered, and with the PC inside a screened enclosure. Even with these precautions, some radiation from the PC and other terrestrial interference was detectable in the strongest sidelobes of the antenna, but at a level several decibels below the average sky background noise. The observation centers on 434 MHz, which had, on average, the lowest level of terrestrial interference at AA7FV.

Figure 8 (left) shows the radiation from the entire visible sky mapped by my antenna at 434 MHz in July 1995. Its presentation is similar to that of Figure 4. The ground radiation is very obvious as the bright rim around the perimeter of the radio photo. Towards the south, however, you can see clearly the radiation from the Milky Way peaking toward the center of our galaxy, a few degrees above my horizon. I made this map at about 18 hours LST, which occurred then just before local midnight; obviously the Sun is not visible in the data.

Figure 8 (right) shows a simulation of what the sky should look like at 434 MHz from Tucson then, but it does not include ground radiation. I smoothed the data from Figure 1 to a 30° beamwidth, matching my own antenna. I plotted the data as for the left image, adjusted for the same time of day and year. Apart from the very strong ground radiation at low elevations in my measurements, the two pictures agree surprisingly well.

Figure 9 shows the variation in noise power from the receiver recorded on February 26, 1995, at about 9:40 MST, when the local Sun elevation was about 31.2°. The antenna was scanned in azimuth, at a fixed 30° elevation. Even with this poor receiving station, the increase in noise temperature from both the Sun and the galaxy is very obvious. The direction of the noise peaks changed with time, at the expected rate of 15° per hour, corresponding to the rotation of the Earth. (Terrestrial interference would have remained fixed in direction.) The antenna beamwidth, measured from the width of the peak in Figure 9 as the beam passes over the Sun, is about 30°.

The ground radiation has different intensities in different horizontal directions. The direction of the strongest ground noise corresponds exactly with the highest mountain peak visible from my location: to the northeast, up to about 15° elevation. Closer local obstacles, such as a neighbor's tree, appear as thermal noise at 434 MHz. For terrestrial VHF and UHF communications, I have an exceptionally poor location.

Conclusions

We can quite easily detect the complex radio sky background—even with very simple communications equipment. Although only relatively large antennas can detect discrete celestial sources, the extended radio emission from our own galaxy can be measured even with a tiny antenna. At least up to ~430 MHz, the sky background noise may set the limiting sensitivity of either terrestrial or space communications links, with large or small antennas and even with relatively poor receivers. For the best sensitivity in receiving space communications at 430 MHz and above, the average side lobe level of an antenna may be a much more important parameter than its forward gain.

Even relatively primitive equipment can map the sky background. I made Figure 8 by scanning the sky at 434 MHz with a single eight-element Yagi, only five feet long. The figure clearly shows the relatively bright galactic nucleus in the south, with the Milky Way extending across the sky to the northeast. A larger antenna would show more detail and be less susceptible to ground radiation at low elevation angles, but it would be—on average—just as susceptible to S/N degradation from the noise of the sky background.

Acknowledgments

I want to thank Dr. Chris Salter from the Arecibo Observatory for many enlightening discussions, and for help in defining the spectral index of the galactic background radiation.

Notes

[12]Darrel Emerson, AA7FV, "The Radio Sky," *QST*, June 1996, pp 32-35.

[13]Contact the Technical Department Secretary at ARRL Headquarters (by any means described on page 10 of this issue) and ask for the Sky Noise package from June 1996 *QST*. The package contains coordinate-conversion equations, additional information that relates sky noise temperature to frequency, coordinate-conversion and ICOM R-7100 interface program listings and a diagram of the author's home sky mapping station. ARRL members send $2 (nonmembers, $4) for shipping and handling. Coordinate-conversion and R-7100-control programs are available electronically from the ARRL "Hiram" BBS (tel 860-594-0306), or the ARRL Internet ftp site: **oak.oakland.edu** (in the **pub/hamradio/arrl/qst-binaries** directory). In either case, look for RADIOSKY.ZIP.

[14]Scientists use the symbol "~" as shorthand for "on the order of."

[15]C. W. Allen, *Astrophysical Quantities* (New York: Oxford University Press, Inc), Third Edition, 1976 (reprinted 1991), pp 192-193.

[16]Bob Atkins, KA1GT, "Noise Temperature, Antenna Temperature and Sun Noise," *The ARRL UHF/Microwave Experimenter's Manual* (Newington: ARRL, 1990; Order no. 3126) pp 7-58 and 7-59; see the ARRL *Publications Catalog* elsewhere in this issue.

[17]David B. Shaffer, W8MIF, "Microwave System Calibration using the Sun and Moon," *The ARRL UHF/Microwave Experimenter's Manual* (Newington: ARRL, 1990; Order no. 3126) pp 7-60 and 7-61; see the ARRL *Publications Catalog* elsewhere in this issue.

[18]D. C. Hogg, "Effective Antenna Temperatures Due to Oxygen and Water Vapor in the Atmosphere," *Journal of Applied Physics*, Vol 30, November 1959, p 1417.

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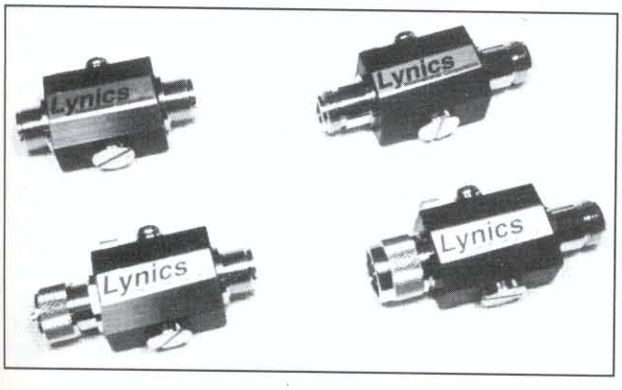

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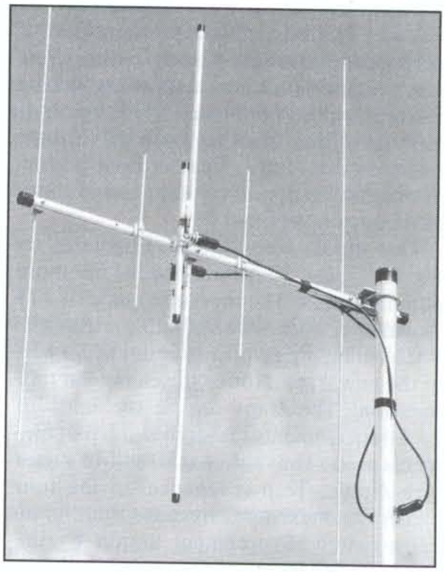

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