The Radio Sky

Sky radiation may limit the performance of your station. Part 1 of this two-part article explains global measurements and how much sky noise to expect at your station.

By Darrel Emerson, AA7FV, G3SYS

From the early 1930s, we have known that broadband radio radiation from the Milky Way may be a limiting factor in the signal-to-noise ratio (S/N) attainable on communications links, both terrestrially and in space. Relatively recent radio-astronomical measurements of the entire sky have characterized this radiation more precisely, and in greater detail than had been available before. Recent data presented here allow you to estimate easily the likely impact on a given communication link. I'll also show the influences of frequency, antenna beamwidths, time of day and season. Although moon-bounce operators, with their sensitive receivers and high-gain antennas, are well aware of the importance of this background radiation, it can also be important for terrestrial communication using today's average receiver sensitivity and even with very small antennas. Simple equipment can map the sky background; in **Part 2** we'll compare measurements made with my very simple receiving system to the standard database.

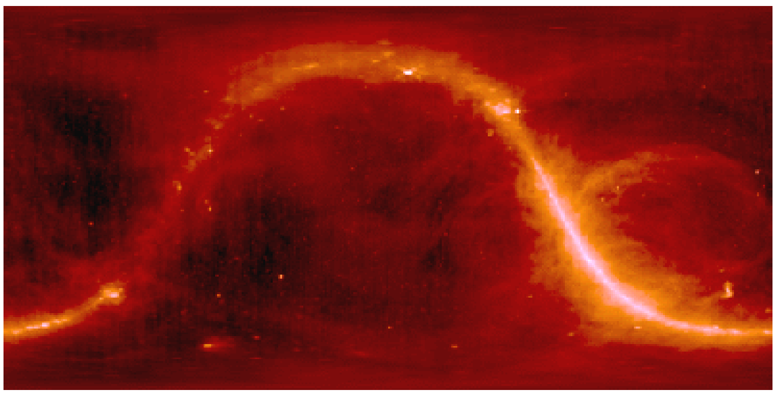


Figure 1—A false-color image of the entire radio sky, observed at 408 MHz; this image is available on the World Wide Web.[6] The coordinate system is RA,dec, with RA = 0 h, dec = 0° at the exact center of the picture. The angular resolution of this image is 0.85°. Strong emission from the plane of our galaxy (the Milky Way) is clear; the galactic nucleus, Sagittarius A, is at lower right in this image. Two strong discrete sources, Cassiopeia A and Cygnus A, appear as white dots near the top of the picture, just to the right of center. Note that, although strong emission occurs close to the galactic plane, there is measurable radio emission over the entire sky.

The Background Radiation

Karl Jansky was the first to discover the extraterrestrial nature of the background sky noise. [1] In a project funded by Bell Laboratories to investigate the limiting S/N of shortwave transatlantic telephone circuits, Jansky constructed a rotatable Bruce-array beam antenna for 20.5 MHz and showed that background radio noise peaked in the direction of the Milky Way's center. A good description of the discovery is available, and a recent analysis of Jansky's chart recordings shows how well his early results correspond with more recent observations. [2] [3] A brief summary of radio astronomy appears in *QST's* July 1995 issue. [4]

Since Jansky's 20.5-MHz observations, there have been many surveys of the galactic background radiation, at frequencies from a few megahertz to several gigahertz. Very few of these surveys are complete, in that they may have included observations from either the Northern or the Southern Hemisphere, but not both. Others were created as a composite picture combined from observations at different frequencies and with different telescopes, with assumptions about how the radiation changes with frequency. Some surveys have been confined to the galactic plane. Others have been very sensitive to discrete background sources but ignored the large-scale distribution of emission. Nevertheless, the general features of the radio background and how those features vary with frequency have become well established.

In 1981, a new and complete survey of the entire radio sky was published. [5] This was the result of some painstaking work carried out over a decade by a group of radio astronomers who used the world's biggest fully steerable radio telescopes—the Jodrell

Bank 76-meter antenna in the UK, the Effelsberg 100-meter antenna in Germany, and the Parkes 64-meter antenna in Australia—to make a carefully calibrated survey of sky emission at 408 MHz, covering both Northern and Southern Hemispheres. These observations have become the definitive survey of the extended, broadband radio-sky background emission at this wavelength, a standard database to which other researchers refer. The data are now in the public domain and available to anyone with access to the World Wide Web. [6] As well as being probably the most precise data available, the survey frequency of 408 MHz is especially convenient for radio amateurs; it allows a good estimate of what to expect in the neighboring amateur bands. The radiation detected is very broadband; its intensity decreases with increasing frequency, but the general picture changes remarkably little from a few megahertz up to many gigahertz. Sironi and Webster have made measurements of the background using scaled antennas at a variety of frequencies; they discuss how the emission changes in intensity and distribution, compared with 408 MHz, at frequencies from 17.5 MHz to 1407 MHz. [7] [8] The changes are relatively subtle, however, and it is safe for the average radio amateur to assume the general distribution of emission remains much the same at all these frequencies, and that we can derive the intensity at any chosen frequency from the 408-MHz emission by means of a suitable scaling factor. One important exception is the 21-cm emission from galactic atomic hydrogen close to 1420.4 MHz, which is generally much brighter than the extended broadband emission at that frequency; we consider only the broadband radiation in this article.

I downloaded the lead photo for this article (**Figure 1**) over the World Wide Web. It shows a false-color image of the entire sky at 408 MHz, as observed with a telescope beamwidth of 0.85°. Over the many years it took to accumulate the data, the observers were careful to avoid contamination of the background emission by solar or planetary emissions. Apart from that, this image shows the whole universe! Most of the emission comes from synchrotron emission, or high-energy electrons spiraling in magnetic fields between the stars in our own galaxy, but these measurements include *all* radio sources in the universe beyond the solar system and visible from the Earth. This image uses the right-ascension, declination (RA,dec) coordinate scheme. RA is a measure of celestial longitude, and dec of latitude. Part 2 of this article and the “Sky Noise” information package from ARRL Headquarters describe conversion between these coordinates and azimuth and elevation at your location. [9] RA is measured in hours. The Local Sidereal Time (LST) at which a source crosses the meridian and reaches its highest point in the sky, corresponds to the RA of that source. The meridian is the line running from north to south, passing directly overhead through the zenith. Note that RA increases from right to left in the image. The dec is simply the angle of the source north of the plane of the Earth’s equator. The bright S-curve of emission extending across the picture is the emission from the plane of our Milky Way. The strongest part of the curve, in the lower right, comes from the center of our own galaxy.

Figure 1 demonstrates a very important feature of the background radiation; as well as very small-scale features and discrete radio sources—that is, sources much smaller than the antenna beamwidth—there is emission along, and even well away from, the galactic plane. A relatively large antenna may be required to detect the discrete sources, but the extended emission can fill the beam of even very small antennas. You do not need a big antenna to detect, and be limited by, the radio noise from the Milky Way. The noise picked up from this celestial emission adds directly to your receiver noise.

Sky Intensities

We usually express the intensity of extended radio emission from the sky in terms of a *brightness temperature*. When the radio power received by the antenna is equal to the thermal noise power available from a resistor at temperature **T** kelvins, we say the *antenna temperature* is **T** kelvins, and—neglecting losses—the observed sky brightness is also **T** kelvins. The actual power received, **P** (in watts), can be calculated from

$$P = k \times T \times B$$

where **k** is Boltzmann’s constant: $k = 1.38 \times 10^{-23}$ joules per kelvin and **B** is the bandwidth in hertz.

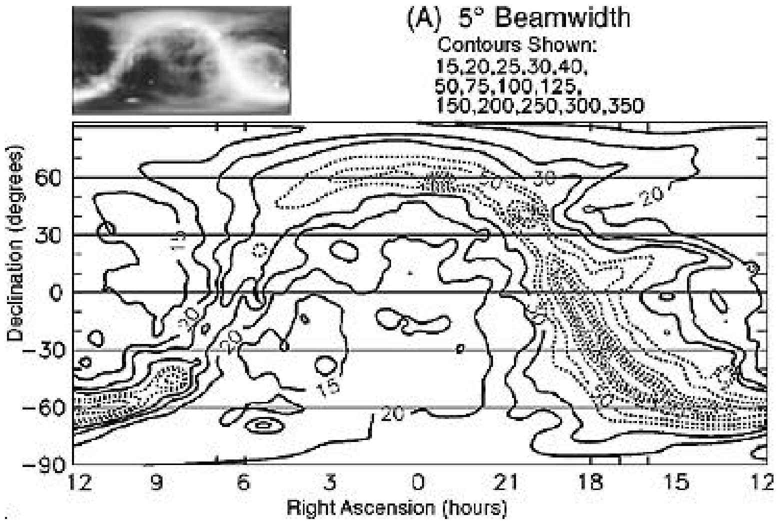
In practice, the antenna temperature observed from the sky depends not only on the background sky temperature, but also on the antenna beamwidth. The background power collected by the antenna is a weighted average of all emissions within its main lobe and all sidelobes.

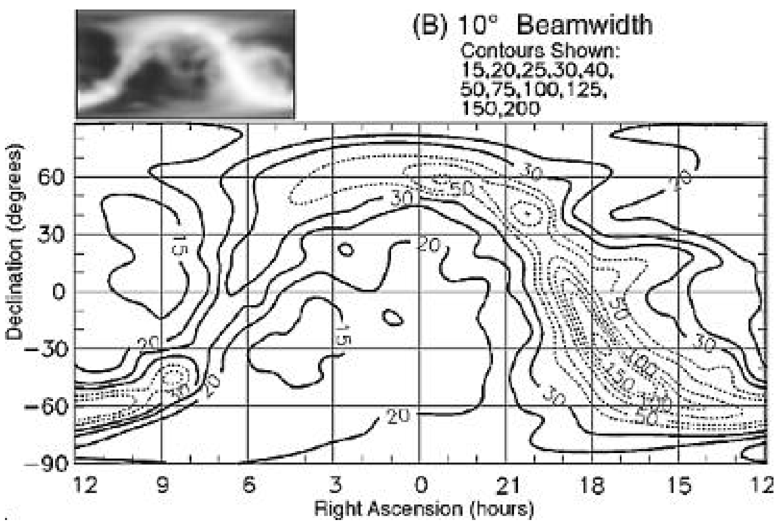
As an example, with an antenna pointing at the ground, which we assume to be totally absorbing and at 290 K (17°C or 63°F), the total power received in a bandwidth of 3 kHz would be:

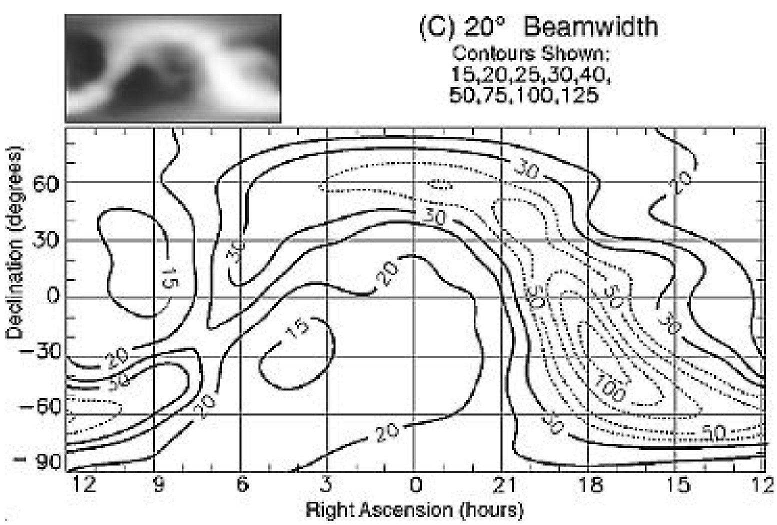
$$P = k \times T \times B = 1.38 \times 10^{-23} \times 290 \times 3000 = 12 \times 10^{-18} \text{ W (or } -139.2 \text{ dBm)}$$

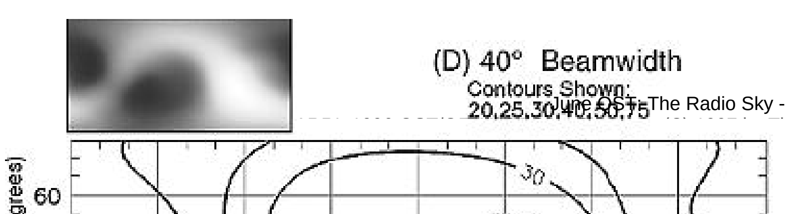
With today’s sensitive receivers, this noise power is likely to be much greater than the internal noise generated by the receiver.

If we point the same antenna exactly at the horizon, then half its beamwidth would see “hot” ground and the other half would see the sky. This would reduce the antenna component of noise power from the ground radiation by one-half.









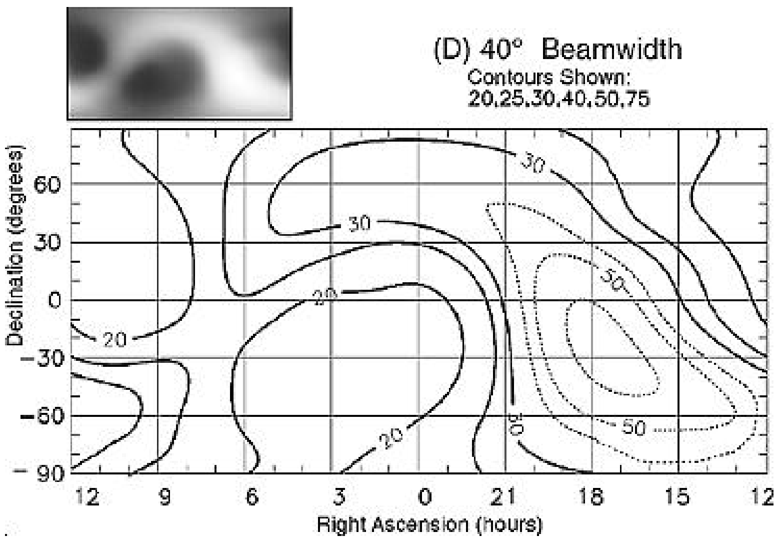


Figure 2—Gray-scale images and contour plots show the expected sky brightness temperature at 432 MHz, for beamwidths from 5 to 40°. Contours of 40 K and greater are drawn as dashed lines. Contours show the level of sky noise collected by an antenna pointing in any specific direction. As with Figure 1, the coordinates are RA,dec (epoch B1950), with RA = 0 h, dec = 0° at the center. Sagittarius A, the galactic nucleus at RA = 17.8 h, dec = –28.9° (epoch J2000), is the strongest source of emission in each plot.

The Effect of Antenna Beamwidth

Figure 1 shows some very extended features that spread over tens of degrees, as well as several discrete sources that are much smaller than the 0.85° antenna beam. If we point a large-beamwidth antenna toward very extended features, the observed antenna temperature nearly equals the true background sky temperature in that direction, if that sky emission nearly fills the antenna's main beam. If we point the same antenna toward a discrete source, however, the source temperature averaged over the broad antenna beam is substantially reduced—by a factor proportional to the area of the antenna beam compared with the area of the source. This beam-averaging effect makes an important difference in observed antenna temperatures. This has been simulated, using a computer program to smooth the data shown in **Figure 1**, to show what might be seen with relatively small antennas.

Figure 2 shows how the sky background appears to antennas with beamwidths of 5, 10, 20 and 40°, representative of what might be seen by amateur antenna systems operating at wavelengths from a few centimeters to a few meters. We can use the contours of **Figure 2** fairly precisely to estimate the antenna temperature at 432 MHz in any chosen direction. The gray-scale images give an overall impression of how the emission varies over the sky. Each image depicts the entire sky—in an RA,dec coordinate system—as in **Figure 1**. Even the 40° beamwidth clearly shows the emission from the Milky Way. The strongest emission peaks in the direction of Sagittarius A, toward the center of our galaxy; this is at 17.8 hours RA and –28.9° dec.

With a 10° or smaller beam, you can see some of the stronger discrete sources, such as Cygnus A at RA 20.0 h, dec 40.7°, and Cassiopeia A at 23.4 h, 58.8° (J2000). [10] With a 0.85° beam (**Figure 1**), the peak antenna temperature in the direction of Cassiopeia A, corrected to 432 MHz, is 3900 K. Averaged over a 10° beamwidth (**Figure 2B**) the brightness in that direction is reduced to 80 K, but some 50 K of that comes from the extended galactic plane, rather than Cassiopeia A itself. The true angular size of this source is about 0.1°, much less than even the 0.85° beam of **Figure 1**. Averaging over a 10° beamwidth, instead of the 0.85° beamwidth, dilutes the intense emission from this small radio source by a factor of ~140. [11] The very extended emission from the galactic plane, on the other hand, can fill much of a 10° beamwidth. So, the beam-averaging effect on the general galactic background, although still present, is much less pronounced. **Figure 3** shows the maximum and minimum antenna temperatures that we would observe from the sky at 432 MHz with beamwidths from 1 to 40°.

Note that if you want to receive radio signals from a satellite that happens to be in the direction of a radio-bright part of the sky, a larger antenna may not help. For example, at 432 MHz, a 16-foot dish would have a beamwidth of about 10°. From **Figure 2B**, the antenna temperature measured with this antenna in the direction of the galactic center would be ~220 K. An antenna with a 40° beamwidth—eg, a small Yagi or a four-foot dish—would only give an antenna temperature in this direction (from **Figure 2D**) of ~90 K. With a sensitive preamp and even with this 40° beam, the sky noise should exceed receiver noise in the direction of the galactic center. The antenna noise has decreased by 4 dB with the smaller antenna. Now an antenna with a 10° beam should have 12.0 dB more gain than a 40° antenna. Neglecting the contribution from receiver and other sources of noise, however, the improvement in S/N with the larger antenna would only be about 8 dB (12 – 4). Allowing for receiver noise, the additional degradation will not be quite so dramatic in practice, but it will probably still be significant. EME operators are fortunate; the Moon never passes in front of the galactic center. It can come within 10°, however, so considerations like these are not entirely academic.

Although you may not always obtain quite the S/N improvement that you had expected in some directions with a larger antenna, this is more than offset by those times you gain *more* than you expected. From **Figure 2**, an antenna with a 10° beamwidth pointed at the wing of the galactic center (about 20° from the galactic plane), will receive about 30 K of antenna noise. A 40° beamwidth will collect about 50 K—~2.4 dB more. Again ignoring receiver noise, the 16-foot dish will potentially improve S/N in this direction by about 14.4 dB (12.0 + 2.4), rather than just the 12.0 dB expected from antenna gain alone. In this example, the high background noise in the direction of the galactic plane has entered into the 40° beam and its sidelobes, to make the S/N somewhat worse than expected. In practice, the precise degradation depends on the details of the sidelobes of the two antennas being compared, and on the exact importance of the receiver and other noise sources.

The situation is a little complicated. When estimating achievable S/N on a weak-signal satellite link or for EME operation, consider the detailed structure of the background radiation, and its relation to antenna beam-width and sidelobes. **Figure 3** shows the sky background at 432 MHz with beamwidths from 5 to 40° (roughly, effective antenna diameters from ~14 to ~1.7 wavelengths). Part 2 of this article describes how sky background noise varies with time of day and frequency.

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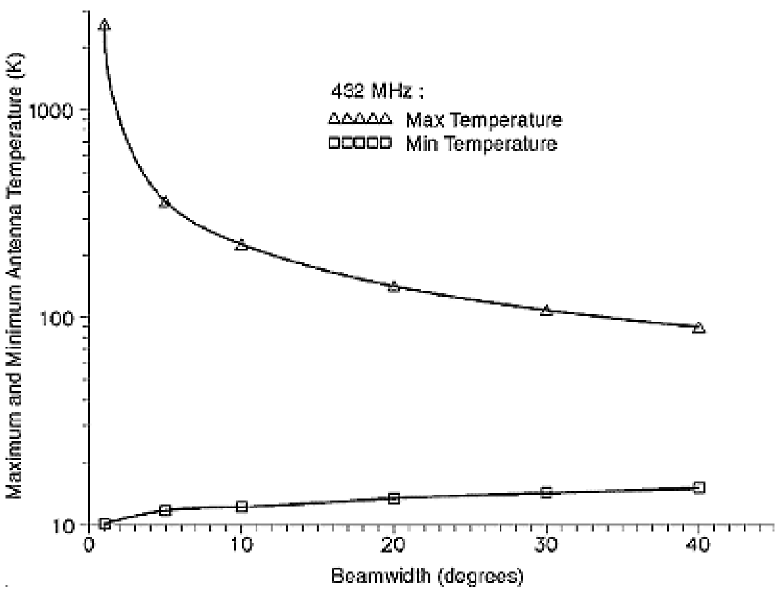

Figure 3—The effect of antenna beamwidth on the expected antenna temperatures, that we might observe at 432 MHz. Note the logarithmic intensity scale. While the minimum sky temperature changes relatively little, from 15 K with a 40° beam down to 10 K with a 1° beam, the peak temperatures vary from ~90 K (40° beam) up to ~2500 K (1° beam). For all but the smallest beam size, the galactic nucleus gives the highest antenna temperature. With an angular resolution of 1° or better, the discrete source Cassiopeia A becomes the brightest point in the radio sky at this wavelength.

Notes

[1]Karl G. Jansky, "Directional Studies of Atmospherics at High Frequencies," *Proceedings of the Institute of Radio Engineers*, Vol 20, 1932, pp 1920-1932.

[2]Woodruff T. Sullivan III, "Karl Jansky and the Discovery of Extraterrestrial Radio Waves," *The Early Years of Radio Astronomy* (Cambridge University Press), 1984, p 3.

[3]Woodruff T. Sullivan III, "A New Look at Karl Jansky's Original Data," *Sky and Telescope*, no. 56, 1978, pp 101-105.

[4]Robert Welsh, N3RW, "Radio Astronomy and the Radio Amateur" *QST,* Jul 1995, pp 46-48.

[5]C. G. T. Haslam, U. Klein, C. J. Salter, H. Stoffel, W. E. Wilson, M. N. Cleary, D. J. Cooke and P. Thomasson, "A 408 MHz All-sky Continuum Survey," *Astronomy and Astrophysics,* Vol 100, 1981, p 209.

[6]World Wide Web site: **http://skview.gsfc.nasa.gov/cgi-bin/skvbasic.** You can download the astronomical data as a GIF file, or as a FITS-format data set. Many different astronomical databases are available from this site.

[7]G. Sironi, "The Spectrum of the Galactic Nonthermal Background Radiation—I," *Monthly Notices of the Royal Astronomical Society,* Vol 166, 1974, p 345.

[8]A. S. Webster, "The Spectrum of the Galactic Nonthermal Background Radiation—II," *Monthly Notices of the Royal Astronomical Society,* Vol 166, 1974, p 355.

[9]Contact the Technical Secretary at ARRL Headquarters (by any means described on **page 10** of this issue) and request the June 1996 *QST* Sky Noise template. ARRL members send $2 (nonmembers, $4) for shipping and handling.

[10]Parenthetical references such as B1950 and J2000 define the astronomical epoch of the associated coordinates. The epochs are needed for precise telescope positioning, but are insignificant for Amateur Radio work.

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