ESTIMATING HARMFUL LEVELS OF RADIO-FREQUENCY RADIATION

PATRICK C. CRANE
National Radio Astronomy Observatory[1]

LYNNE A. HILLENBRAND
National Radio Astronomy Observatory and Princeton University

I. INTRODUCTION

Determining whether a particular radio transmitter will produce harmful levels of radio-frequency radiation at a location of interest (the "receiver," be it a nearby home or a distant radio telescope), has two steps. The first is to determine which standard for harm applies: Section II reviews those for human exposure, for interference with electronic devices, for interference with optical and infrared astronomy, and for interference with radio astronomy.

The second step is to estimate the propagation losses between the transmitter and the "receiver." Many factors, several highly time variable, contribute to such losses - including atmospheric refraction, diffraction by obstacles, tropospheric scattering, and atmospheric absorption - and are discussed in Section III.

Models and algorithms, often highly idealized, exist for many aspects of the propagation of radio-frequency radiation that make implementation of a computer program to estimate propagation losses straightforward, in principle at least. The development of such a program is described in Section IV. The calculations are inexact, but still provide the best estimates available.

II. WHAT IS A HARMFUL LEVEL OF RADIO-FREQUENCY RADIATION?

Several criteria for harmful levels of radio-frequency radiation exist: The Federal Communications Commission (F.C.C.) has adopted a standard for public safety but that standard may well change if further research reveals harmful effects of low-level radio-frequency radiation. The standards for radio astronomy are easily specified but will change as our receivers improve. The standards for electronic devices and for optical and infrared astronomy are "soft"

---

[1] NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation

- e.g., not based upon any fundamental properties of the devices in use.

A. Public Safety

The F.C.C. has adopted the standard of the American National Standards Institute (A.N.S.I.) C95.1-1982 for human exposure to radio-frequency radiation (Gomez and Breed 1987). The corresponding power flux density, as a function of frequency, is given by

$$F_h(\mathrm{W/m2}) = \begin{cases} 1000, & 0.3 < f(\mathrm{MHz}) \le 3 \\ 9000/f^2, & 3 < f(\mathrm{MHz}) \le 30 \\ 10, & 30 < f(\mathrm{MHz}) \le 300 \\ f/30, & 300 < f(\mathrm{MHz}) \le 1500 \\ 50, & 1500 < f(\mathrm{MHz}) \le 100{,}000. \end{cases}$$

The standard is most stringent for the frequency range 30-300 MHz (wavelength range 10-1 m) where the human body is a good antenna and absorption is the greatest. Many other governmental bodies and agencies have also adopted the A.N.S.I. standard. But some organizations (e.g., the International Radiation Protection Association and the National Council on Radiation Protection and Measurements) have drafted or approved standards that are even stricter, because fundamental questions about the hazards of low-level radio-frequency radiation remain (cf., Foster and Pickard 1987, Slesin 1987, and Peterson 1987).

B. Interference with Electronic Devices

Electronic devices like personal computers typically are susceptible to electric-field strengths of 1 V/m, which is about the same as a power flux density of 1 $\mathrm{mW/m^2}$ which I use. The F.C.C. sets standards for radio-frequency emissions from "radio-emitting" devices like personal computers but no one sets standards for the susceptibility of such devices to interference. This limit is "soft."

C. Interference with Optical and Infrared Astronomy

The International Astronomical Union (I.A.U.) and the International Commission on Illumination (C.I.E.) have recommended a standard for radio-frequency interference at optical observatories (Cayrel, Smith, Fisher, and de Boer 1980). The proposed limiting power flux density of -57 dBW/m2 lacks the technical basis of those for radio astronomy and, consequently, is "soft."

D. Interference with Radio Astronomy

Radio telescopes are intrinsically extremely sensitive to radio-frequency interference for obvious reasons. But unlike criteria A-C which are concerned with total power flux densities, regardless of frequency, radio-astronomical receivers discriminate on the basis of frequency. Transmitters (usually) radiate most of their power in narrow frequency bands; regulations of the F.C.C. and the National Telecommunications and Information Administration (N.T.I.A.) limit the so-called "out-of-band" emissions at other frequencies. The tables of frequency allocations help prevent interference with radio astronomy at the primary frequencies of such transmissions, but radio astronomers are very concerned about out-of-band emissions at harmonics of the primary frequencies or in radio-astronomical allocations adjacent to the primary frequencies.

Furthermore, while criteria A-C are not usually concerned with the direction of arrival of radio-frequency radiation, radio antennas are designed to have high degrees of angular discrimination which go hand-in-hand with high peak antenna gains - the beam width varying with wavelength and antenna diameter D as

$$\Theta = \lambda / D,$$

and the gain as

$$G = \eta \pi^2 D^2 / \lambda^2,$$

where η is the aperture efficiency. The response pattern of a radio antenna outside the main beam is called the "sidelobe" pattern and is difficult to quantify. A reference level of 0 dBi (equals the antenna gain of an ideal isotropically transmitting or receiving antenna, with a collecting area of $\lambda^2/4\pi$) is used as an estimate of an upper limit to the amplitude of the distant sidelobes. Over most of the sky radio astronomers need worry only about interference received through the distant, "isotropic" sidelobes of the antenna, but for observations in nearly the same direction as that of the interfering signal, the peak gain of the antenna must be considered (which for an antenna 25 meters in diameter ranges between 23 dBi at 330 MHz and 79 dBi at 43 GHz). Transmitting antennas also have gain; for some like the broadcast services (AM, FM, and TV) the antenna patterns are fixed with respect to the terrain and for others like radars the orientations of the patterns change with time.

With these considerations in mind, radio astronomers are concerned with five levels of radio-frequency interference:

1. Damage receiver

Very strong radio-frequency interference can damage a radio-astronomical receiver. Modern GaAsFET and HEMT radio-frequency amplifiers will be damaged by signals with received powers of 0.1 W and 0.01 W, respectively (Weinreb 1987). If received through isotropic sidelobes, these received powers correspond to power flux densities ranging between approximately -10 and +40 dBW/m^2 at centimeter wavelengths.

2. Saturate receiver

Strong radio-frequency interference that occurs within the passbands of the radio-frequency or intermediate-frequency amplifiers of a radio-astronomical receiver can cause gain compression - the receiver no longer responds linearly. The interfering signal need not fall within the detected bandwidth of astronomical interest. The standard usually adopted is the power flux density that will cause one-percent gain compression in the receiver, with typical values of -70 to -30 dBW/m^2 at centimeter wavelengths, if received through isotropic sidelobes (Thompson and Schlecht 1985).

3. Single-antenna total-power radio telescope

The harmful interference level for observations with a single antenna has been analyzed in C.C.I.R. Report 224-6 (1986a) as that level of interference which equals one tenth of the r.m.s. noise level which sets the fundamental limit of the data. For a total-power receiver the harmful interference level, or power flux density, is given by

$$F_h = \frac{0.4\pi f^2 k T_s \sqrt{B}}{c^2 G_s \sqrt{t}} ,$$

where f is the observing frequency; k, Boltzman's constant; T_s, the system temperature; B, the observing bandwidth; c, the speed of light; G_s, the gain, with respect to an ideal isotropic antenna, of the antenna in the direction of arrival of the interfering signal; and t, the total integration time. For spectral-line observations at centimeter wavelengths, typical values of F_h range between -200 and -150 dBW/m^2, received through isotropic sidelobes.

4. Connected-element aperture-synthesis radio telescope

As discussed by Thompson (1982a), two effects reduce the sensitivity to interference of an connected-element aperture-synthesis radio telescope. The first is an averaging effect that applies to any interfering signal: A terrestrial source of interference will have a natural fringe rate of zero while that of an astronomical signal will usually range between a few milliHertz and tens of Hertz (depending upon the spacing of each pair of antennas, the observing frequency, and the position of the source on the sky). If the data are averaged for a time T, the amplitude of the interfering signal will be reduced by a factor sinc(πfT), where f is the natural fringe frequency. Thompson's analysis for a twelve-hour aperture-synthesis observation provides the following result for the power flux density which adds one tenth of the r.m.s noise level:

$$F_h = \frac{0.4\pi f^2 k T_s \sqrt{(2\omega_0 B L)}}{c^2 G_s \sqrt{\lambda}} ,$$

where ω_0 is the angular rotation velocity of the earth and L is a measure of the physical size of the telescope.

The second effect is important for broadband interfering signals. The geometrical time delays in an aperture-synthesis array for a terrestrial source of interference usually differ from those of the astronomical signal (call the difference t_d); when the signals are multiplied together, the interfering signal will be decorrelated by an amount sinc($\pi B t_d$). The decorrelation factor is not amenable to a general analysis.

Connected-element aperture-synthesis radio telescopes, depending upon the scale size L, are typically about 10-20 dB less sensitive (i.e., have higher F_h's) to radio-frequency interference than are single-antenna total-power radio telescopes.

5. Very-long-baseline aperture-synthesis radio telescope

Such a radio telescope will be much less sensitive to interfering signals than any other type of radio telescope, primarily because of its vastly greater geographical scale. The natural fringe frequencies, delay inequalities, and decorrelation factors are correspondingly even more effective in reducing the sensitivity to interfering signals. Except for an interfering signal of extraterrestrial origin (a satellite or space probe), such a signal is unlikely to be present at a harmful level at more than one antenna.

More significant for such a radio telescope will be the degradation of its performance by the addition of uncorrelated power at the individual antennas which effectively increases the noise level. The harmful level for such interference is estimated to be one percent of the system noise level (Thompson 1982b), or

$$F_h = \frac{0.4\pi f^2 k T_s B}{c^2 G_s} .$$

As a consequence very-long-baseline aperture-synthesis radio telescopes are about 40 dB less sensitive to radio-frequency interference than are single-antenna total-power radio telescopes.

Thompson, Moran, and Swenson (1986) provide an excellent general discussion of these points. Crane (1985) has applied these criteria to two aperture-synthesis radio telescopes - the Very Large Array (V.L.A.) and the Very Long Baseline Array (V.L.B.A.).

III. PROPAGATION OF RADIO-FREQUENCY RADIATION

One can apply the above criteria to determine minimum line-of-sight distances between a transmitter of given characteristics and a "receiver," say a radio telescope. For the least stringent criteria (A, B, C, and D.1) this is usually all that needs to be done. The remaining criteria, however, imply such low power flux densities that propagation over much greater distances - i.e., over the horizon - must be considered, and then other factors are important:

A. Refraction

A radio ray propagating through the earth's atmosphere will encounter variations in the index of refraction, n, of the atmosphere along its trajectory that will cause its path to curve. The radio refractivity, N, defined by N = (n-1)x106, is usually of order 300 near the surface of the earth and approaches zero with increasing height. Radio-ray paths typically curve downward, but under certain conditions atmospheric "ducting" occurs and propagation is similar to that through a waveguide.

B. Diffraction

The curvature of the earth, if not intervening mountains and other terrain, will often block a direct line of sight between the transmitter and the "receiver." The obstruction will not be absolute because the radio waves will diffract or bend over and around obstacles; but significant losses will occur.

C. Tropospheric scattering

For long tropospheric paths forward scattering is often a more important propagation mechanism than diffraction. (This is the basis of some over-the horizon radars.)

D. Atmospheric absorption

Atmospheric absorption at centimeter wavelengths is not a significant loss mechanism under most conditions in which radio, infrared, and optical astronomers are willing to observe (only a few dB at the zenith even on the peak of the water-vapor line at 22.235 GHz). At millimeter wavelengths, on the other hand, it is very important, with the major contributions arising from several resonant lines of molecular oxygen and water vapor and their highly pressure-broadened wings (Thompson, Moran, and Swenson 1986; C.C.I.R. Report 719-2 1986b).

E. Miscellaneous

Many other factors should be included when evaluating the impact of a particular transmitter on a particular "receiver." Such factors include the characteristics of the terrain between the two, the electrical constants (permittivity and conductivity of the surface) which determine the effects of reflections, radio climate and its variations, antenna heights, polarization, to name a few.

IV. CONSIDERATIONS FOR IMPLEMENTATION OF A COMPUTER PROGRAM

While doing a complete and accurate calculation of the propagation of a radio signal from a transmitter to a "receiver" is not feasible, radio astronomers, and many others, have concerns about the potential for harmful levels of radio-frequency radiation. With radio telescopes of vast geographical scale (e.g., the V.L.B.A.) and extremely sensitive receivers potentially susceptible to radio-frequency interference from new systems - e.g., air-, balloon-, and satellite-borne transmitter and radar systems - at great distances, implementation of a computer program utilizing the latest research into the propagation of radio-frequency radiation and nation-wide data bases offers the best approach to evaluate the potential for harmful levels of radio-frequency radiation in the myriad of circumstances faced by radio astronomy.

How to do so? There are nearly as many methodologies for doing these calculations as there are groups doing them. [A recent comparison (Grosskopf

1987) of eleven methods showed mean errors ranging between -14.2 and +6.8 dB and standard deviations of about 10 dB.] The discussion below addresses several of the considerations involved in the implementation of a computer program for such calculations:

A. Digital Terrain Data

Digital terrain data with a resolution of thirty arcseconds (approximately 2700 feet on the ground) and rounded to the nearest 20 feet are available from the National Geophysical Data Center (N.G.D.C.) of the National Oceanic and Atmospheric Administration (N.O.A.A.). The data base covers some 1295 square degrees of the coterminous United States and adjacent parts of Canada and Mexico, requires a minimum of 36 Mbytes of storage, and costs $520. Digital terrain data are also available from the National Cartographic Information Center (N.C.I.C.) of the U.S. Geological Survey (U.S.G.S.) but are manageable only if applied to limited geographical regions: the parent to the N.G.D.C. data base - three-arcsecond (270-feet) data from the Defense Mapping Agency ($90 setup plus $7 per square degree), and a new series of 30-meter data for each U.S.G.S. 7.5-minute quadrangle ($100 per quadrangle).

B. Reduced Surface-Refractivity Data

Atmospheric refractivities are measured at ground level at many stations around the country. The most useful form of these surface-refractivity measurements, N_s, is to reduce them to sea level according to (Bean and Dutton 1968)

$$N_0 = N_s \exp(z/H^*),$$

where z is the elevation and H* is a scale height (7.0 km is normally used.) Use of N_0 produces a simpler map with a smaller range of variation, and N_s at an arbitrary location is more easily and accurately estimated provided only that the elevation is known. George Hufford (1987) of the N.T.I.A. has provided minimum monthly mean values of N_0 at one-degree intervals for the coterminous United States.

C. Modified Effective-Earth-Radius Model for Atmospheric Refraction

As discussed above the vertical variation in atmospheric refractivity will usually cause radio-ray paths to curve downward. The effective-earth-radius model (Bean and Dutton 1968) assumes an earth whose radius is larger than the actual radius, a, by a factor, k, so that the curvature of the radio ray is absorbed into the curvature of the effective earth. For rays propagating nearly horizontally, k is given by

$$k = \frac{1}{1 + \frac{a}{n}\frac{dn}{dh}},$$

where h is height.

Because the height and the refractivity will vary along a radio-ray path, so will the effective earth radius. One approach is to calculate k at several points along the ray path using the exponential model for atmospheric refractivity described by Bean and Dutton (1968) and Hufford's reduced surface-refractivity data and use the mean value of k for subsequent calculations.

D. Models and Theories of Radio Propagation

Much of the fundamental work in radio propagation has been done by a group at what is now the Institute of Telecommunications Studies (I.T.S.) of the N.T.I.A. or under the aegis of the International Radio Consultative Committee (C.C.I.R.) of the International Telecommunications Union (I.T.U.). The work of the I.T.S. is reported in a large body of publications (Rice, Longley, Norton, and Barsis 1967; Longley and Rice 1968; Bean and Dutton 1968; Hufford, Longley, and Kissick 1982; Vogler 1981,1982,1983). That of the C.C.I.R. is updated quadrennially (most recently in 1986) in fourteen volumes of recommendations and reports; of greatest relevance to the present discussion are Volumes II and V on Space Research and Radioastronomy (1986c) and Propagation in Non-Ionized Media (1986d), respectively. These studies cover topics that include diffraction over a single isolated obstacle - knife edge or rounded, with and without ground reflections; diffraction over multiple knife edges; diffraction over the smooth earth and ocean and over irregular terrain; tropospheric scattering; atmospheric absorption; and diurnal and seasonal variability. Most results have been expressed in forms suitable for implementation in computer programs.

E. The Computer Program PROPAGATION

A computer program, called PROPAGATION, based upon the above considerations, has been written at the N.R.A.O. The current version is written in VAX FORTRAN and utilizes the VAX/VMS Run-Time Library and the Caltech PGPLOT Graphics Subroutine Library. It utilizes the N.G.D.C. digital terrain data and Hufford's reduced surface-refractivity data, and implements the modified effective-earth-radius model based upon the exponential atmospheric model. The propagation calculations use the I.T.S. and C.C.I.R. models for diffraction by knife-edge and rounded obstacles, by multiple knife-edge obstacles, and by the smooth earth and ocean; the I.T.S. model for tropospheric scattering; and the C.C.I.R. model for atmospheric absorption.

REFERENCES

Bean, B.R., and Dutton, E.J. 1968, Radio Meteorology (New York: Dover).

Cayrel, R., Smith, F.G., Fisher, A.J., and de Boer, J.B. 1980, "Guide Lines for Minimizing Urban Sky Glow Near Astronomical Observatories," Pub. I.A.U./C.I.E. No. 1.

C.C.I.R. 1986a, "Interference Protection Criteria for the Radio Astronomy

Service," Recommendations and Reports, Vol. II (Geneva: Int. Telecommun. Union), Rep.[0m 224-6, 493.
C.C.I.R. 1986b, "Attenuation by Atmospheric Gases," Recommendations and Reports, Vol. V (Geneva: Int. Telecommun. Union), Rep. 719-2, 167.
C.C.I.R. 1986c, Recommendations and Reports, Vol. II, Space Research and Radioastronomy (Geneva: Int. Telecommun. Union).
C.C.I.R. 1986d, Recommendations and Reports, Vol. V, Propagation in Non-Ionized Media (Geneva: Int. Telecommun. Union).
Crane, P.C. 1985, "The Responses of the Very Large Array and the Very Long Baseline Array to Interfering Signals", V.L.A. Scientific Memorandum No. 156.
Foster, K.R., and Pickard, W.F. 1987, "Microwaves: The Risks of Risk Research," Nature, 330, 531.
Gomez, M., and Breed, G.A. 1987, "RF Radiation Hazards: An Update on Standards and Regulations," RF Design, 10, 33.
Grosskopf, R. 1987, "Comparison of Different Methods for the Prediction of the Field Strength in the VHF Range," I.E.E.E. Transactions on Antennas and Propagation, AP-35, 852.
Hufford, G.A. 1987, private communication.
Hufford, G.A., Longley, A.G., and Kissick, W.A. 1982, "A Guide to the Use of the ITS Irregular Terrain Model in the Area Prediction Mode," N.T.I.A. Report 82-100.
Longley, A.G., and Rice, P.L. 1968, "Prediction of Tropospheric Radio Transmission Loss Over Irregular Terrain: A Computer Method - 1968," E.S.S.A. Technical Report ERL 79-ITS 67.
Peterson, C. 1987, "Reddy Kilowatt Didn't Tell Us Everything," Washington Post National Weekly Edition, 5, 10.
Rice, P.L., Longley, A.G., Norton, K.A., and Barsis, A.P. 1967, "Transmission Loss Predictions for Tropospheric Communication Circuits," N.B.S. Technical Note 101, Vol. I and II.
Slesin, L. 1987, "Power Lines and Cancer: The Evidence Grows," Technology Review, 90, 53.
Thompson, A.R. 1982a, "The Response of a Radio-Astronomy Synthesis Array to Interfering Signals," I.E.E.E. Transactions on Antennas and Propagation, AP-30, 450.
Thompson, A.R. 1982b, "Frequency Protection for the Transcontinental Radio Telescope," V.L.B.A. Memorandum No. 81.
Thompson, A.R., Moran, J.M., and Swenson, G.W. 1986, Interferometry and Synthesis in Radio Astronomy (New York: Wiley-Interscience).
Thompson, A.R., and Schlecht, E. 1985, "Dynamic Range and Interference Thresholds in the Front-End and IF Units," V.L.B.A. Electronics Memorandum No. 39.
Vogler, L.E. 1981, "The Attenuation of Electromagnetic Waves by Multiple Knife-Edge Diffraction," N.T.I.A. Report 81-86.
Vogler, L.E. 1982, "An Attenuation Function for Multiple Knife-Edge Diffraction," Radio Science, 17, 1541.
Vogler, L.E. 1983, "Further Investigations of the Multiple Knife-Edge Attenuation Function," N.T.I.A. Report 83-124.
Weinreb, S. 1987, private communication.