

INTERFERENCE AND RADIOASTRONOMY

The radioastronomer's struggle against a growing flood of interfering sources, from garage door openers to digital audio broadcast satellites, must be fought in the technical and political arenas.

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Radioastronomy began in 1933 with Karl Jansky's accidental discovery of radio emission from the center of the Galaxy as he was studying the effect of thunderstorms on transatlantic telecommunications. Six decades later, telecommunications and other radio services are threatening the future of radioastronomy. Whether searching for the signature of a protogalaxy, studying the maser-emission signposts of star formation or pursuing answers to any of the myriad questions of modern astrophysics, today's radioastronomer is often frustrated by man-made radio interference. From satellites, radar, radio and television transmitters, and wireless personal communication systems of all sorts to microwave ovens, computers and even garage door openers, the same technology that lets us study the universe at radio wavelengths is producing a flood of man-made signals. Figure 1 illustrates how noisy the radio spectrum has become at wavelengths around 1 meter. (The remedy offered in the figure is, alas, just an astronomer's fantasy.)

The evolution of radioastronomy from a curiosity to a place at the forefront of astronomy began at the end of the Second World War. Much of the early work resulted from ingenious adaptation of surplus radar gear. Although the technology has improved enormously over the years, radioastronomy has remained remarkably cost effective. Expanding on military and commercial technologies, radioastronomy has unveiled the existence of pulsars, the cosmic background radiation, radio galaxies and interstellar molecules. It gave us the first observation of quasars and strong evidence for the existence of black holes and gravitational radiation. Maintaining the viability of this precious window on the cosmos should be a serious concern of the physics and astronomy communities.

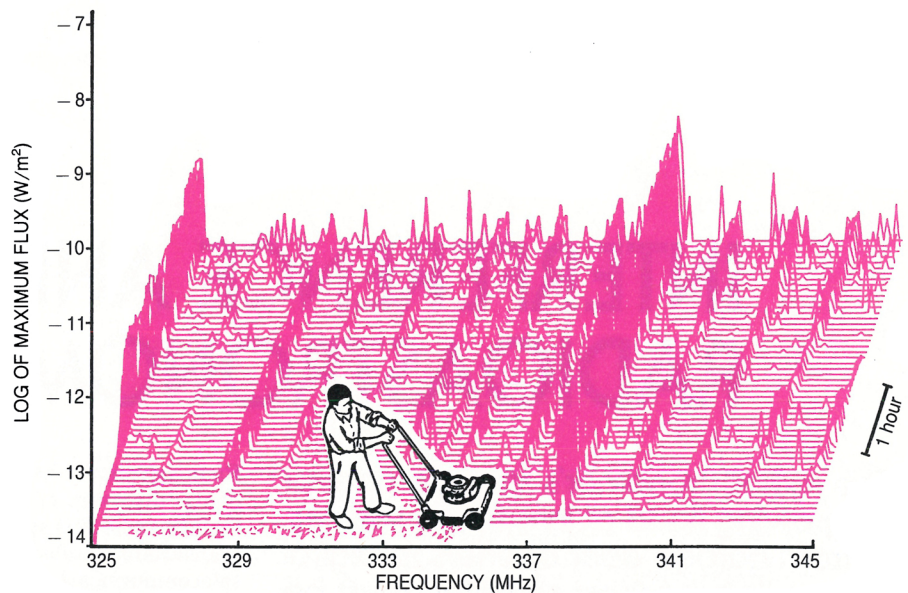
The World Administrative Radio Conference of 1959 granted official recognition to radioastronomy as a "radio service," thus admitting the fledgling scientific enterprise to the ranks of soap operas and marine communications. Since that time a number of wavelength bands have been allocated to radioastronomy, some exclusively and some shared with other services. Unfortunately, these allocations do not fully cover the needs of the science, and they are increasingly threatened by the expanding requirements of other services.

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A few typical hours of the interference radioastronomers have to contend with at wavelengths around 1 meter. An effective general method (like the one depicted) for removing such signals from the celestial data they pollute remains a radioastronomer's fantasy. **Figure 1**



An indication of the strength of the competition for spectral bandwidth is given by its equivalent dollar value, which has increased greatly over the past decade. Recent estimates of the value of bandwidth allocated to cellular telephone services in the heavily used region from 100 MHz to 3 GHz come to about a billion dollars per megahertz.¹ Early next year a World Administrative Radio Conference will be convened to find bandwidth accommodation for more services. This will certainly put further pressure on radioastronomy.

Vulnerability of radioastronomy

Studies at the cutting edge of the science involve signals of power flux density (per unit bandwidth) 6 to 12 orders of magnitude weaker than those commonly encountered in communications and other services. Thus spurious, out-of-band emissions at levels low enough to be acceptable to other services can be quite harmful to radioastronomy. For example, a personal communication system *on the Moon*, isotropically radiating only 0.1 W spread over 10 MHz, would produce a power flux density at the Earth of about 1 jansky—the standard unit of radioastronomy, equal to $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$. That would be a fairly strong astronomical source. A weak but readily observable signal would be 10^{-4} jansky.

Suppose one were pointing a radiotelescope at a fairly weak astronomical source some 45° away from this little personal communicator on the Moon. The telescope's sidelobes would pick up the communication signal at a power level comparable to the power of the astronomical signal received through the telescope's main beam. (Words like "beam" and "sidelobes" have essentially the same meanings for radio reception as they do for transmission.)

A second problem is that many of the astronomically important frequencies are spectral lines of particular atoms and molecules. Some of these lines were discovered

early enough to obtain protection through allocations to astronomy; others have no such protection. For example, the second strongest maser line in the sky, a line of methanol near 6 GHz, was discovered only this year.² But it lies in a band allocated to fixed and mobile communications.

The problem is further complicated by Doppler shifts. Most allocations for radioastronomy lines are wide enough to take account of motions within our Galaxy, and in some cases in nearby galaxies. The band 1400–1427 MHz, for example, was allocated to observation of the line of neutral atomic hydrogen at 1420 MHz. But for many distant galaxies from which we can detect hydrogen emission, the 1420-MHz line appears in the 1300–1400-MHz region allocated to radiolocation and aeronautical navigation.

As an *absorption* feature in the synchrotron emission of powerful sources, the hydrogen line can be detected from much greater distances and correspondingly greater redshifts. The 1420-MHz line has been observed in the uhf television bands below 890 MHz. Recently Juan Uson and his colleagues at the National Radio Astronomy Observatory's Very Large Array in Socorro, New Mexico (see figure 2), made a most remarkable detection³ of the line in both emission and absorption with a redshift of 3.395. This moves the frequency all the way down to 323.5 MHz. It may, in fact, be the first detection of "Zel'dovich pancakes," sheetlike hydrogen concentrations that are thought to predate the formation of galaxies. There is clearly no hope of reserving such wide pieces of the radio spectrum for science.

Cosmic radio emissions look like random noise. To reduce the noise fluctuations in the measured power, one can average the output of the receiver for minutes or hours. The presence of weak interference in a single such measurement of received power is impossible to detect, and the reliability of the data is only confirmed by consistency of observations. Interference is thus most



The Very Large Array of radiotelescopes in Socorro, New Mexico, is a Y-shaped string of 27 movable antennas that can range over 63 km of track. Interferometric techniques with such multiple-antenna systems can reduce sensitivity to radio interference by 20 dB. The VLA recently detected³ the 1420-MHz atomic-hydrogen line enormously redshifted to 323 MHz. **Figure 2**

insidious when it is weak, because it is then most likely to go unrecognized.

A radioastronomer's view of the spectrum

The internationally allocated range of the radio spectrum extends from 9 kHz to 275 GHz, more than seven decades in frequency. At the low-frequency end, radioastronomy usage is limited to wavelengths shorter than 10 meters by the ionosphere and the antenna size needed for adequate angular resolution. It is in the range from 100 MHz to 3 GHz (wavelengths from 3 m to 10 cm) that the competition for spectrum is currently most severe.

Various technical considerations make this range particularly desirable for mobile communication systems. Consider an antenna with a beam that covers a solid angle of one hemisphere. In reception the effective absorbed area of a wavefront is about one-sixth of a square wavelength. Thus sensitivity is inversely proportional to frequency squared. That argues against very high frequencies for hand-held devices communicating with satellites. Furthermore, diffractive propagation beyond the horizon or over mountains becomes less effective with increasing frequency. Quite generally, the cost of the technology rises with the frequency.

On the other hand, if one goes too low in frequency, little bandwidth is available, and antennas become very large. For all these reasons, frequencies from a few hundred megahertz to a few gigahertz are the most suitable for personal and mobile communication systems. The use of such systems appears to be on the verge of an explosive increase.

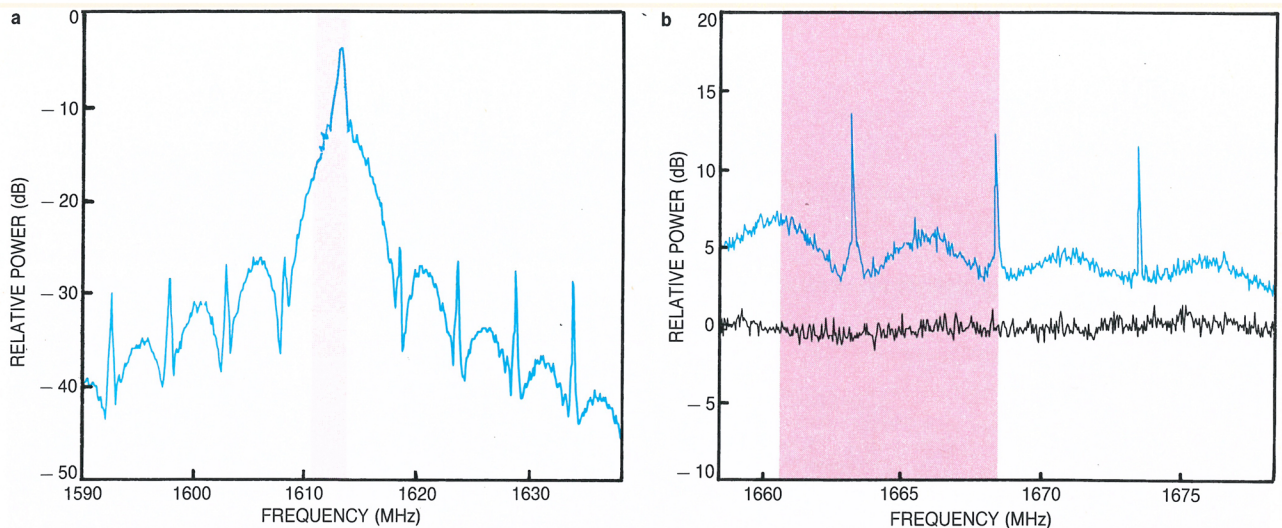
Unfortunately, this same part of the spectrum is

particularly interesting to radioastronomers. It contains the much sought and only recently detected⁴ 327-MHz line of deuterium, the 1420-MHz hydrogen line and the four lines of the hydroxyl radical (OH) at 1612, 1665, 1667 and 1720 MHz. This spectral region is also of prime importance for observing pulsars, whose nonthermal (magnetobremstrahlung) emission decreases rapidly with frequency. Some quasars and radio galaxies exhibit similar nonthermal emission.

Far from exhausting the scientific possibilities in this frequency range, 40 years of radioastronomy have continually expanded them through steady improvements in instrumentation and technique. It has become possible, for example, to obtain direct estimates of the distances to the center of our Galaxy by measuring both the Doppler shift and the transverse motion of water- or hydroxyl-maser sources.

From 3 GHz to 30 GHz (wavelengths from 10 cm to 1 cm) competition for pieces of the spectrum is somewhat less intense. These very short wavelengths are most effectively used for line-of-sight communication with high-gain directional antennas. Molecular spectral lines of importance to astronomy appear in greater numbers here, and some of them are threatened by satellite transmissions. Observations of continuum emissions from cosmic sources in the centimeter regime continue to be of great importance because of the high angular resolution achievable at these wavelengths.

Above 30 GHz, radioastronomy suffers much less from man-made interference. This is the millimeter regime, where radioastronomy is largely concerned with molecular spectral lines and thermal, rather than synchrotron,



Spread-spectrum modulation, a widely used technique of modern radio communication, troubles astronomers by spreading messages over very wide bands. **a:** Direct-sequence spread-spectrum signal (blue) from a Soviet Glonass navigation satellite, as received by a radiotelescope. A navigational receiver would use only the 10-MHz-wide central maximum. The broad secondary maxima simply pollute the radio environment. The spikes are phase-modulation imperfections. Tinted band shows the secondary allocation to radioastronomy for the 1612-MHz hydroxyl line. (Adapted from J. Galt, *Light Pollution, Radio Interference and Space Debris*, conf. ser. 17, D. L. Crawford, ed., Astron. Soc. Pacif., San Francisco, 1991, p. 213.) **b:** Glonass signal is so widened by spread-spectrum modulation that it spills over into the 1665 MHz band (tinted) allocated to radioastronomy. The full 24-satellite Glonass system will broadcast at numerous (central) frequencies within this astronomy band. The lower trace is the telescope's noise level when it points away from the satellite. (Adapted from J. Galt, *Nature* **345**, 483, 1990.)

Figure 3

continuum emission. Limitations on the sensitivity of radiotelescopes at these ultrashort wavelengths come primarily from atmospheric attenuation, smaller antennas and less sensitive receivers.

Satellites and garage door openers

Some satellites produce spurious, out-of-band emissions that interfere with radioastronomy. These emissions are particularly troublesome because the common practice of siting an observatory in a place remote from civilization or surrounded by mountains to shield it from terrestrial radio transmitters is useless against satellite transmissions. An offending satellite is very unlikely to pass right through the main beam of a large radiotelescope, which is, after all, only a few arcminutes wide. So what's the problem? It's the sidelobes of the antenna. They can pick up signals from almost any direction. And even though the sidelobe sensitivity is lower than that of the main beam by several orders of magnitude, it's enough to contaminate the astronomical signal with harmful interference.

Sidelobes in radiotelescopes are due to things like diffraction, irregularities of the parabolic reflector surface and reflections off structural members.

From satellites in low Earth orbit with periods on the order of a few hours the interference is transient. But that's small comfort to the astronomer who loses precious observing time on a prime instrument. Geostationary satellites present a different problem. A number of such satellites distributed around an orbit could effectively block out an entire band on the sky at certain frequencies. The astronomer would have to go to an observatory at a different location. The apparent position of the geostationary orbit changes by about 10° on the sky when the observer moves from midnorthern to midsouthern latitudes.

Another serious problem for radioastronomers is

posed by the modern communications technique called spread-spectrum modulation. In this scheme a signal modulated with information is spread over a wide bandwidth by further modulation of the frequency or phase, usually by the use of a pseudorandom code. The bandwidth after this kind of spreading is typically 100 times that required for the information alone. When such a signal is received, a locally generated version of the spreading code is used to remove the spreading modulation, a process referred to as despreading. If a second signal, spread with a different code, is received along with the desired signal, its spectrum remains unchanged by the despreading. Thus if the output of the despreading circuit is put through a filter of width equal to the information bandwidth, all of the desired signal passes through, but typically only 1% of the power of the unwanted second signal comes along.

In this way spread-spectrum modulation offers a degree of privacy and the ability to overlay signals and then separate them after reception. For the radioastronomer the main problem is that the most common spreading procedure, known as direct-sequence spreading, effectively spreads the spectrum by much more than the desired spreading factor. It adds a very wide series of sidebands that fall off only slowly with frequency, as one can see in figure 3a. For example, the nominal transmission band for the satellites of the Soviet Glonass navigational system⁵ is 1597–1617 MHz, but figure 3b shows that its sidebands can be picked up by radiotelescopes at 1670 MHz. Such sidebands can be removed by filtering at the transmitter, but a filter is often omitted for reasons of cost or weight, because the sidebands may be weak enough not to interfere with most other services.

Another class of objects that threatens radioastronomy is the whole series of low-power devices for which Federal Communications Commission licensing is not

required. Among these are remote-control devices such as garage door openers, security devices and the many new "wireless" interconnections for computer systems, audio systems and the like. Such devices avoid mutual interference by keeping the power low, and sometimes also by using spread-spectrum modulation. The market for these devices is expanding rapidly. This proliferation could well lead to an increase in the background radio noise over wide bands of the spectrum.⁶ It will become increasingly difficult to protect radiotelescopes from such devices. Even remote observatories usually have communities and public roads nearby.

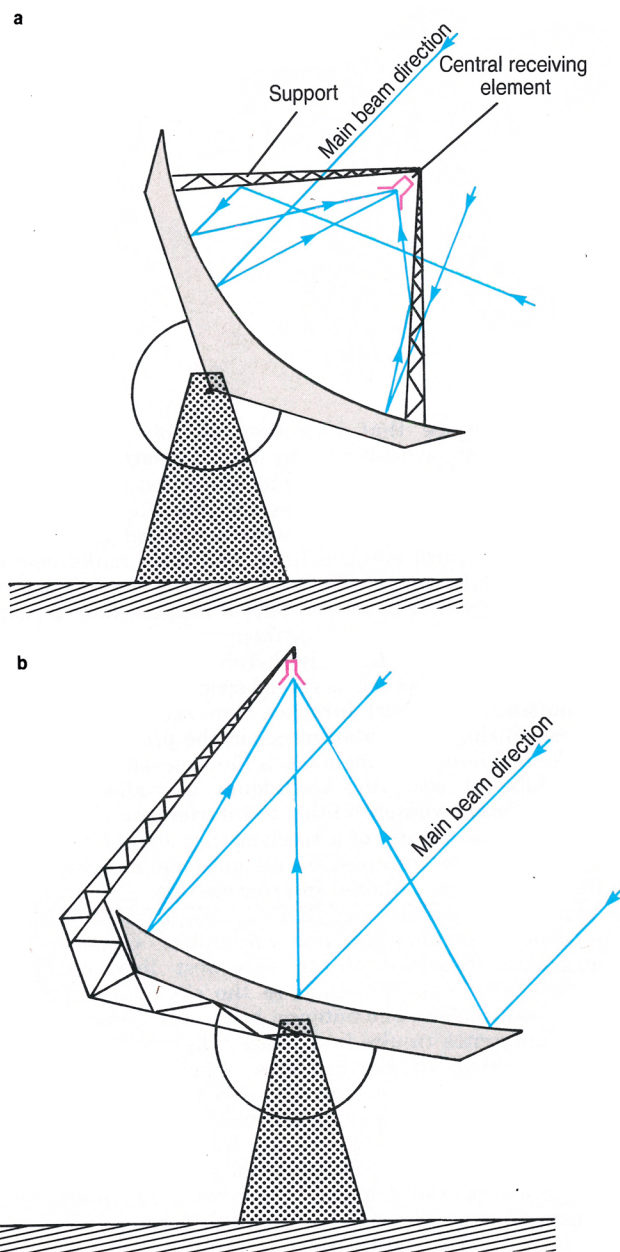
Technical solutions

A basic approach to reducing interference is to minimize the sensitivity of the antenna sidelobes through which most interference is received. In a large parabolic-reflector antenna the sidelobes at angles greater than about 20° from the axis of the main beam result mostly from scattering of radiation by the focal support structure. It's easiest to think of such an antenna as a transmitter. In that case power is radiated towards the parabolic reflector from a feed horn at the focus. Some of that power reflects off the legs of the tripod or quadrupod that customarily supports the equipment at the focus. Furthermore, the plane waves formed by the radiation properly reflected off the parabolic surface are also partially intercepted by the support structure as they leave the antenna. (See figure 4a.) Typically 2% to 10% of the radiated power is scattered in this way, much of it at wide angles from the main beam axis.

When the antenna is used as a receiver rather than as a transmitter, one gets precisely the same sidelobes. Reducing the area of the structural members facing the antenna helps reduce the sidelobes, but the best solution is to use a design with no obstruction above the dish. One can get a clear aperture by configuring the reflector as an off-center part of a paraboloid that does not include the vertex. The focal equipment can then be supported by an arm at the side of the reflecting surface that does not intersect the wavefronts either before or after reflection from the parabolic surface. (See figure 4b.)

Offset-feed reflectors of this type cost more to build than symmetrical reflectors. With the exception of the 100-meter NRAO telescope now being constructed at Green Bank, West Virginia, no offset-feed radiotelescope has been built with a diameter much larger than 10 meters. (Figure 5 shows a model of what the completed Green Bank telescope will look like.) These asymmetrical telescopes still exhibit sidelobes from imperfections other than reflection off the focal support structure. But the sidelobes are typically down by 10–20 dB compared with antennas of conventional design.

The new Green Bank telescope will enjoy the additional protection of being situated in the National Radio Quiet Zone.⁷ Obtaining a license to operate a fixed transmitter within this privileged precinct requires notifying NRAO. The licensing process includes a technical review by NRAO. Thanks to this procedure and continuing support from the FCC, Green Bank remains relatively free of interference from fixed ground-based transmitters.



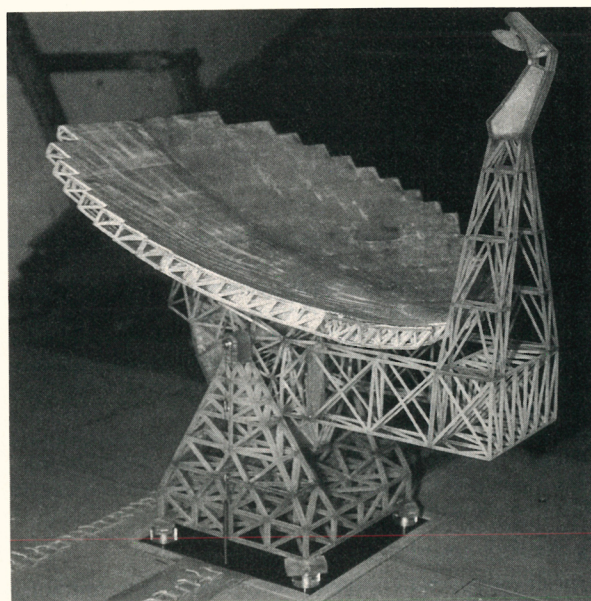
Support structure that holds the central receiving element in place at the focus of the parabolic reflector causes scattering, and hence troublesome sidelobes, in a radiotelescope of conventional, symmetric design (a). With an offset parabolic antenna design (b), where the off-center parabolic surface does not include the vertex, the support structure can be kept entirely out of the way, so that it will not scatter sidelobe signals to the focus. **Figure 4**

Interference that is rather sharply localized in frequency can be dealt with by using a spectral processor to analyze the received signal as a function of frequency. One can then discard data from the offending parts of the spectrum. Such processors were developed initially to measure natural spectral lines, and most make use of digital signal analysis. The total receiving band, typically several megahertz to several tens of megahertz wide, can be broken up into hundreds or thousands of channels. This technique is not generally helpful against wideband interfering signals such as spread-spectrum transmissions or pulses of very short duration. Here again, the problem of recognizing weak interference in the presence of noise in the individual channels sets a limit on sensitivity.

Different observing techniques in radioastronomy have different vulnerabilities to interference. The most vulnerable is the use of a receiver that simply measures the total power received by an antenna in a specified frequency band. Radio interferometers and imaging arrays that combine signals from one or more pairs of separated antennas are less vulnerable. Consider two antennas, separated on an east-west line, receiving signals from some direction in the sky. The incoming wavefront reaches one antenna before the other, and the time difference results in a phase difference that varies continuously as the Earth rotates. When the signals from the two antennas are combined in a voltage-multiplying circuit, the output is a quasisinusoidal fringe pattern similar to what one gets with an optical interferometer.

If the direction of the celestial source is known, the frequency of the fringes is precisely calculable. By contrast, a fixed *terrestrial* transmitter produces no fringe variation, and a satellite-borne transmitter yields a fringe frequency related to its orbital period. Thus one can remove interference by analyzing the fringe pattern in frequency. For an array of antennas like the Very Large Array (figure 2),⁸ this kind of fringe filtering reduces the relative sensitivity to interference by 12–20 dB relative to simple total-power receivers.⁹

Very-long-baseline interferometry, which combines signals from antennas spaced hundreds or thousands of miles apart, reduces the sensitivity to interference by another 20 dB. Unfortunately, interferometers and arrays are not suitable for all types of astronomical observations. The vulnerable total-power technique re-



Model of the new 100-meter radiotelescope under construction in Green Bank, West Virginia. Its asymmetrical parabolic reflector minimizes sidelobes by keeping the central receiving element's support structure out of the telescope's aperture. **Figure 5**

mains particularly important for observing extended, low-brightness objects.

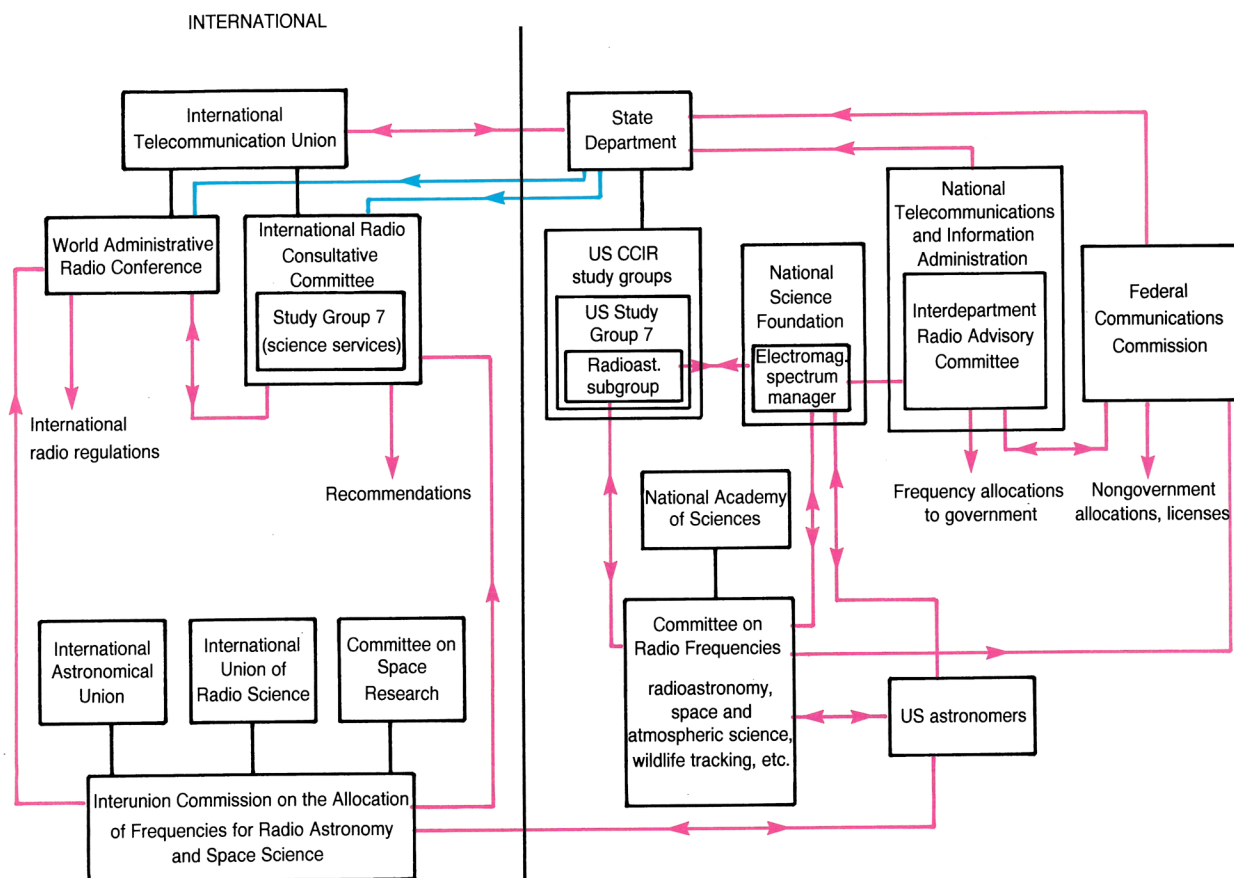
Time-sharing schemes, such as blanking the output of a radioastronomy receiver during the occurrence of pulsed radar interference, are useful in limited cases. An obvious strategy is to use a second receiver just to detect radar pulses and blank the astronomy receiver during each pulse. But the radar-detection receiver must have a very short signal-averaging time if it is to detect the rising edge of a radar pulse. That makes it much less sensitive to weak signals than the astronomy receiver. Pulses the radar receiver cannot detect can still be strong enough to cause harmful interference.

These various technical fix-ups are useful, but they do not provide a general solution to the interference problem. The reductions in vulnerability resulting from interferometry or reduced sidelobes lie in the range of 10–40 dB. But interfering man-made signals are often 60 dB above the radioastronomer's threshold of pain. Thus we must look to international regulation.

Working through the regulatory system

At the highest levels, regulation of the radio spectrum takes place through the International Telecommunication Union, a specialized agency of the UN. The international tables of frequency allocations result from World Administrative Radio Conferences. Countries that participate in a WARC usually endorse the results in the form of a treaty. WARCs that affect large parts of the radio spectrum occur every five to ten years. The technical branch of the ITU is the International Radio Consultative Committee (CCIR), which is divided into a number of study groups that deal with different aspects of frequency coordination. Recommendations and reports of the CCIR are published on a four-year cycle.¹⁰

Signatories to the WARC treaties may deviate from the international regulations within their own borders to



Interrelationships among national and international frequency-regulating agencies and the community of radioastronomers. Black lines indicate management structure, red lines show information flow, and blue lines indicate the sending of delegations. **Figure 6**

the international regulations within their own borders to the extent that this does not cause interference to services of other nations. Thus most governments develop their own frequency allocation tables, which differ somewhat from the international table. In this country the job is done by the FCC and the National Telecommunications and Information Agency. The FCC administers the regulations in the private sector. The NTIA, with input from the Interdepartment Radio Advisory Committee, plays a similar role for government services.

Radioastronomers have several means of injecting input into the regulatory system. The Interunion Commission for the Allocation of Frequencies for Radio Astronomy and Space Science arose from preparatory activities for the WARC of 1959, and it has continued to be active in the protection of radioastronomy. It consists of ten members, representing the International Astronomical Union, the International Union on Radio Science and the Committee on Space Research. Within the US, radioastronomers are represented by CORF, the National Research Council's committee on radio frequencies, which works with government and private organizations in supporting radioastronomy. Astronomers can also contact the National Science Foundation's electromagnetic-spectrum manager. Figure 6 attempts to clarify the interrelationships among these various national and international agencies and the US community of radioastronomers.

The regulations provide several levels of protection for radioastronomy. Primary allocations of wavelength

bands are legally protected from interference. Secondary allocations do not give protection from primary users in the same band. There are also footnotes in the regulations that draw attention to the use of various bands by radio astronomers and request that "all practicable steps" be taken to avoid harmful interference.

Even primary allocation of a particular band to radioastronomy does not guarantee freedom from interference that may result from out-of-band emissions. Radio Regulation 344 states that other radio services are required to protect radioastronomy from harmful interference only to the extent that such services are afforded protection from one another. Unfortunately, this degree of protection is rarely, if ever, adequate for radioastronomy.

WARC-92

The last World Administrative Radio Conference that dealt with allocations for the full range of the radio spectrum was held¹¹ in 1979. The WARC to be held in 1992 will, among other things, consider the allocations in the 500–3000-MHz band, where the competition among services is most severe. Details of the status of the protection of radioastronomy bands in this range are given in the table on page 48. The US position on WARC-92, so far as we can determine it, contains no specific threats to any of these radioastronomy allocations. However, there is intense competition for spectrum in the vicinity of these allocations by other services also supported in the US position. We will discuss four of these services that

engender some concern among radioastronomers:

▷ The Broadcast Satellite Service, also referred to as Digital Audio Broadcasting, will permit the distribution of "compact-disk quality" sound over wide geographical areas. Estimates of the bandwidth required by this service range from 60 to 120 MHz worldwide. Transmitters will be located on satellites in geostationary or highly elliptical polar orbits, and they will deliver up to 1.5 kW of rf power. Consequently, sharing between radio observatories and broadcasting satellites within their lines of sight is out of the question. A possible allocation in the lower portion of the 1435–1525-MHz band to digital audio broadcasting is under consideration in some countries. This troubles radioastronomers because out-of-band emissions might affect their 1400–1427-MHz band.

▷ The Radiodetermination Satellite Service provides radiolocation and limited communication services for aircraft, ships and land vehicles. Location is usually determined from the propagation times of signals between satellites and receivers or transponders on the vehicles. The 1610–1626.5-MHz band, allocated to this service in 1987 on a primary, shared basis, includes the secondary

allocation to astronomers for observing the hydroxyl line at 1612 MHz.

▷ The Mobile Satellite Service uses satellites for communication with aircraft, ships and land vehicles. In addition to systems using geostationary satellites, several recent proposals for this service are based on constellations of smaller satellites in low Earth orbit. These would be cheaper than geostationary satellites, and they would need less transmitter power. Motorola's proposed Iridium system, for example, would use 77 satellites at a height of 413 nautical miles. Operating in the frequency range 0.5–3 GHz, the Mobile Satellite Service is likely to require a spectral bandwidth of about 300 MHz.

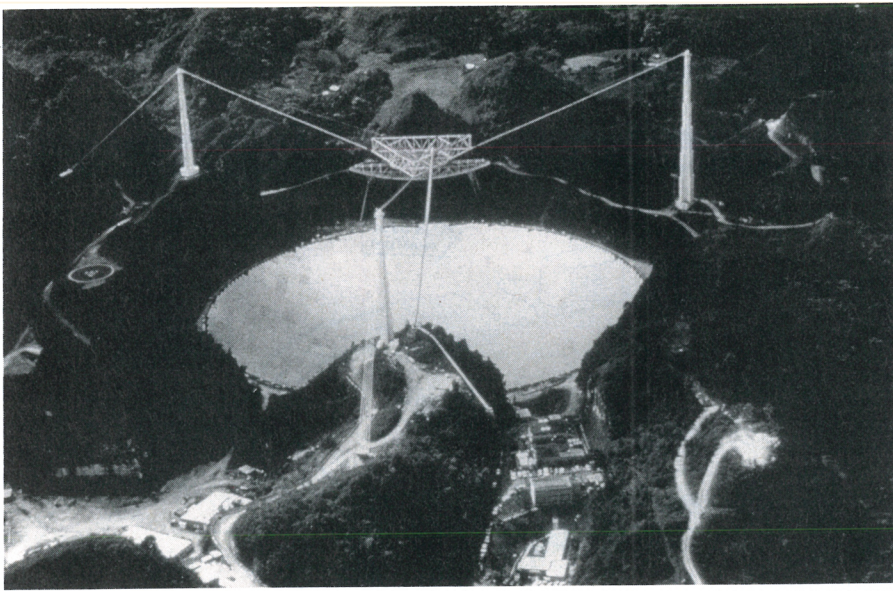
▷ The Future Public Land Mobile Telecommunication System, envisaged as a worldwide personal telecommunication service, would provide voice and data transmission facilities at all times, any place on Earth. This would be accomplished through a combination of hand-held portable terminals, base stations and access to mobile satellites. The spectrum bandwidth required by this service is estimated to be about 230 MHz. Its proponents would like to operate in the frequency range 1.7–2.3 GHz, which

Radioastronomy bands recognized in ITU regulations for the range 100–3000 MHz

Frequency band (MHz)	Allocation status	Radioastronomy usage	Remarks
150.05–153	Primary, shared with fixed and mobile communications in Region 1,* India and Australia	Continuum observations; important for Giant Meter-Wave Radio Telescope**	
322–328.6	Primary, shared with fixed and mobile communications, not allocated to astronomy in US	Deuterium line (327 MHz); continuum	
406.1–410	Primary, shared with fixed and mobile communications	Continuum	Difficult for radioastronomy in US because of heavy usage by sharing services
608–614	Primary in Region 2 and China; secondary in Regions 1 and 3*	Important for very-long-baseline interferometry	
1330–1400	Footnote protection only	Redshifted hydrogen line	
1400–1427	Primary, passive services only	Hydrogen line (1420 MHz)	
1610.6–1613.8	Secondary	OH line (1612.23 MHz)	Radiodetermination Satellite Service also in this band
1660–1660.5	Primary, shared with Aeronautical Mobile Satellite	Redshifted OH lines (1665.40 and 1667.36 MHz)	
1660.5–1668.4	Primary	OH lines (1665.40 and 1667.36 MHz)	
1668.4–1670	Primary, shared with fixed, mobile and meteorological aids	Blueshifted OH lines (1665.40 and 1667.36 MHz)	
1718.8–1722.2	Secondary, shared with fixed and mobile communications	OH line (1720.53 MHz)	
2655–2690	Secondary, shared with fixed, mobile and broadcasting satellites	Continuum	Usable for radioastronomy only so long as not used for broadcasting satellites
2690–2700	Primary	Continuum	Could suffer from sidebands of broadcasting satellites

* Region 1 is Europe, Africa and Northern Asia. Region 2 is the Americas. Region 3 is southern Asia and Australia.

** Under construction in India. See G. Swarup *et al.*, *Curr. Sci. (Indian Acad. Sci.)* **60**, 95 (1991).



Radiotelescope at Arecibo in Puerto Rico has a spherical reflector 305 m in diameter, fixed on the ground. Its beam direction is varied by moving the central receiving element, which is suspended above the dish on cables. A planned upgrade will significantly widen the receiver's bandwidth. At the same time a reflecting ground screen will be laid around the periphery of the dish to diminish its sensitivity to interference. **Figure 7**

includes the hydroxyl line at 1720.5 MHz.

These four services represent only some of those to be considered at WARC-92. Nevertheless, they are requesting something like 650 MHz of spectrum in a region that is already allocated. Further sharing among services is the most likely solution. Power flux densities of signals required by the various services in the 500–3000-MHz range are typically 50–90 dB greater than the threshold levels for harmful interference in the *sidelobes* of radio telescopes. Thus radioastronomy cannot share so long as there is line of sight between the radiotelescope and the transmitter. If the transmitter is in a band adjacent to a radioastronomy band, out-of-band emissions must be suppressed to avoid interference.

Keeping the window open

Following the development of radio technology to ever shorter wavelengths, the spectrum has tended to fill from the low frequencies upwards, and the region of most intense usage has expanded up the frequency spectrum with time. Within this intensely used region radioastronomy is confined to allocations that are often too narrow and polluted by out-of-band emission from other services. A few decades ago, when intense usage extended no higher than a few hundred megahertz, radioastronomers had little to lose by moving to higher frequencies. Now the expanding region of general use is in the process of engulfing the hydrogen- and hydroxyl-line bands and the observing range for pulsars, which are uniquely valuable objects of study.

The expanding exploitation of higher frequencies and the increasing use of satellites are the principal reasons for the present serious problem of interference in radioastronomy. Conservation of selected spectral bands, an essential factor in maintaining the science, is threatened by the enormous commercial value of spectral bandwidth. The situation can only become more difficult with the spread of population and the ever increasing market for high-technology devices worldwide. The radioastronomer's dilemma bears some comparison with that of biologists contemplating the shrinking rain forest.

Designers of new instruments for radioastronomy will have to pay very serious attention to interference rejection. The new Green Bank telescope and the upgrade of the Arecibo telescope¹² (see figure 7) will serve as notable

examples. Future WARCs on limited parts of the spectrum are expected to be convened as often as every two years. The whole situation could be exacerbated by fashionable management concepts such as treating the spectrum as a marketable commodity.¹

To preserve the clarity of their unique cosmic window, radioastronomers must prepare for increased participation in the regulatory and political processes. Preservation of certain bands for the exclusive use of passive (nontransmitting) services, stricter controls on radio emission from electronic devices and stronger steps to reduce out-of-band emissions from satellites are absolutely essential to the continued flow of scientific discovery that has thus far remained unabated since radioastronomy began.

References

1. Natl. Telecommun. Inf. Agency, "US Spectrum Management Policy; Agenda for the Future," special publ. 91-23, NTIA, Washington, D. C. (1990).
2. K. M. Menten, to appear in *Astrophys. J. Lett.* (1991).
3. J. M. Uson, D. S. Bagri, T. S. Cornwell, submitted to *Phys. Rev. Lett.* (1991).
4. P. R. McCullough, C. Heiles, A. E. Glassgold, *Bull. Am. Astron. Soc.* **23**, 933 (1991).
5. P. J. Daly, *J. Navigation* **41**, 186 (1988).
6. M. C. Cudak, G. W. Swenson Jr, W. W. Cochran, *Radio Sci.* **26**, 773 (1991).
7. W. A. Sizemore, in *Light Pollution, Radio Interference and Space Debris*, conf. ser. 17, D. L. Crawford, ed., Astron. Soc. Pacif., San Francisco (1991), p. 176.
8. P. J. Napier, A. R. Thompson, R. D. Ekers, *Proc. IEEE* **71**, 1295 (1983).
9. A. R. Thompson, J. M. Moran, G. W. Swenson Jr, *Interferometry and Synthesis in Radio Astronomy*, Wiley, New York (1986), and Kreiger, Malabar, Fla. (1991), ch. 14.
10. See, for example, Int. Radio Consultative Comm., *Recommendations of the CCIR*, vol. II, and *Reports of the CCIR*, annex to vol. II, Int. Telecommun. Union, Geneva (1990).
11. V. Pankonin, R. M. Price, *IEEE Trans. Electromagn. Compatibility* **23**, 308 (1981).
12. J. H. Taylor, M. Davis, eds., *Scientific Benefits of an Upgraded Arecibo Telescope*, Proc. Wksp., Cornell U., October 1986, Natl. Astron. Ionosphere Center, Arecibo, Puerto Rico (1987). ■