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Protecting the Science of Radio Astronomy

New uses of space may harm radio astronomy unless there is effective international protection.

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During the last few years radio astronomers of many countries have become concerned that their science may be in danger. The danger is that the radio spectrum will become so filled with signals that no space will be left for radio astronomers to use. This article describes and assesses this danger, tells something of the measures which have already been taken by international agreement to protect radio astronomy, and describes what radio astronomers hope for in the future.

Radio astronomy has grown up very quickly in an atmosphere of rapid technological advance. It has gained enormously from the advances made in electronics and antenna design, and radio astronomers themselves have contributed to these advances. But the technological revolution of the last 30 years also poses threats to science. These threats can be described in terms of the impact on basic science of specific new technological projects, but there is a serious general threat which derives from the violent way in which man is improving his technological environment. This technological revolution is based to a considerable extent on pure scientific discoveries, but the resulting technology endangers the science on which the revolution is based.

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One good example of a new technology which has grown from science yet which may endanger science is that of radio communication. There is an ever-growing need for better ways of exchanging messages by radio over long distances. Safe and swift communications may be essential to avoid an unnecessary war; they are certainly essential to consolidate and improve an uneasy peace. With our improved technology we can plan better communications by using radio relay stations in satellites, or even by reflecting radio waves from balloons or belts of small metal dipoles in orbit around the earth. The resulting improvements in communications may well be startling, but there will also be, as we shall see, concurrent added dangers to science.

We can assess the dangers to radio astronomy with considerable accuracy, since we know enough to make a good scientific appraisal of the problem. We make this assessment by discussing (i) the accuracy with which radio astronomers could observe and measure the natural radio sources if there were no man-made radio interference; (ii) the sources of man-made interference, and how such interference can be avoided; and (iii) the ways in which radio astronomers may protect their science without asking for unreasonable limitations on essential technological advances in other fields.

Fundamental Limits

Let us first consider whether there are any fundamental limits imposed on the accuracy and sensitivity of radio astronomy observations. The answer in general is that both our environment on or near the earth's surface and our use of instruments obeying physical laws impose limits on the accuracy of our measurements. In order to see what these limits are we must examine in more detail the ways in which experiments are made in radio astronomy.

A radio astronomer equips himself with a radio telescope, which is simply a large radio antenna connected to a sensitive radio receiver. He points the antenna at the part of the sky he wants to observe and measures the amount of radio-frequency power which his antenna receives. If he suspects there is a radio source to be found, he may leave his antenna fixed in position relative to the earth and let the earth carry the antenna beam through the sky. The beam, if it traverses a small radio source, will give a receiver output (called a "drift curve") of the sort shown in Fig. 1. By such observations the radio astronomer can locate sources, and if he calibrates his equipment carefully he can measure the power received from the source. This simple measurement can be modified to measure the intensity distribution across extended radio sources in the sky, or within large areas of the sky. Observations at different radio frequencies will measure the spectra of the sources, and with suitable antennas, polarization measurements can also be made. Antennas are of course also used to follow positions in the sky, so that the power received can be integrated for considerable periods of time to reach high sensitivities or to look for possible variations in the intensity of the source.

The radio signal that the radio telescope receives may be approximately described as "white noise"—that is, the power spectral density function is constant over all frequencies. Of course, radio sources do not emit exactly white noise. However, the receivers which are

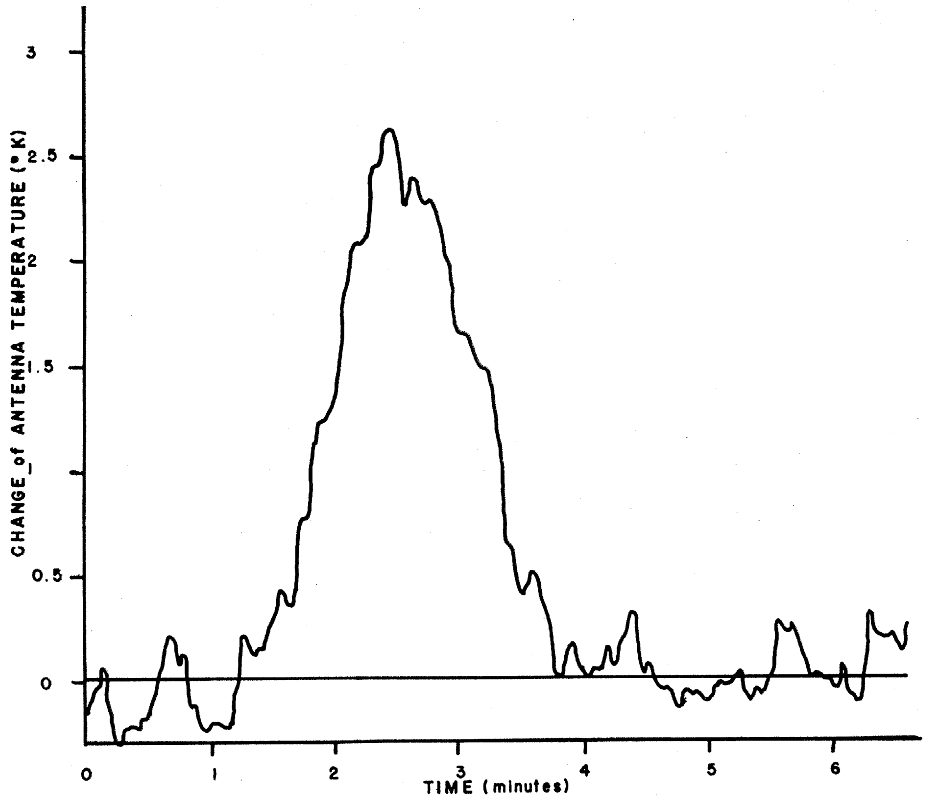

Fig. 1. A drift curve for the radio source 3C123, taken with an 85-foot radio telescope at 10-centimeter wavelength. (Time constant, 2 seconds; band width, 200 Mcy/sec.)

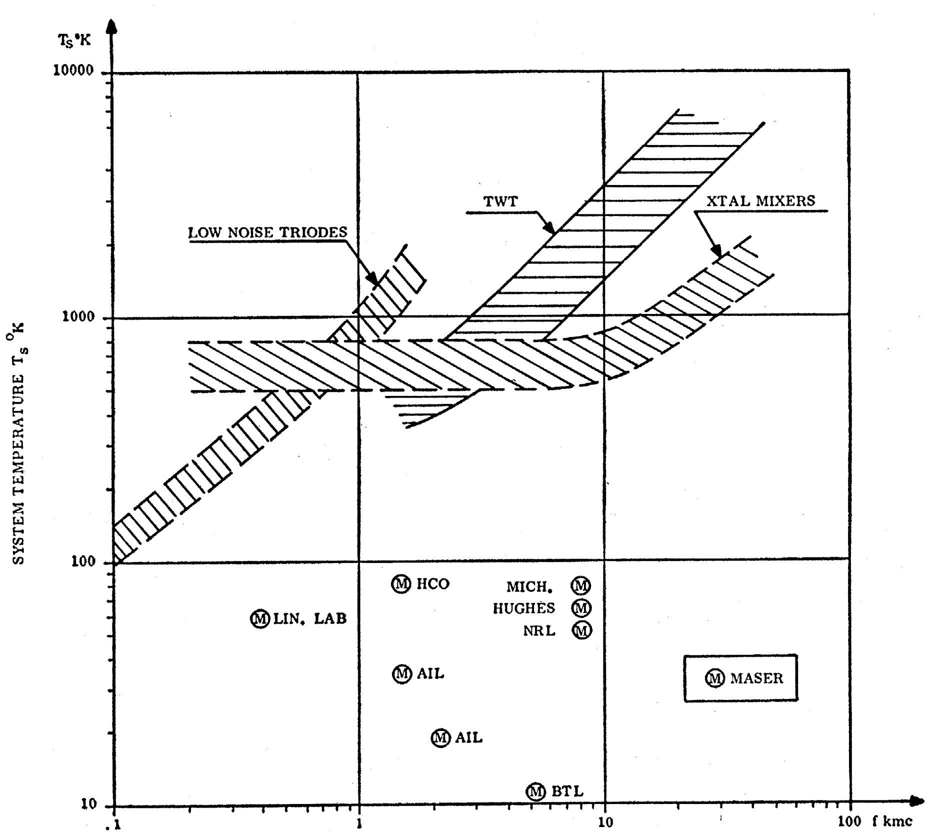

Fig. 2. System temperatures for radio astronomy receivers. *M*, maser receivers; *TWT*, traveling wave tube receivers; *XTAL mixers*, crystal mixer receivers. (AIL) Airborne Instrument Laboratories; (BTL) Bell Telephone Laboratory; (HCO) Harvard College Observatory; (Hughes) Hughes Aircraft; (Lin. Lab) Lincoln Laboratory, M.I.T.; (Mich.) University of Michigan and Willow Run Laboratory; (NRL) Naval Research Laboratory.

used are sensitive only over relatively narrow regions of the spectrum (or have relatively narrow band widths), and so it is fair to consider the power received within this band width as being white noise.

This reasonable assumption about the nature of the radio astronomy signal allows us to state the first fundamental limit to the accuracy of a radio astronomy measurement. It derives from the statistical fluctuations of the power received by or generated in the receiver system. We have said that the radio signal from a radio source is essentially white noise. So also, unfortunately for radio astronomers, are the radio noise signals generated by the receiver or picked up by the antenna. Even the best receivers generate unwanted noise. The best antennas, with their feeds, waveguides, and cables pick up or generate some unwanted noise. The surface of the earth radiates radio noise into the antenna. So also may the earth's atmosphere, or even the earth's ionosphere. To study the statistical limitation of the sensitivity of a receiver we must recognize that all these noise contributions may be present and then see how the total noise fluctuates.

We will do this by estimating the amounts of power fed into or generated within a radio telescope system from these various sources. For convenience, we will measure all the power contributions in terms of the changes in antenna temperature they produce. This concept of antenna temperature is a very useful one for simplifying the discussion of a radio telescope system.

Let us consider an experiment giving the result shown in Fig. 1. From such a record, by calibrating the receiver one can determine the power in watts collected by the antenna from the radio source and delivered to the receiver. This is always a very small amount; in the record shown in Fig. 1 it is almost 7×10^{-15} watt. If, instead of the antenna, a resistor (of resistance equal to the antenna radiation resistance) were connected to the input of the receiver, this resistor would generate noise by the random thermal motions of the electrons in the resistor. Theory shows that the noise power delivered by such a resistor to the receiver is kTB, where k is Boltzmann's constant (1.38×10^{-16} erg per degree), T is the absolute temperature of the resistor, and B is the band width of the receiver. Suppose we change the temperature of this resistor by t degrees Kelvin to make the change in receiver output exactly equal to the change due to the radio source, as observed in Fig. 1. The power changes resulting from transit of the source and the temperature change of the resistor would be the same. We then say that the radio source produced a change in *antenna temperature* of t°K, and we use this as a measure of the power received from the source. In a similar way, we may relate any output of the receiver due to noise power fed into or generated within the antenna or receiver system to its corresponding antenna temperature. So if we have an imperfect antenna and receiver system we can measure all the unwanted noise in it as if the noise had been generated in a heated resistor placed at the receiver input. The temperature to which this resistor would have to be heated we call the system temperature (T_s) of the radio telescope system. Even in the best and newest radio telescopes it is about 100°K, and many radio telescopes are still working with system temperatures of 1000°K.

It is interesting to see where the various amounts of noise are generated in a practical radio telescope. The maser receiver at the Agassiz Station of the Harvard College Observatory (*1*) has a total system temperature of only about 90°K. Of this, about 20°K is noise picked up by the antenna from the ground, about 65° comes from noise generated in components essential to the maser (cables and circulators) and in the following stages of the receiver, and only about 2° is noise generated in the maser itself.

We can now return to a discussion of the smallest signal that the radio telescope can detect, and we shall measure this by the smallest change $\Delta T°$ in antenna temperature that the system can detect. It can be shown that if the system temperature is T_s°K, if the band width is B cycles per second, and if the output of the receiver after the detector stage is integrated for a time T seconds, then the root mean square of the fluctuations in the output, ΔT_{rms} measured in units of antenna temperature, is given by

$$\Delta T_{rms} \approx T_s/(B \cdot T)^{\frac{1}{2}} \text{ °K}$$

This equation is not exact, since an exact expression can be written only for a particular design of receiver, but it is correct to a factor of the order of unity for all receivers.

It is clearly impossible to make a single radio astronomical observation if the antenna-temperature change due to the source is less than ΔT_{rms}, so we may adopt this as a measure of the sensitivity of the radio telescope system. The value of ΔT_{rms} depends on T_s, B, and T. Practical limits can be stated for all these quantities. Figure 2 shows some of the lowest values of system temperature which have been achieved so far with various low-noise antennas and receivers.

From Fig. 2, using the known band widths of the receivers and reasonable integration times, we can arrive at Fig. 3, which shows the values of ΔT_{rms}. Figure 3, then, may be regarded as showing the instrumental limit of usefulness of existing good radio astronomy receivers.

There are still other sources of noise which may further limit the sensitivity of radio astronomy observations. The whole sky radiates radio noise, particularly at frequencies below a few hundred megacycles per second. Many maps of this noise have been made, and they show that more noise comes from the plane of our galaxy than from the poles of the galaxy. Nevertheless, wherever we point our radio telescope it must pick up some background noise, and this in turn will add to the antenna temperature of our radio astronomy system.

There is a further limitation to the sensitivity of radio astronomy measurements at the higher radio frequencies. The lower atmosphere of the earth can radiate appreciable amounts of power from the water vapor and oxygen molecules. Even if the atmosphere were uniform and stable this added system temperature would increase the fluctuations in the output of the receiver and so limit the sensitivity. In preparing Fig. 3 we took account of the added system noise at the lower frequencies that is due to the galactic background and the steady component of the noise at high frequencies that is due to the lower atmosphere.

Recent experiments at the National Radio Astronomy Observatory (*2*) are, however, confirming what has long been suspected: that because the atmosphere is irregular in composition, radio astronomy measurements are of limited accuracy. For example, water vapor is concentrated in clouds, and these clouds as they pass in front of a radio tele-

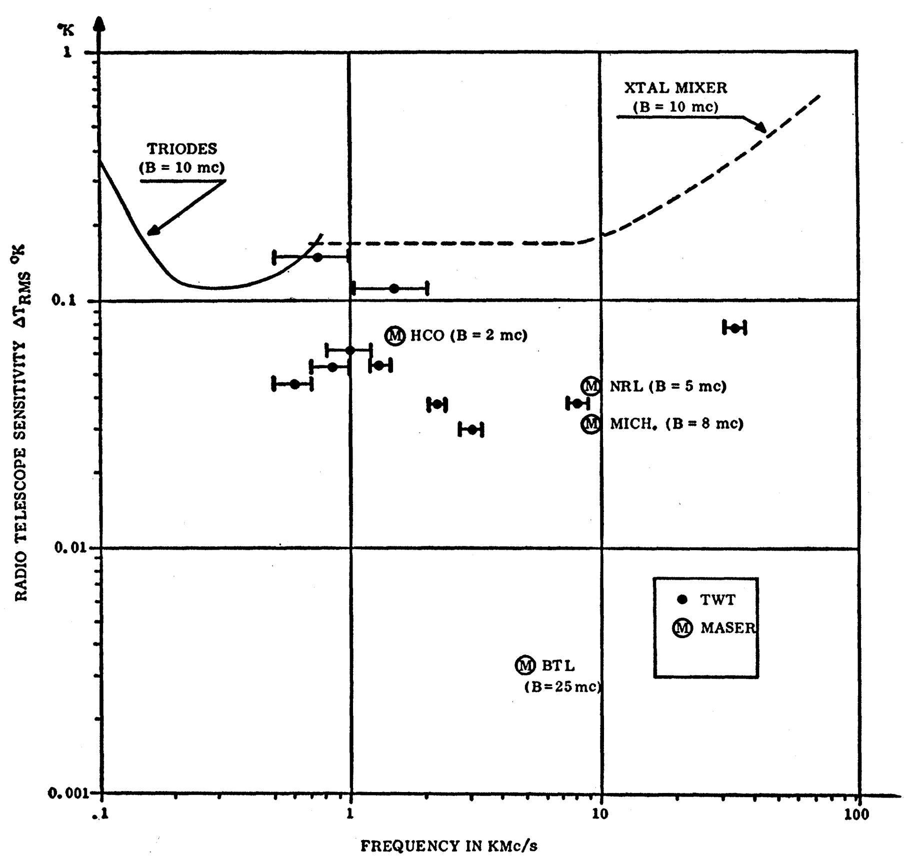

Fig. 3. Radio telescope sensitivity. B, band width of system; M, maser receiver; *TWT*, traveling wave tube receivers; *XTAL mixer*, crystal mixer receiver. (BTL) Bell Telephone Laboratory; (HCO) Harvard College Observatory; (Mich.) University of Michigan and Willow Run Laboratory; (NRL) Naval Research Laboratory.

scope radiate a changing amount of power to the telescope. As a result, the receiver output fluctuates with time, particularly on cloudy days, and the radio astronomy measurements are affected. The observations show at present that the effects may be serious at frequencies of 8000 megacycles per second and may be apparent even at 3000 megacycles per second. By a suitable choice of the antenna system and the observational techniques to be used, these atmospheric effects can be greatly reduced. I will therefore not attempt at present to estimate the limits imposed by these effects on radio astronomy sensitivity but will only note that the effects exist, are being studied, and may possibly prove to set a limit to earth-bound observations of the highest sensitivity at the higher radio frequencies.

In Fig. 3, therefore, we believe we have the first assessment we need. The present-day limits to radio astronomy sensitivity are shown in that figure. To look to the future is much more difficult. Further improvements in technique will certainly be made. System temperatures in the 10° to 50°K range should be attainable in the next few years, and corresponding increases in sensitivity can be expected to follow. However, we may proceed with our study on the basis of present-day radio astronomy sensitivities, since, as we shall see, the problems of reducing interference from man-made sources are not yet solved even at these levels.

Interference

We now turn to the kinds of radio interference which may be particularly damaging to radio astronomy. We could make a list of all sources of interference and study their possible effects. However, many kinds of interference can be very much reduced if we are observing on a carefully selected site, where radio signals from ground-based and aircraft transmissions are already reduced to a minimum by the location and where the levels of man-made radio noise are already low. The National Radio Astronomy Observatory site is good, though not perfect, in all these respects (*3*).

Even at such a quiet site, some signals from man-made sources of radio power can be detected. Automobiles, electric machinery, and power transmission lines all can radiate noise. Despite the excellent mountain shielding, which is shown by the example in Fig. 4 of the east-west land profile through the Observatory, some radio transmissions enter the site. Tropospheric scatter and direct transmission along the valleys explain these. Aircraft flying through the radio telescope beams may radiate signals or may scatter signals radiated from the ground. However, it is true that, for a site such as Green Bank and for the present levels of activity, none of these kinds of interference seriously limits present radio astronomy observations. Also, as has been described elsewhere (*3*), a very considerable measure of protection has been given to the quiet zone around Green Bank and Sugar Grove to reduce the likelihood of future encroachment of harmful interference on this zone.

With the increased use of space vehicles which can be foreseen, this happy situation may no longer exist. Satellite systems are already being tested or proposed which can threaten radio astronomy. No secluded site is adequately secluded from satellites in space. Although all users of space are potentially dangerous, the projects proposed for long-distance radio communications perhaps worry radio astronomers the most. Everyone wants better and cheaper communications, and the proposed ways of achieving these by satellites carrying radio repeaters (active systems) or by satellites which reflect back to earth the signals beamed at them (passive systems) are all practical and can be realized. However, such systems pose perhaps a major threat to radio astronomy.

The active systems are difficult to assess, since it appears that no radio telescope would or could ever be used to observe on a frequency allocated to such a system. The danger to radio astronomy would come from spurious radiation on the radio astronomy frequency from such a satellite. These spurious radiations may be difficult to avoid at the power levels which are safe in terms of radio astronomy sensitivity. For example, the 300-foot transit telescope now being completed at the National Radio Astronomy Observatory (Fig. 5), equipped with a receiver as good as those shown in Fig. 3, would suffer interference from a satellite at 2000 kilometers radiating only 5×10^{-9} watts of power. This very small power is damaging only when the telescope is pointed at the satellite; if the satellite is well away from the telescope beam, radiated power as high as 1 milliwatt can be tolerated. It seems reasonable, therefore, for radio astronomers to hope that active communication satellites will not radiate spurious emissions of sufficient intensity to harm observations generally, but will do no more than produce some interference as they pass the telescope beam.

The interference to radio astronomy from passive satellite communication systems arises from the possible scattering of energy from ground-based transmitters. The passive satellites will be designed to scatter energy to the communication link receiver, but this scattered energy can also enter the radio telescopes and give spurious signals that will interfere with radio astronomy measurements. Also, the possibility that any radio signals incident on the satellites will be scattered must be considered.

Any object in the sky that is illuminated by radio waves from a transmitter will scatter some of the power back to the earth. The calculations of the amount of scattered energy are quite straightforward, and they are of course well tested, since all radar systems operate on the basis of these principles. For example, the Echo balloon, which was placed in orbit on 12 August 1960, was specifically intended to demonstrate the feasibility of communicating over long distances by reflecting microwaves from a satellite. One such balloon would worry radio astronomers only if they were trying to observe on radio frequencies which were illuminating the balloon and if the balloon were in or near the radio telescope beam. Both these conditions can easily be avoided. However, if there were many such balloons in the sky there might be enough scattered power from ground-based radio transmitters to cause interference. Even the best radio telescopes collect some energy which arrives from directions well away from the direction in which the telescope is pointed. Good design can keep the collection of this unwanted power to very low levels but cannot entirely eliminate it. A particular example will show that this effect could become troublesome if there were very many Echo balloons in the sky at one time.

Let us suppose that there are 25 Echo balloons in the sky above a radio telescope, each 2000 kilometers from the radio telescope, and that all are illuminated by a single radio transmitter on the ground 2000 kilometers from each balloon. Let us assume that the

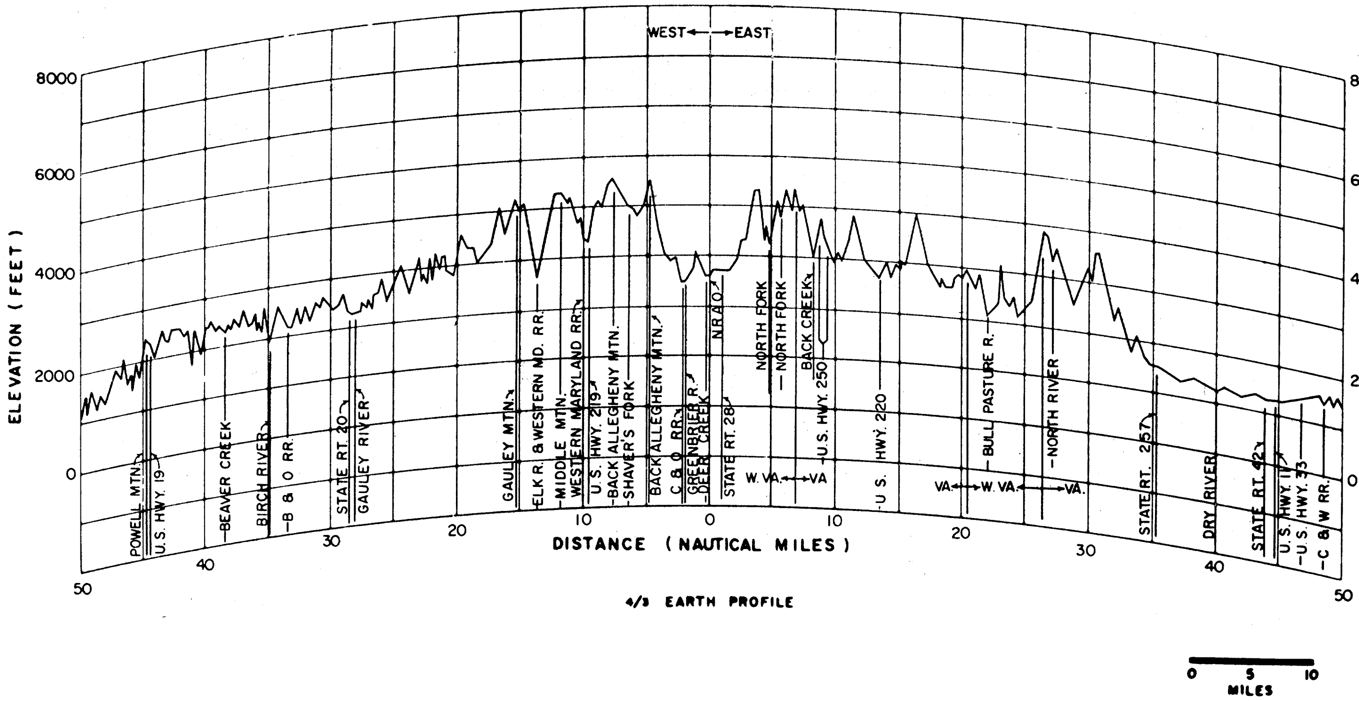

Fig. 4. Path profile east and west from the National Radio Astronomy Observatory.

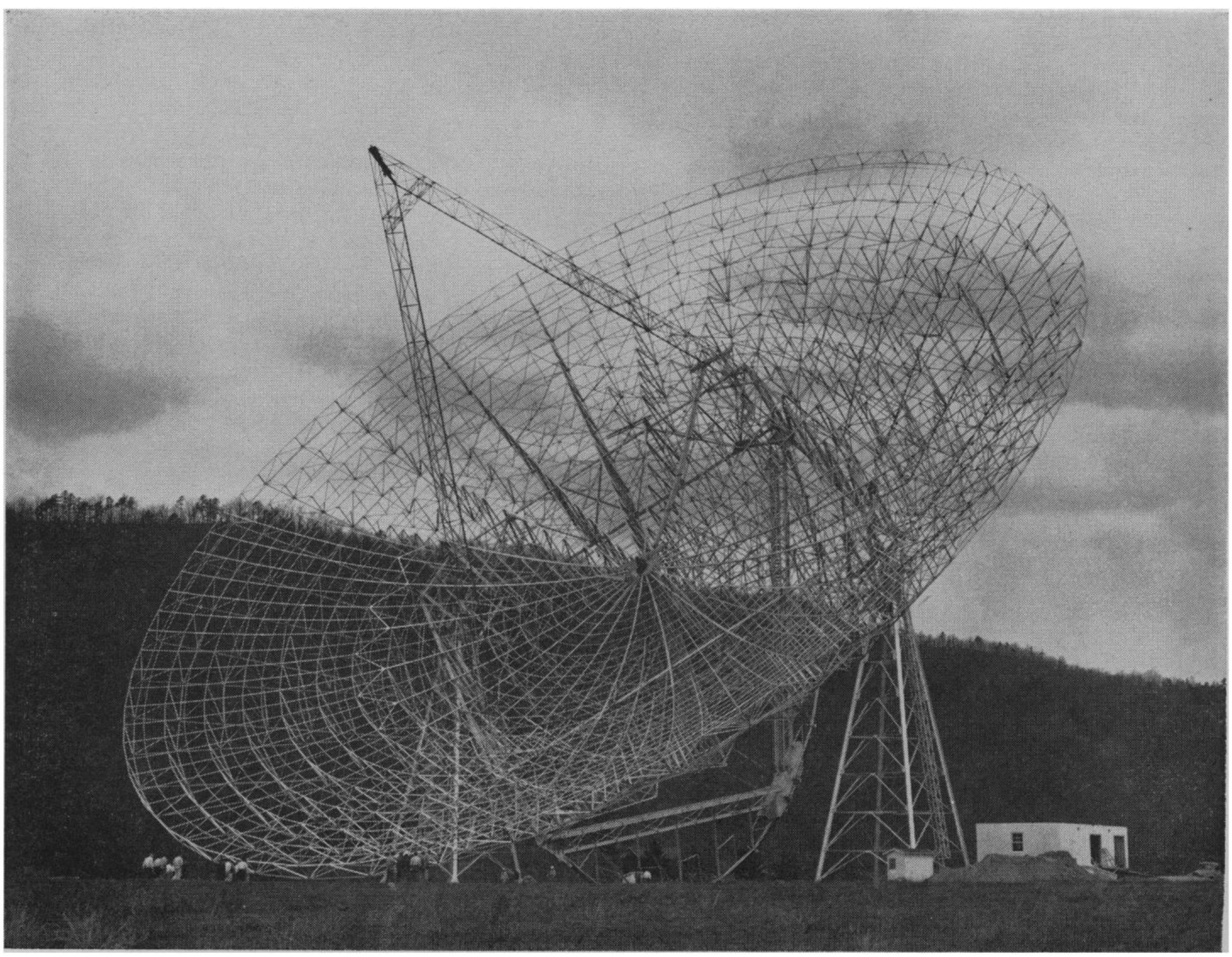

Fig. 5. The 300-foot transit telescope at the National Radio Astronomy Observatory (the mesh reflector surface is not yet fitted).

transmitter radiates 1000 kilowatts of power toward the balloons. Then, so long as all the balloons are well outside the radio telescope beam, the extra antenna temperature of the telescope due to power scattered from the balloons will be 0.003°K. (We have assumed a collecting area for the far sidelobes of the telescope equal to that of a dipole at 1000 megacycles per second and a receiver band width of 5 megacycles per second.) Of course, if any one of the balloons enters the main beam of a large radio telescope the scattered power will give an enormous increase in antenna temperature (2000°K for a 300-foot dish). Although we hope radio astronomers can avoid ever having a balloon in the main beam of the radio telescope, this might be impossible to avoid in some kinds of modern radio telescope systems. Figure 3 shows that even 0.003°K is approaching the harmful level for future radio astronomy systems, and larger interference would certainly be harmful now.

Another type of scattering object which will be placed in orbit around the earth is a cloud of small metallic dipoles. Such a plan is being undertaken, under the name West Ford (*4*), to test a belt of orbiting dipoles as a long-range communication system. Calculations similar to those sketched for the Echo balloon have been made for West Ford (*5*), and these show an increase in antenna temperature of several degrees for a radio telescope 60 feet in diameter directed toward the illuminated patch of the West Ford belt. If the radio telescope is directed well away from the West Ford belt, the observed increases in antenna temperature due to one West Ford transmitter will be less by a factor of about 1 million. The West Ford dipoles scatter best at their resonant frequency (about 8000 Mcy/sec) and thus pose less of a problem than balloons for other frequencies. Nevertheless, if denser belts than that of the proposed West Ford experiment were formed, or if illuminating powers were much increased, radio astronomy would begin to suffer seriously.

Besides these artificial objects in the high atmosphere, nature has also provided effective scatterers of radio waves in the form of the free electrons in the earth's ionosphere. Sir J. J. Thompson showed, in a classical study in 1903, that a free electron scatters x-rays. His theory shows that an electron also scatters radio waves, and that it does so equally well for all frequencies. This scattering has been measured and is in fact being used to study the electron distribution in the ionosphere. Each electron behaves like a small scattering area of about 8×10^{-30} square meter.

At frequencies above about 30 megacycles per second the earth's ionosphere is almost transparent to radio waves and a radio telescope collects radio waves which have passed through the ionosphere. The telescope will also collect any power scattered by the electrons from transmitters that are illuminating them. The magnitude of this effect can again be shown by an idealized example. Suppose a radio telescope is directed toward the zenith, and that all the electrons which lie within the beam of the radio telescope scatter back into the telescope some of the power from a 100-kilowatt transmitter on the ground. The radio-telescope antenna temperature will rise by 0.12°K as a result of this scattered power (*6*). As Fig. 3 shows, this level of interference is harmful even to present-day receivers.

Protective Measures

All the examples we have considered lead to the following assessment of the sources of man-made interference dangerous to radio astronomy now and in the future. High-powered radio transmitters on the surface of the earth can cause harmful interference by scattering from objects placed in orbit by man, and even by scattering from the earth's ionosphere itself. It would be unreasonable for radio astronomers to ask that the sky be cleared of orbiting objects, especially since even this would not solve the problem, in view of the ionospheric effects. Instead, radio astronomers must choose to make their most sensitive observations only in fairly narrow frequency bands of the radio spectrum which are free of all transmissions. No such bands, of course, exist by chance in the crowded spectrum, but if they were set aside and kept free from man-made radio signals the scientific work could go forward unimpeded.

To this end, radio astronomers asked some years ago for the establishment of such quiet frequency bands. The first step in making such a request is, of course, to get international agreement among scientists as to what the needs of the science are. This agreement is reached by discussions within the framework of the International Council of Scientific Unions (ICSU), the International Astronomical Union, the International Scientific Radio Union, and the Committee on Space Research.

An international committee of scientists formed by ICSU is now working continuously to refine and improve on the statement of the needs of scientists. The work of this interunion committee is supported by groups of scientists in the various countries. In the United States such a group has been formed by the National Academy of Sciences.

It is of interest to see how the needs of the scientists, once stated by such committees, get considered and finally acted upon. The final stage in the process of agreeing internationally to the use of a specific frequency band is reached at a full Administrative Radio Conference of the International Telecommunications Union (ITU). Such a conference was last held in Geneva in 1959, when 87 member countries of the ITU were represented. The final acts of the conference represent an international agreement governing the whole practice of radio communications.

Requests for frequencies for radio astronomy at such a conference must be made by some of the member countries, and the whole conference must reach agreement on how to treat the requests. The approach of scientists to such a conference must be through their own governments. It is obvious that such an approach cannot succeed unless the scientists in many countries are agreed on their needs. As we have seen, the existence of international scientific groups makes it possible to hold discussions needed to reach such agreement. Scientists in various countries work with their national administrations in the hope of presenting the needs of their sciences at the ITU conference. Another valuable channel exists, and is used, to present scientific needs to the ITU conference through the help of the International Radio Consultative Committee (CCIR), which advises the ITU on scientific and technical matters. The CCIR has national and international working groups, and through this medium the needs of scientists can be made known to the ITU and supported by technical evidence.

This somewhat lengthy process was followed for the first time by radio astronomers before the 1959 ITU conference, and the first steps were taken at that conference to clear channels for radio astronomy. The very important band of frequencies near the hydrogen line (1400 to 1427 Mcy/sec) was cleared, as a result of almost complete agreement. Various other frequency bands were given less protection, generally by allowing radio astronomy to share the band with other users. Although the results of the 1959 conference obviously fall short of all that radio astronomers hope for, the conference represents to scientists a very valuable first step.

This article has attempted to show that further needs for clear frequency bands exist, and it has told of the work now going on in preparation for the next radio conference. There will be a special ITU conference in 1963 to allocate frequencies for radio communications for space research, and it is the hope of radio astronomers that their science and its needs may be further considered at that time.

References and Notes

1. J. V. Jelley and B. F. C. Cooper, *Rev. Sci. Instr.* **32**, 166 (1961).
2. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.
3. J. W. Findlay, *Proc. I.R.E.* (*Inst. Radio Engrs.*) **46**, 35 (1958).
4. W. E. Morrow and D. C. MacLellan, *Astron. J.* **66**, 107 (1961).
5. A. E. Lilley, *ibid.* **66**, 116 (1961).
6. In this example we have to assume the effective area of the transmitting antenna (we have taken 10 m^2) and a receiver band width (5 Mcy/sec), and we have assumed an electron content of the ionosphere typical of a winter noon at Washington, D.C.

The Quest for Human Cancer Viruses

A new approach to an old problem reveals cancer induction in hamsters by human adenovirus.

John J. Trentin, Yoshiro Yabe, Grant Taylor

Many forms of cancer in many species of animals are now known to be caused by viruses (*1*). While all attempts to isolate causative viruses from human cancer have thus far been unsuccessful, it would appear to be biologically unusual if at least some forms of human cancer were not also caused by viruses. By far the most fruitful technique for the demonstration of tumor viruses in animals has been the inoculation of extracts of tumors, or of nontumorous tissues from tumor-bearing animals, into newborn animals of the same species. This technique is obviously denied to the searcher for human cancer viruses. Attempts to induce cancer in the young of other species by inoculation of human tumor extracts have thus far been negative or inconclusive.

The technique perhaps most widely used at present is the attempted propagation of human cancer viruses in vitro by inoculation of tissue cultures with human cancer materials. Yet this tissue culture technique has not resulted in the discovery of a single animal tumor virus, and only secondarily has it been possible to grow easily some exceptional animal tumor viruses in tissue culture. Because of the severe limitations imposed on the virologist concerned with human cancer, we must continue to use the tissue culture screening approach. But the need for new approaches is obvious. One such new approach is described in this article.

It was demonstrated by Duran-Reynals (*2*) that known animal tumor viruses can, under certain conditions of host susceptibility, produce acute noncancerous diseases. The production of tumors appeared to be a late manifestation of the slow growth of virus in a relatively resistant host. It therefore appeared possible that some human viruses already known for their acute disease manifestations might, under other conditions of host resistance or in a host surviving the acute disease, produce the late manifestation known as cancer. Some of the already known (or unknown) human viruses of acute diseases of childhood might therefore also be cancer viruses.

Another large group of already isolated viruses should also be suspect—the human "orphan" viruses. These are viruses that have been isolated from humans but whose disease manifestations are unknown—"viruses in search of disease." Cancer may well be the disease that some or many of these viruses are at present "orphan" to! With these concepts in mind, we initiated a program of testing known human viruses for cancer-inducing effect in newborn animals. The newborn Syrian hamster was selected as the test animal of choice because of its known relative susceptibility to tumor induction by tumor viruses of other species (*3*), and because of its relatively poor defense against the growth of normal-tissue and tumor-tissue transplants from other species, including the human (*4*). Newborn hamsters are actually more susceptible to tumor induction by polyoma virus of the mouse than are newborn mice (*5*). In spite of the many great advantages of inbred mice in other areas of cancer research, mice were excluded as test animals in this study because of the numerous tumor (and nontumor) viruses which they are known to harbor, and because of past experience with interference by such viruses in attempts to isolate human cancer viruses by other methods (*6*).

One of the first groups of human viruses chosen for extensive testing was the adeno group, because of similarities to some known animal tumor viruses, including polyoma virus, and because of the latency of adenoviruses in a large percentage of children. The adeno-

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