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RADIO ASTRONOMY WITH THE 65-METER MILLIMETER WAVE ANTENNA

1. Description of the Telescope

A general description of the 65-meter telescope as it is presently being designed is given in a companion paper (dated October 10, 1970 by J. W. Findlay). We will thus list here only the goals towards which the design is working:

(a) The telescope will be an altitude-azimuth instrument 65 meters in diameter.

(b) Wheel and track azimuth bearings and conventional elevation bearings will be used.

(c) Elevation range — from the horizon to a few degrees beyond the zenith.

(d) Azimuth range — a total of 420°.

(e) Reflector system — to be used as either a prime-focus instrument with f/D = 0.42 or as a Cassegrain telescope.

(f) Short wavelength limit — the goal is to have operation at 3.5 mm wavelength with an RMS surface accuracy of 0.22 mm. This goal may be met only under benign wind and temperature conditions.

(g) Pointing precision — this should achieve 3 arc seconds under benign atmospheric conditions.

(h) The design should ensure no permanent deformation or damage to the telescope in winds of 100 miles/hour at the dish center.

(i) Equipment rooms, each about 10x10x12 feet, will be supplied at the vertex of the dish and just outside the prime focus.

The reasons for the choice of these goals, particularly the size of the telescope and its short wavelength limit, come partly from the range of scientific work which can be accomplished and partly from more general considerations of what can be built for a reasonable cost. Before describing the scientific possibilities of the instrument, a short discussion of these more general considerations may be of value.

2. General Guidelines for the Telescope Design

(a) Intention

The telescope incorporates new design principles and applies these to an instrument which will work in a most urgent field of astronomical observation. It will also serve as a prototype for various future large precise radio telescopes.

The most exciting future discoveries are certainly those which nobody can guess at present, and any instrumental breakthrough would be desirable. At present, some of the most urgent fields of observation are (1) molecular lines, (2) the short wavelength variability of quasars, and of related N-type and Seyfert galaxies, down to normal ellipticals; (3) a sky survey at short wavelengths for young quasars and exploding galaxies at larger red-shifts; (4) structure and dynamics of our own and nearby galaxies; (5) observations of novae and extensive stellar envelopes; and (6) observations of the fine structure in H II regions.

This leads to a demand for short wavelengths, say $\lambda \leq 1$ cm, but also to the need for a large diameter in order to find and study a satisfactorily large number of objects within a manageably short time. Furthermore, the telescope should still be competitive with other existing telescopes in the range 1 to 3-cm wavelength.

In summary, we want a telescope as large as is financially feasible and one which works at a wavelength (below 1 cm) which is as short as technically possible. It must be designed for short wavelength surveys.

(b) Basic Design Principles

Any large radio telescope is basically designed for stability in survival conditions, and these conditions define the major part of the cost. High accuracy, up to some natural limits, can be achieved by careful design and engineering with only low extra costs.

For the present design, high accuracy is achieved by the following new basic principles:

(i) Homologous deformations — Permits crossing the gravitational limit in Fig. 1, up to the thermal limit, at almost no extra cost.

(ii) Optical pointing reference — No structural accuracy is needed between the center of the back-up structure and the ground. This system minimizes the effects of (1) soil settlement; (2) rail deviations; (3) thermal deformations; and (4) slow wind deformations of trucks, towers, and telescope suspension.

(iii) Surface plates with internal adjustments — Each plate of 13 ft^2 has 36 internal adjustment screws, to be adjusted by manufacturer before delivery. (This is estimated to take about one hour per plate.) High accuracy (an RMS of 2 - 3 x 10^{-3} inch) can be achieved.

(iv) New telescope measuring techniques — Fast and very accurate distance measurements are possible with the Hewlett-Packard laser-beam interferometer (better than one part per million). A method used by Zeiss gives ± 0.15 mm, with pentaprism and tape. The Mekometer announced by Kern (Swiss) claims ± 0.20 mm, but looks improvable.

(c) The Selection of a Telescope Size and a Shortest Usable Wavelength

The factors which have in a general way governed these selections are:

(i) The existence of usable atmospheric windows (Fig. 2).

(ii) The likelihood that a surface plate accuracy good for 3.5 mm operation can be achieved.

(iii) The estimate that the thermal limitation due to temperature differences across the structure will permit work to 3.5 mm at 65-meters diameter. This is shown by the "thermal-limit" line in Fig. 1.

(iv) The fact that a 65-meter telescope is of a size to compete with others in the world and yet is not likely to be expensive.

(d) The Selection of a Cassegrain and a Prime-Focus Instrument

The Cassegrain is very good at the short wavelengths where the possibility of using several beams at the same time for sky surveys is most valuable. Low antenna temperatures and large equipment rooms are possible and useful. For longer wavelengths ($\lambda > 3$ cm) the prime focus use is simple and practical, and the Cassegrain use becomes more difficult.

3. Scientific Research Areas for the Antenna

In the following paragraphs we list and discuss the various areas of research in astronomy and astrophysics where it seems possible to predict that new knowledge is needed and that it can be obtained by the 65-meter instrument. Before doing this, the possibility of new discoveries must be emphasized. The spectral range of the 65 meter is only at present covered by much smaller telescopes. Practically no survey work in space or in frequency has been done. No one can predict with certainty that new phenomena will be found, but the existence of the possibility gives considerable weight to the value of the telescope.

4. Studies of Interstellar Molecules

This subject is treated first since it is, at present, the research area with the most obvious rapid growth and interest. The mm-wave portion of the spectrum is an important region for studying interstellar molecules and related astrophysics. A number of molecular lines have already been discovered. The following list covers microwave interstellar lines detected up until October 1970.

Molecule	Wavelength
OH	180.0 mm
H_2CO	62.0 mm
	20.6 mm
	10.3 mm

continued -

Molecule	Wavelength
HC_3N	33.0 mm
H_2O	13.5 mm
NH_3	12.0 mm
HCN	3.4 mm
X-ogen	3.4 mm
CO	2.6 mm
CN	2.6 mm

Studies of the molecular clouds which contain these various molecules with a resolution down to 15" of arc will provide some very interesting answers to some intriguing questions concerning their chemical composition and structure. This resolution is obtained from the HCN, X-ogen, CO and CN lines and would allow detailed study of the amount of each molecule in a particular cloud and cloud size. Present resolution (∿ 1' of arc) does not allow one to distinguish between a large homogeneous cloud with small optical depth and many small clouds with large optical depth filling part of the telescope beam. Evidence from pulsar experiments on hydrogen clouds, isotope ratios and interferometric measurements suggests that the clouds are very small and clumped. Determination of the true optical depth is important in assessing molecular abundances. From this information we hope to determine the relative amounts of various molecules and some indication of the direction of chemical evolution on the interstellar medium.

A resolution of 15" will also be important in determining the structure and dynamics of small regions of the galaxy. The lines emitted by the gas in interstellar clouds allow a determination of the velocity across a particular region, whereas at present we may be only observing an integrated velocity for the cloud. Two important regions which are rich in molecular clouds are the Orion nebulae and the galactic center. Orion is only 0.5 kpc away and so resolutions of 0.01 pc would be possible. The galactic center is a complex region with a very broad feature extending from 0 to +100 km/s in most molecules. It is probable that this feature will break up into various velocity components under sufficient resolution. Hence a detailed study would provide valuable information on the dynamics of the galactic center. At present we have four lines that could be used with the 210-foot telescope to produce a resolution of 15" of arc.

It can, of course, be argued that these molecular lines may not prove to be of very great astronomical value. Two questions will help decide their importance: (1) To what extent will line sources be identified with "objects" about which we have other sources of data; and (2) will it be possible to obtain useful information about the nature of the emitting regions, other than the fact that molecules exist there. In any case, the 65-meter telescope would probably be most useful for picking out weaker sources and mapping strong sources with good resolution. One possibility that is discussed in the current literature is that many of the molecular lines will be associated with stellar "atmospheres". This relation to a mainstream topic in astronomy would probably enhance the importance of such research.

5. Extragalactic Radio Astronomy

Extragalactic radio sources stand as one of the most exciting fields of research in modern astfonomy. They are interesting for two reasons: First, since they are very luminous, they can be seen from great distances, and so a knowledge of their spatial distribution is important for cosmology; second, the mere existence of radio galaxies and quasars poses challenging problems for the theoretician about the source of energy, the conversion of this energy into relativistic particles, and the subsequent evolution of the relativistic electron clouds. We have learned very much about these fundamental problems in recent years, but the basic questions are still unanswered and many new questions have arisen.

The outstanding problem is still that of the source of energy. From past studies of spectra, time variations, and structure we now realize that the relativistic particles are produced in outbursts lasting a few months or less, with up to 10^{55} ergs of energy in each outburst. The initial size of a radio source is of the order of a few light months across, the initial magnetic field about 1 Gauss, and the initial electron energy distribution of the form $N(E) \sim KE^{-1}$.

The following further measurements are needed to understand better the events at the critical epoch of particle acceleration.

(a) Studies of Time Variations

Studies of time variations of the intensity of radio sources over a wide range of wavelengths will define better the rate of production of relativistic electrons and give information about the changes in the magnetic field strength and electron energy distribution as a function of time. Studies of the variations in degree and direction of polarization will further limit the range of models to be explored. Polarization studies are particularly difficult, as typical polarizations are only a few percent and greatly increased sensitivities are required to obtain an accurate measure of polarization changes.

The 65-meter telescope will be especially valuable for studies of this type because of its large collecting area and high efficiency at the short wavelengths where these variations are known to be most intense and most rapid. Observations at the shortest wavelengths (0.3 cm to 3 cm) are particularly important, as these correspond to the earliest epochs of the events and are most likely to reflect the detailed nature of the acceleration process. The use of the telescope for studies of this type will be considerably enhanced if it is possible to make observations easily over a wide range of wavelengths.

(b) Long Baseline Interferometry

Studies of the structure of extragalactic sources with resolutions much better than about 1" arc will require radio-link and tape-recording interferometers with baselines in the range of several miles to several thousand miles. For baselines up to about 100 or 200 miles, the use of a small, highly portable antenna together with a large, fixed antenna appears to be the best way of obtaining adequate and rapid coverage of the UV plane. The large collecting area of the 65-meter telescope will permit adequate sensitivity in such experiments when it is combined with a portable antenna of the order of 10 meters in diameter.

For longer baselines fixed antennas will probably be used. Except for the 22-meter antennas in the USSR, other existing millimeter antennas have dimensions in the range 5-12 meters, so that at least one large antenna is required to do long baseline interferometry at millimeter wavelengths. Observations at millimeter wavelengths with baselines of the order of earth dimensions appear to be necessary to resolve the smallest components in the compact sources.

High-resolution observations of this type are required to study further the size and structure of the young compact sources. The measurement of the size of the variable sources as a function of time will allow the direct measurement of the rate of expansion of variable sources. Combined with measurements of the variations in the spectrum and polarization, this will determine the law of variation of the magnetic field with time, and in the case of identified sources whose distances are known, a direct measure of the energy involved in each individual outburst.

(c) Spectral Observations

Studies of radio-source spectra have always been important in providing information on the origin and evolution of the sources. The spectra are determined by the distribution of electron energies and the distribution of density (optical depth). For optically thin sources, the spectra reflect the history of the relativistic particles, in particular the rate at which electrons of different energy lose energy. In this way important additional data is obtained about the age and magnetic field strengths. Detailed data of this kind is just becoming available on the strongest sources, but much greater collecting areas are required to explore a reasonable number of sources at the shorter wavelengths.

Some extragalactic objects radiate intensely in the far infrared. High-sensitivity measurements are urgently required at short millimeter wavelengths in an attempt to understand the relation between the radio and infrared emission.

Statistical studies of spectra are important for two reasons. First, in studying the properties of the sources themselves, in particular in relating the observed spectra to other properties. Second, only the radio spectra can be used to estimate redshifts and thus distances without the need for optical identifications. The ability to determine distances independent of optical identification is important if the full potential of radio astronomy is to be realized, particularly for cosmological studies.

The measurement of the redshift of individual sources is at present impossible due to the lack of any prominent features in the spectra of extragalactic sources. But statistical studies are possible due to the expected dependence between flux density and spectral index for sources with large redshifts (i.e., the effect of the K correction). Studies of this type involve the measurement of a large number of sources at many wavelengths and over a wide range of flux density; this, in turn, says that large collecting areas are required in order to sample an adequate number of sources in reasonable time.

At short centimeter wavelengths, about 80 percent of all extragalactic sources are of a type which are almost invisible at the meter wavelengths where most radio source surveys have been made. We believe that only a small fraction of these sources have been discovered, mostly from limited surveys made between 6 and 21 cm. Just as these surveys have uncovered a new class of source, sources which are prominent at millimeter wavelengths may only be discovered from surveys made at millimeter and short centimeter wavelengths. Present techniques do not permit reasonable efficient surveys to be made at short centimeter wavelengths. Nevertheless, surveys of the sky at short centimeter and millimeter wavelengths are vitally needed to give a picture of the sky at these wavelengths comparable to that now available from longer wavelength surveys. The 65-meter telescope can be equipped with multiple feeds, and it will be uniquely suited for this type of work.

The cataloging of centimeter wavelength sources is important for two reasons. Firstly, in discovering new compact sources suitable for long baseline and time-variation studies; and secondly, because their number-flux relation is expected to differ significantly from that of the meter wavelength sources, an important new approach to cosmological studies is opened which will complement the extensive work being carried out at longer wavelengths in the United Kingdom, Australia, and The Netherlands.

(d) Spectral Lines in Other Galaxies

The high resolution available at molecular and recombination-line frequencies will allow of a study of the chemical composition and excitation conditions within individual H II regions in extragalactic systems. Here there is the obvious advantage of an unambiguous galactocentric distance, R, for the object. This is of special importance since optical studies indicate a variation of the abundance of nitrogen and possibly sulphur and oxygen with R. In addition, H II regions in galaxies of different structural types may be studied and intercompared.

6. Galactic Continuum Observations

(a) Mapping Fine Structure in H II Regions

Because it would be a fine instrument for measuring thermal radiation, the 65-meter telescope would be a very powerful instrument for mapping fine structure or detecting thermal radiation from thermal sources like H II regions and planetary nebulae. A great deal of work in the last few years has indicated that considerable fine structure should exist in most bright H II regions on the size scale of 15". Both a sensitive instrument and considerable time will be needed to study such structure. Such mapping in the continuum and at spectral-line frequencies should provide a great deal of information about density and temperature variations in these objects. Of course, it is hard to guess how important this will be ten years from now. There is one possibility that would make it a continually important area for research. This would happen if there were a clear relation between much of this structure and protostar clouds. Again, as in the case of the molecular lines, a strong common interest with optical research would enhance the importance of the 65-meter telescope. It is a fact, for instance, that most optical nebular studies are made with diaphragms of 10-20"; hence the 65-meter would be the ideal instrument for studying nebulae on the small-size scale.

(b) Stellar Envelopes

The recent success in detecting novae at 3.5 and 9.5 mm with the 36-foot telescope (at the 0.2 to 0.6 f.u. level) shows that another new field of research will exist for the 65-meter; thermally emitting stellar envelopes and/or coronae. It is clear that most novae detected optically will be observable at the appropriate stages in the evolution of their cast-off envelopes. The important aspects of these observations will be: (1) the problem of angular diameters and distances; and (2) the study of envelope evolution which will be important theories of the nova explosion process.

It is probable that for at least a few cases the large envelopes associated with Be stars, shell stars, Wolf-Rayet stars, Of stars, supergiants, long-period variable stars, etc., will be detectable by the 65-meter telescope. Again, the importance of this is hard to estimate, but it could be quite important because of the common interests of large numbers of optical astronomers.

7. The Sun, Moon, and Planets

(a) The Sun

Millimeter-wave observations of the sun with the 15-foot and 36-foot antennas have shown very interesting correlations with Hα bright plage regions and filaments or prominenances. The improved resolution of the 65-meter telescope should allow detailed study of the structure of these regions. At 3.5 mm wavelength one is looking at the chromosphere, an important region of the sun's atmosphere where the temperature is close to minimum and important energy transfer processes are taking place. We would hope to learn more about how the sun heats its corona and the role of spicules, filaments, plages, and flares in this process.

(b) The Moon

There are a number of interesting places on the moon to point the 65-meter telescope. The 15" resolution would allow one to investigate the variations in thermal emission across a crater like Tycho. Some of the highlands and Mare would also be important since one could possibly distinguish compositional differences. The question of the effect of lunar rock in the various anomalous craters could be determined since the resolution would be comparable to lunar infrared studies.

(c) The Planets

An important problem that has not been solved concerns the presence of water vapor in the Venus atmosphere. Infrared measurements presumably measure the amount of water above the cloud tops and give very low values. A very large, well-calibrated radio telescope may be able to determine water vapor content in the lower atmosphere. The Russian probe experiments indicate that there is a considerable amount. Measurements would have to be made around the water line from 5 mm to 20 mm to determine the details of the sloping Venus spectrum. If this could be done during inferior conjunction when the telescope beam is smaller than the planet, the resolution would provide some information on the distribution of water in the atmosphere. It would also be interesting to determine if other molecules, such as HCN, are present in the Venus atmosphere.

Measurements of the variation of temperature across the disk of both Venus and Jupiter would be very interesting. On Venus one is interested in regions identified as radar anomalies as well as the limb temperature decrease which will aid in making atmospheric models. On Jupiter the red spot and the satellite Io are particularly interesting, as well as the intense infrared emission from the satellite's shadow. All these should be studied with the 15" resolution.

Straightforward radiometric measurements of the equivalent black-body temperatures of several of the outer planets (Jupiter and beyond) can be made; these are of considerable importance in studying the radiation balance of the planets and thus finding whether there are significant sources of internal planetary heating.

(d) Radar Astronomy

Although the small beam size appears to offer hemispheric separation in range-doppler radar planetary studies, it does not seem likely that, in fact, the telescope would contribute much in this field. The transmitter power limitations are considerable, and, for the most interesting planet--Venue--millimeter waves do not penetrate to the planetary surface. However, some lunar work might be of interest.

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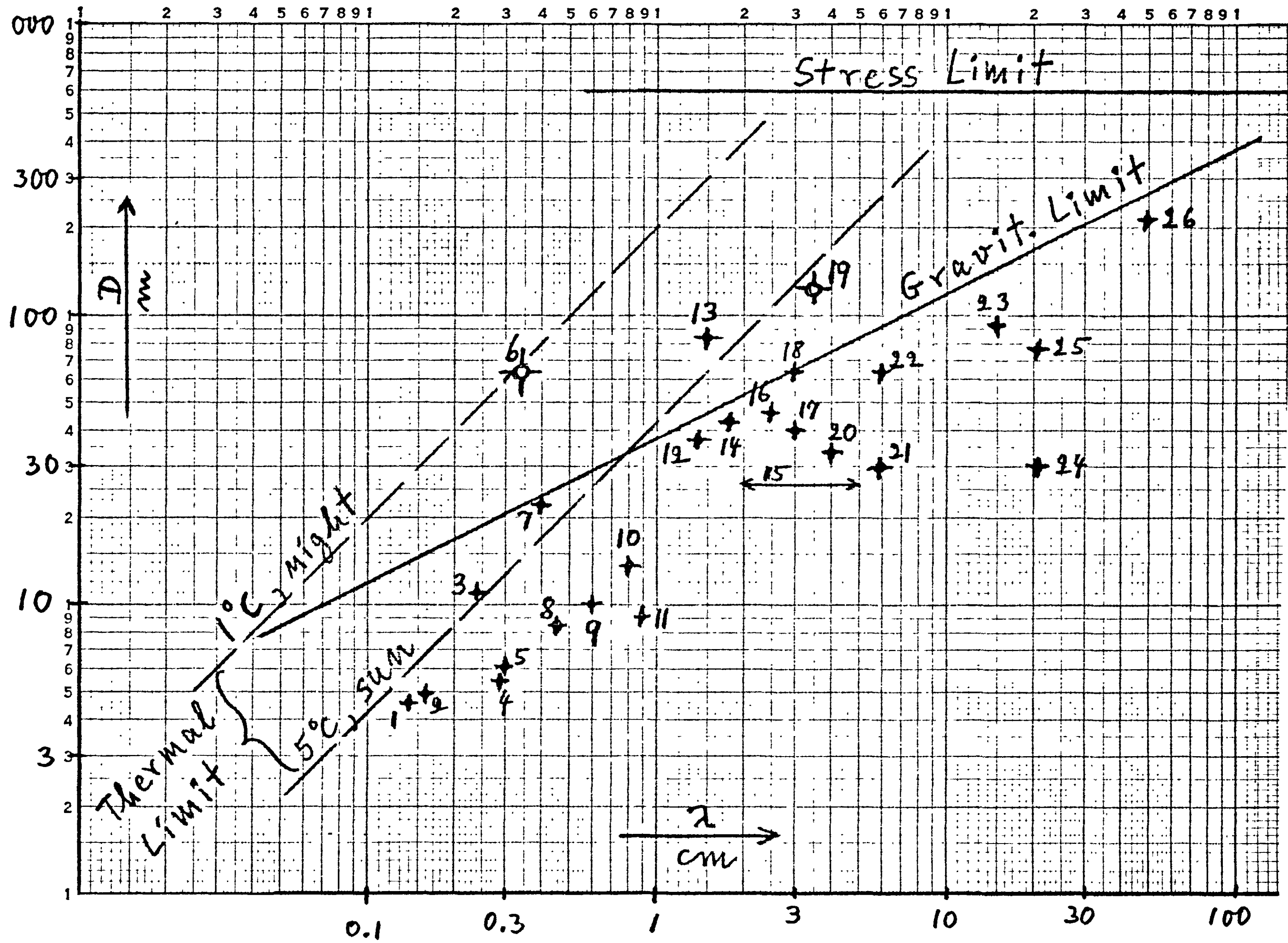

1. Aerospace
2. Univ. Texas
3. Kitt Peak, NRAO
4. JPL
5. Hat Creek
6. Homol. Tel. Design
7. RT-22, Crimea, Russia
8. MIT, Lincoln Lab.
9. Bonn, Germany
10. Itapetinga, Brazil
11. CRC, Canada
12. Haystack, MIT
13. Bonn, Germany
14. 140-ft, NRAO
15. Various 85-ft Tel.
16. Algonquin, Canada
17. Owens VAlley
18. Goldstone
19. NEROC Design
20. Werthoven, Germany
21. Mark II, England
22. Parkes, Australia
23. 300-ft, NRAO
24. Mark III, England
25. Mark I, England
26. Arecibo

Fig. 1. Three Natural Limits for Tiltable Conventional Telescopes

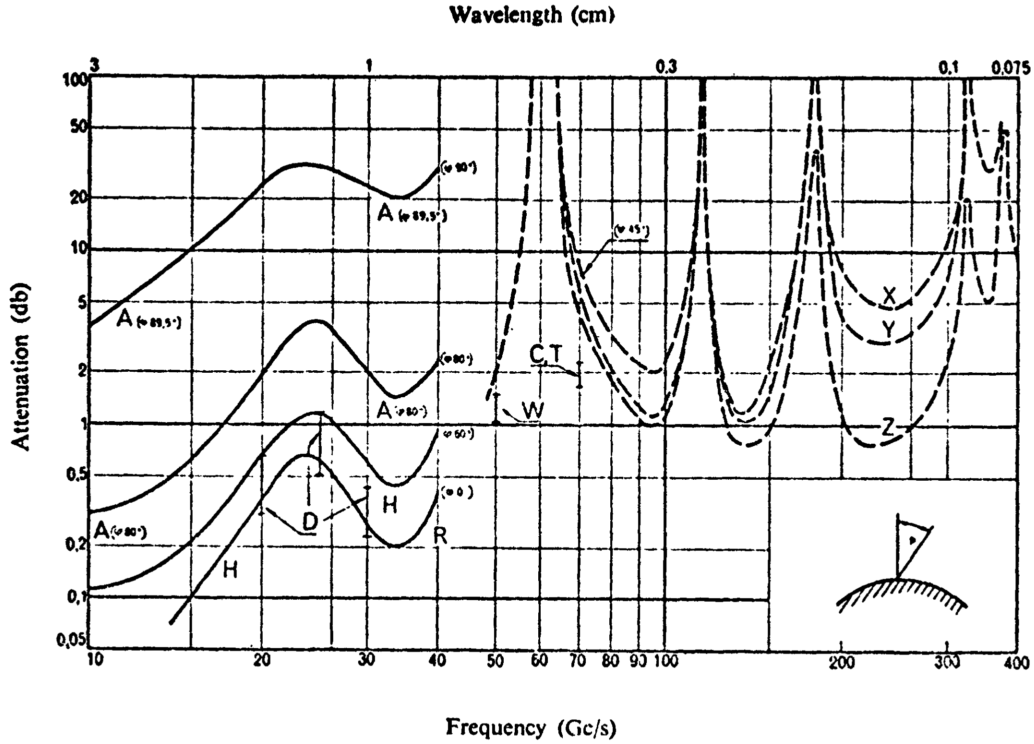

FIGURE 2

Total attenuation for a one-way transmission through the atmosphere

A: AARONS 1958
D: DICKE et al 1946
W: WHITEHURST 1957
T: TEXAS 1960
C: COATES 1958
H: Handbook Geoph. 1960
R: RING (HOGG 1960)
——— HOGG 1959, 1960
— — — THEISSING and KAPLAN 1958
X: humid
Y: mean
Z: dry

Table 1. Atmospheric Windows

λ (mm)	Atten. (db)	Limits D(m), Fig. 1	
		gravit.	Therm, night
0.83	5	11	17
1.3	0.8	14	26
2.2	0.8	18	42
3.2	1.0	22	65
8.8	0.2	35	170