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Earth-Based Remote Sensing of Planetary Surfaces and Atmospheres at Radio Wavelengths

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Abstract

Radio observations of the planets are providing much valuable information about these remote environments. Most of these objects are black bodies emitting thermal radiation which appears brighter at short wavelengths but we generally wish to investigate the effects of atmospheric absorption and subsurface heat condition on them which requires observations using a wide variety of astronomical techniques over a large range of wavelengths. Most parameters change only slowly with wavelength so that continuum radiometry at selected wavelengths is sufficient in most cases.

Many of the planetary signals are weak and it is very important to accurately separate their emission from that of the background sky and nearby confusing sources. This involves continuous comparison with the nearby background by various switching, on-off, and scanning techniques plus reobservation of the same spot in the sky after the planet has moved away. Often, over 2/3 of the time required for an observation is actually spent on comparison rather than looking at the actual target planet. Recently, aperture synthesis observations using interferometers have provided very high resolution pictures of some of the planets and removed many of the background problems.

Another important concern is calibration of the results so we can have accurate values of the absolute temperatures of these bodies. This requires measurement of the antenna parameters and also the effects of the earth's atmosphere upon the incoming signals. With careful evaluation it is possible to obtain an absolute accuracy of better than 7% at all wavelengths and relative values are known to a few percent.

The planets themselves can be divided into three natural categories: 1) those which are essentially all atmosphere, namely the giant gasous Jovian planets; 2) those without atmospheres, including the moon, Mercury, most sat-

ellites, and the asteroids; and 3) those for which both surface and atmospheric effects are important, such as Venus. In the first case, by measuring at several wavelengths across the spectral band of ammonia which acts as the major opacity source in the atmospheres of the giant planets, we are able to accurately determine its abundance and also measure the temperature distributions in the low atmospheres below the visible cloud layers. The atmosphereless bodies are in equilibrium with incoming solar radiation and by measurements at different phases in their diurnal cycles we can establish the heat flow and radiative properties of their subsurface layers. These are related to the physical properties of thermal inertia and dielectric constant. For the terrestrial planets with both solid surfaces and atmospheres, a complete analysis of the transfer of radiation through both the surface materials and the atmosphere above can provide knowledge about both regions. By using a large range of wavelengths we can choose some spectral regions where the atmospheric opacity is complete and others where we see down to the solid surface. Finally interferometric observations of the synchrotron emission from Jupiter's radiation belts has given us a wealth of detailed information about the planets' magnetic field and energetic particle environment.

Observations in the near future will include more high resolution aperture synthesis to see individual features on many bodies and also radiometry on a larger sample of the smaller bodies.

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I. Introduction

Although the use of space vehicles has now allowed us to directly sample some planetary environments, there is still a great need for remote sensing from the Earth for two major reasons. (1) Space exploration, particularly below the surface or underneath cloud layers, has been limited to only a very few planets and we need a broader sample of the full range of objects if we are to understand how these various bodies fit into a consistent distribution and evolutionary pattern for the solar system. (2) We often wish to know how a particular planet will behave under changing conditions of solar illumination including diurnal effects, seasons, the sunspot cycle, etc. This requires a program of regular monitoring which is currently impractical with a limited number of space probes.

At radio wavelengths reflected solar radiation is negligible and most bodies in the solar system are simple thermal emitters, radiating in proportion to their temperatures according to the Planck law:

$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT}-1} \tag{1}$$

where I_ν is the intensity of the radiation at a given frequency ν, h is Planck's constant, c is the speed of light, k is Boltzman's constant, and T is the absolute temperature. The measured flux density, S_ν, generally expressed in MKS units of watts m^{-2} Hz^{-1}, is then given by the expression

$$S_\nu = I_\nu \cdot \Omega \tag{2}$$

where Ω is the solid angle in the sky subtended by the body. If the size is known, it is possible from these relations to determine the brightness temper-

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ature of a planet. This black-body emission is continuous, but some molecules with microwave transitions have been found in the atmospheres of some planets and a limited amount of spectroscopy has been performed on them to determine the composition and structure of the atmospheres.

The only examples of non-thermal radio emission in the solar system (excluding the Sun) are found for Jupiter (see the review in reference 1), and to a much lesser extent Saturn, which have large magnetospheres containing trapped relativistic electrons. These produce synchrotron radiation and also interact with the ionosphere or upper atmosphere of the planets in a manner which is still not fully understood to produce bursts of low frequency emission. Because most objects are black-bodies, we shall emphasize continuum radiometry but also give some discussion of spectroscopic techniques and the measurement of non-thermal emission.

II. Observing Procedures

Historically most planetary observations have been made with single parabolic-reflector antennas. These have angular power response patterns in the sky which are complex Bessel functions but can generally be quite well represented by Gaussian distributions. For a circular aperture, the half-power beamwidth, HPBW, can be well approximated by

$$\mathrm{HPBW} \simeq 1.2\ \lambda/D \quad \text{(radians)} \tag{3}$$

where λ is the wavelength and D is the diameter of the telescope. The exact value of the constant depends upon the detailed illumination of the reflector

[1]Berge, G.L. and Gulkis, S. 1976, in Jupiter, ed. by T. Gehrels (Tucson: Univ. of Arizona Press), 621.

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surface by the feed element located at the focus[2] but the beamwidth will generally be much larger than the angular size of any planet. Thus investigation of longitudinal differences requires repeated measurements as the body rotates and no resolution in latitude is available.

Recent advances in interferometric techniques using more than one antenna have now allowed us to obtain greatly improved resolution and make aperture synthesis maps of several of the larger planets. This has allowed us to see, for the first time, the actual brightness distribution across the disk and has led to greatly improved understanding of many phenomena. Several aspects of observing are common to both single-dish and aperture-synthesis techniques. These will be presented together, but the specific procedures for each type of observing will be discussed separately.

A. Choice of Observing Frequency

There are several factors affecting the optimum frequency with which to observe a given planet. Because most of them have temperatures between about 50 and 750 kelvin, their emission peaks in the infrared, and we wish to observe at as high a radio frequency as possible in order to record the strongest signal. A high frequency or short wavelength is also desirable to obtain good resolution as shown by equation (3) in which the half power beamwidth of the antenna is directly proportional to the wavelength.

On the other hand, radio telescopes are often easier to operate at low frequencies. The surface tolerance of a parabolic reflector should be maintained to within an rms accuracy of one-sixteenth wavelength for good effici-

[2]Kraus, J.D. 1966, Radio Astronomy, (New York: McGraw-Hill) chapter 6.

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ency[3] and to date, no telescopes larger than about 15 m in diameter have been constructed to maintain that accuracy at millimeter wavelengths. Thus the largest telescopes operating at centimeter wavelengths currently offer better resolution than can be obtained at millimeter wavelengths. A new 25-m telescope being proposed by the National Radio Astronomy Observatory and a 30-m telescope being constructed by the Max Planck Institute for Radioastronomy should help to correct this problem.

Another equipmental problem is that parametric and maser amplifiers are difficult to construct at short wavelengths so that in the millimeter range the signal must be fed directly into a lossy mixer in a superheterodyne receiver system with no preamplification. These mixers can be cooled to reduce their noise level but are still not as effective as systems with some preamplification of the signal before mixing down to a lower frequency for additional processing. A promising new improvement in mixer technology is an SIS (superconductor-insulator-superconductor) device currently being developed[4]. In addition, wide-band bolometers, which are starting to be developed at millimeter wavelengths, should also help to alleviate this situation.

B. Measurements with Single Telescopes

1. General Techniques

a) On-off. The simplest method to measure the brightness of a planet is to merely move the beam on and off the position of the planet and record the difference in the signal. A typical time for the integration at each position

[3]Rusch, W.V.T. 1976 in Methods of Experimental Physics - Astrophysics, Radio Telescopes, volume 12, part B, edited by M.L. Meeks (New York: Academic Press), chapter 1.3.

[4]Phillips, T.G., Woody, D.P., Dolan, G.J., Miller, R.E. and Linke, R.A. 1981, IEEE Trans., MAG, 17, 684.

is perhaps one minute. For longer intervals, receiver or atmospheric fluctuations may cause a variable response, while for shorter intervals, too much time is spent in moving the telescope between positions. For weak signals many integrations may be added together to obtain the desired signal-to-noise ratio which is proportional to the square root of the observing time.

Unfortunately, several practical problems arise with a simple on-off technique. One is that there are numerous small-scale irregularities in the earth's atmosphere which can alter the propagation of radio signals between the on and off positions. We can compensate for much of this atmospheric fluctuation by employing two identical feed elements which are placed close together on opposite sides of the focal point of the telescope. The receiver is switched rapidly (tens of times per second) between these two feeds and the difference signal is synchronously detected. The separation is such that the two resultant beams are only a few beamwidths apart. In the near field of the telescope where the radiation patterns are nearly uniform cylinders, the two beams will overlap almost completely; where they start to diverge significantly because of diffraction depends upon the illumination patterns of the antenna but is approximately the Rayleigh distance, $D^2/2\lambda$, where D is the diameter of the telescope and λ the wavelength. Most of the turbulent eddies which cause the fluctuations occur within a few miles of the earth's surface well within the near field of most telescopes, and thus generally appear in both beams. The fluctuations caused by these common elements will be cancelled by the switching process, leaving only the contribution from the very small or distant cells which do not lie within both beams.[5]

In addition to atmospheric contributions, there can also be fluctuations in the background emission caused by other sources within the beam, possible

[5]Baars, J.W.M. 1970, Ph.D. thesis, University of Delft, chapter 5.

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sidelobe response from the sun or other strong neighboring sources, and even spurious pickup from objects on the ground. These can significantly alter the detected signal even when switching over a small angle. Because the planets move through the sky, we can correct for these effects by repeating the measurement at the same position on a subsequent day after the planet has moved away and then subtracting the two signals to obtain just the planetary emission. The schematic program for such a technique is shown in Figure 1. In this case we were observing Titan, the largest satellite of Saturn, and needed to consider spurious sidelobe responses from the bright planet. The path of Titan relative to Saturn for March 16-20, 1975 is shown by the curved line with the position at midnight on each date labeled. On March 19, beam switching observations were made at the position of Titan east of Saturn. First the positive responding beam (solid circle) was aimed at Titan while the negative responding one was on the sky background south of the satellite. Next the negative beam was directed at Titan's position while the positive one became the "off" beam to the north. The result of subtraction of the two switched radiometer outputs can be represented by the equation

$$\text{Signal} = [(\text{Titan} + \text{background}) - \text{background south}] - [\text{background north} - (\text{Titan} + \text{background})] \tag{4a}$$

$$= 2\ \text{Titan} + 2\ \text{background} - (\text{background north} + \text{background south}). \tag{4b}$$

Then, if the variation in the background is linear, we can set

$$\text{background} = \frac{\text{background north} + \text{background south}}{2}$$

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and the net result is

$$\text{signal} = 2 \cdot \text{Titan}. \tag{4c}$$

Because one beam is always on source, the signal-to-noise ratio in such a measurement is twice that of an ordinary on-off measurement.

A similar set of observations at exactly the same position was made on March 17 before Titan was there. The resultant of these represented the background emission from the sky at the satellite's position and so final subtraction of the measurement on March 17 from that on March 19 gave the true brightness of Titan. Finally, because spurious sidelobes in the antenna beam pattern should be symmetric, the observations were repeated at an exactly opposite point on the other (west) side of Saturn. They gave a similar result to the blank sky measurement as expected. The much smaller satellite Hyperion, although in the vicinity, was too weak to produce any detectable effect.

2. Scanning

If the position of the moving planet is not well known or if the pointing of the telescope is uncertain-often a problem at high frequencies because of both mechanical and atmospheric refraction effects - then an on-off technique can either miss the planet altogether or at least seriously degrade the response to the object. The position becomes a pair of new unknowns which therefore require additional data. These could be obtained by observing at an additional position in each of two perpendicular coordinates such that the beam was partially on the planet but the additional time for telescope motion generally makes it more practical to operate in a scanning mode. In this case the receiver output is sampled rapidly while scanning the telescope across the source in the direction along which the two beams are separated so that again the responses of both the positive and negative beams to the planet are recorded. It is most efficient to go forward and then backward across the source on the same line so that time is not wasted in telescope motion when data cannot be recorded.

The scans must be long enough to reach the background on each end so that a baseline may be interpolated and the flux density of the planet measured above it. For a Gaussian beam, for example, the intensity falls to 1 percent of the central value at a distance of 1.3 beamwidths from the peak. By then the signal is generally lost in the noise anyway so that a scan of total lengths 7-8 beamwidths will usually provide some baseline at each end of a dual-beam scan.

The peak position of the object can be found by a fit of the beam pattern to the data through a least squares procedure - often on-line - and then a perpendicular scan can be made through the peak of the first scan to complete the measurement. For the perpendicular scan, the feed apparatus should be rotated by 90° so that both beams again pass across the planet. The peak intensity on the second beam is, of course, the true source brightness and once the complete position is known, the peak intensity on the first scan can be corrected for the fractional offset of the beam. Generally relative positioning is known better than absolute, so if the planet is too faint to be seen on a single scan, several can be made over the same position and the data added together before fitting the averaged scan.

3. Polarization Measurements

Although thermal emission is intrinsically unpolarized, a small polarization will be generated as the emission from within the planet crosses the surface outward. The Fresnel equation for propagation at the interface between the surface and atmosphere can be evaluated to give the observed polarization as a function of dielectric constant and viewing angle[6]. This has been particularly useful in studying the moon and other terrestrial planets by interferometric techniques where a small change can very significantly affect the visibility functions (see Section IIc, below) parallel and perpendicular to the interferometer baseline[7,8]. In addition, valuable studies have also been made of the highly polarized synchrotron emission from Jupiter's radiation belts.

Because a given feed element can receive only one sense of polarization, either one orientation of linear or one handedness of circular, the general procedure is to switch between two orthogonal but concentric feeds in order to record directly one of the polarized intensities or Stokes parameters of the incoming radiation. Rotation of this feed system by 45° (or a phase shift for circular feeds) can then give a second Stokes parameter. The total intensity is determined by the standard beam-switching observations described above and the three parameters can completely specify a linearly polarized signal. To measure the circular polarization requires an additional parameter which can be obtained by insertion of a phase shifter between the two perpendicular feeds. For interferometric observations in which we have two separate antennas, the feeds in one can be rotated with respect to the other in order to achieve the same result when their signals are combined. With two concentric orthogonal feeds in each antenna, there are 4 possible pairs so the full polarization can be specified in a single observation.

[6]Heiles, C.E. and Drake, F.D. 1963, Icarus, 2, 281.
[7]Schloerb, F.P., Muhleman, D.O., and Berge, G.L. 1976, Icarus, 2a, 329.
[8]Muhleman, D.O., Orton, G.S., and Berge, G.L. 1979, Astrophys. J., 234, 733.

C. Aperture Synthesis

With the improvement of interferometric techniques in the last twenty years[9] it has become possible to obtain sub-arcsecond resolution at radio wavelengths and it is now possible to map the brightness distribution across most of the major planets. A full development of the techniques of aperture synthesis is far beyond the scope of this paper but we shall describe here a few of the key points. More information can be found in various review articles such as those in references 10, 11, and 12.

The brightness distribution of a complex radio source can be represented as a summation of Fourier components each of which is a sinusoidal temperature distribution of some amplitude, phase, and spatial frequency. This, of course, is an angular distribution and thus the spatial frequency is the number of cycles per radian across the sky rather than the more usual time varying function. If we can measure these components and add their contributions we can then reproduce the brightness distribution of the object. To see how we obtain such data let us consider the response of a pair of radio telescope separated by some distance, d, to radiation from a source at some angle θ with respect to the line joining the pair (see figure 2). The voltage at antenna B is the time varying function:

$$E \cos(\omega t)$$

where E is the amplitude, ω the angular frequency of the radiation, and t the time. At antenna A the signal will be the same except delayed by the longer path length it must travel or

[9] Ryle, M. and Hewish, A. 1960, Monthly Notices Royal Astron. Soc., 120, 220.
[10] Swenson, G.W. 1969, Annual Reviews of Astron. and Astrophys., 7, 353.
[11] Fomalont, E.B. and Wright, M.C.H. 1974, in Galactic and Extragalactic Radio Astronomy, ed. by G.L. Verschuur and K.I. Kellermann, (New York: Springer-Verlag) chapter 10.
[12] Hjellming, R.M. 1978, An Introduction to the Very Large Array, NRAO publication.

$$E \cos(\omega t + \frac{2\pi d}{\lambda} \cos \theta).$$

If the two signals are correlated in the receiver, generally by multiplication, and then passed through a low-pass filter to remove the rapidly varying radio frequency component, the resultant power will have the form:

$$V(A,B) = I \cos (\frac{2\pi d}{\lambda} \cos \theta) \tag{5a}$$

where V is called the visibility of the antenna pair A, B separated by distance, d, and I is the intensity which is directly proportional to E^2. This is the fundamental equation of interferometry and represents a quasi-sinusoidal fringe on the sky, the spacing of which depends only upon the separation of the two antennas in wavelengths. One fringe length is given by the angle θ which causes a one wavelength difference in the path length to the two antennas. As the earth rotates, the source appears to move across the sky through this fringe and so we can measure the amplitude and phase of this particular spatial frequency.

Our discussion so far has been one dimensional but if we could record the signal from a collection of pairs each with a different spacing, d, and in different directions we could build up a full two-dimensional picture of an object in the sky. Using the complex form of representation for the visibility of a point source given in equation (5a), we have

$$V(\underset{\sim}{b}) = I \cdot e^{2\pi i(\underset{\sim}{b} \cdot \underset{\sim}{s})} \tag{5b}$$

where $\underset{\sim}{b}$ is now the vector projection of the interferometer baseline onto the sky in wavelengths and $\underset{\sim}{s}$ is the vector position of the source in the sky. $\underset{\sim}{b}$ is often broken into two perpendicular components, u and v, in the east-west and north-south directions, respectively. $\underset{\sim}{s}$ is similarly expressed in terms of perpendicular coordinates, generally the astronomical coordinates of right ascension, α, and declination, δ. If the intensity is a variable function of position in the sky then equation (5b) becomes

$$V(u,v) = \iint I(\alpha,\delta)\, e^{2\pi i(\underset{\sim}{b}\cdot} d\alpha d\delta \tag{5c}$$

where I has been appropriately weighted by the response pattern of the individual antennas in the pair.

Equation (5c) can be recognized as a Fourier integral and so applying the properties of Fourier transforms, (e.g. reference 13), we can obtain the intensity distribution of the planet or other object from the relation

$$I(\alpha,\delta) = \iint V(u,b)\, e^{-2\pi i(\underset{\sim}{b}\cdot\underset{\sim}{s})} du dv. \tag{6}$$

Proper solution of this integral requires full coverage at each spacing in each direction which is only available from a completely filled aperture of large dimensions. In the practical application of aperture synthesis, a reasonable number of points are sampled and then uniformly gridded to allow fast Fourier transform algorithms to be applied to the data. Most instruments employ several antenna elements and also use changes in the source-fringe geometry caused by the earth's rotation to build up a large number of pair spacings. As the earth spins on its axis a given baseline located on its spherical surface will appear to rotate and also be differentially foreshortened with respect to a point on the sky so that a range of projected base-

[13]Bracewell, R.N. 1980, The Fourier Transform and its Applications, (New York: McGraw-Hill).

lines over a full semi-circle of directions can be obtained from a single pair in 12 hours of observing. The individual visibilities are stored as they are measured in a computer for the subsequent analysis. Usually one 12-hour observation is sufficient for a good map but sometimes the antennas are moved to a new baseline configuration and an additional set of visibilities is accumulated before a map is constructed.

Even well sampled maps are still incomplete, however, and the resultant synthesized beams can have significant sidelobe patterns which can distort the apparent brightness of an extended object. The general approach to correct for this messy antenna pattern is to "clean" the data.[14] This is done by an iterative process in which the "dirty" beam from an aperture synthesis observation is successively subtracted from the brightest spot on the map until some desired noise level is reached. Then the subtracted components are restored to the map with a Gaussian shaped pattern of the same beamwidth. In this manner the sidelobes of bright sources at different points are removed from other positions on the map and only the true brightness remains. Some attempts are also being made with planetary observations to subtract a uniform disk from the data to obtain a map of only the fine structure which is visible on the disk of the planet.

D. Calibration

1. Intermediate Calibration

It is simple to compare the signal from a planet with a known amount of power injected into the system between the feed element and the receiver. This provides a ready reference but leaves two problems if we are to measure the actual amount of radiation from the planet. First is the efficiency of

[14] Hogbom, J.A. 1974, Astron. and Astrophys. Suppl., 15, 417.

the telescope and second is absorption by the earth's atmosphere. Both of these can vary with time and position as will be described below so that a frequent (generally more often than once per hour) external calibration is important. This is provided by measurement of some cosmic source of known flux density which is near in the sky to the object of interest. Any change in the response to this known source can then be interpolated to give a calibration function for the system. A grid of bright calibration sources can be secured from various catalogs of sources which are available and it is usually possible to find such a source close to the program object so that changes between them are negligible. At high frequencies, Jupiter is often used as a good intermediate calibration for other planetary observations.

2. Absolute Calibration

The intermediate calibrators allow determination of very good relative values but we must know their absolute flux densities if we are to determine the true flux density of the planet in which we are interested. This requires determining the absolute gain of the antenna system and the atmospheric extinction.

a) Antenna gain - The absolute gain of a parabolic reflector and feed is extremely difficult to calculate exactly because of irregularities in the surface which are difficult to assess, spurious reflections from the support legs for the feed at the focal point, distortion of the illumination of the reflector by the feeds, etc. Also, as an antenna follows a source across the sky, the changing gravitational pull can alter all of the parameters. At long wavelengths absolute measurements have been made using large waveguide horns for which the gain can be accurately calculated (see the review in reference 15). These horns, of necessity, have fairly small apertures so that only the very strongest sources are bright enough to be accurately measured and then weaker sources must be compared with those to set up the full intermediate calibration grid. Sometimes a black disk of known temperature can be set up several kilometers away in the far field of the antennas and the response of the system recorded as it is scanned past the disk.[16] The disk is a well calibrated emitter but there can still be some spurious response from local terrain so the absolute values have an uncertainty of about 10%.

The primary calibrator at frequencies below about 25 GHz is the supernova remnant Cassiopeia A. The absolute measurements of it have been made at several frequencies,[17] and the spectrum can be well fit by a power law with decreasing flux density at higher frequencies, characteristic of synchrotron radiation rather than the thermal emission most common for the planets. Although this source which is the remains of an exploded star, is expanding and slowly fading, its decrease in flux density is well documented[18,19] and the absolute flux density should be known to better than 5% at any given frequency and date.

Because of its reduced flux density at higher frequencies and its somewhat extended size Cas A is not a good calibrator above about 25 GHz, however, and another source must be chosen. This is usually the compact ionized hydrogen cloud (HII region) called DR21. Its temperature and density can both be determined from its optical emission and because it is a thermal radiator the absolute radio spectrum of DR21 can be accurately calculated to provide a

[15] Findlay, J.W. 1966, Annual Review of Astron. and Astrophys., 4, 77.
[16] Troitsky, V.S. and Tseitlin, N.M. 1962, Radiofizica, 5, 623.
[17] Baars, J.W.M., Genzel, R., Pauliny-Toth, I.I.K., and Witzel, A. 1977, Astron. and Astrophys., 61, 99.
[18] Dent, W.A., Aller, H.D. and Olsen, E.T. 1974, Astrophys. J. Letters, 188, L11.
[19] Baars, J.W.M., Genzel, R., Pauliny-Toth, I.I.K., and Witzel, A. 1977, Astron. and Astrophys., 61, 99.

reference.[20] At still higher frequencies (greater than about 100 GHz) the emission from dust grains in the vicinity of DR21 make the spectrum of that object uncertain[21] and still other calibration techniques must be employed. These usually involve a careful calculation of all factors affecting the antenna pattern and then correction for the effect of the earth's atmosphere upon the signal.

b) Atmospheric effects - Molecular oxygen and water vapor in the earth's atmosphere have a number of rotational transitions at microwave frequencies which produce significant and variable absorption. Thus particularly where no calibrator outside the earth's atmosphere is available we must consider the extinction by the atmosphere. The transfer of radio signals through this atmosphere can be represented by

$$T_B(\nu) = T_o(\nu)\, e^{-\tau_\nu} + \int_0^{\tau_\nu} T_K e^{-(\tau_\nu - t_\nu)} dt_\nu \qquad (7)$$

where all quantities are at a given frequency, ν. T_B is the measured brightness temperature, T_o is the true brightness temperature of the source, T_K is the kinetic temperature of the atmosphere, τ is the total optical depth of the medium or $\int dt$, and dt is the opacity given by the expression $dt = \kappa ds$ where κ is the absorption coefficient and ds is the incremental path length through the medium. The first term on the right hand side of equation (7) represents the extinction of the source brightness; the second term adds an additional signal to the apparent brightness from the atmosphere. Because in the beam-switching mode the path through the troposphere of the two beams is nearly identical, the second term drops out in the difference expression and

[20] Dent, W.A. 1972, Astrophys. J., 177, 93.
[21] Ulich, B.L. 1974, Icarus, 21, 254.

we need consider only the extinction to determine the true brightness of the observed planet or other source. We might point out, however, that the atmospheric contribution in the second term does add noise to the system thus affecting the sensitivity.

At a given observing site the atmosphere can be well approximated by a series of plane parallel layers so that the path length and thus extinction through the atmosphere will vary as the secant of the zenith angle, Z. Measurements at two zenith angles should therefore be sufficient to determine the optical depth, τ. Often, however, the atmosphere varies on a time scale which is faster than that required for the source to move through a significant zenith angle and so the extinction is measured by taking "dip curves" with the antenna. In this procedure we utilize the second term in the right hand side of equation (7) by turning off the beam switch and observing blank sky at several positions between the zenith and the horizon. With virtually no background radiation the observed signal will be the temperature of the earth's atmosphere times the absorption coefficient integrated over the path length which again varies as secant (Zenith angle). The extinction and noise contributed by the atmosphere can be determined by a least squares fit to several points at different zenith angle. To tie all the measured signals to an absolute basis, a microwave absorber at a known temperature can be alternately placed in front of the feed to give an accurately known amount of power for comparison with the other values.[22] After consideration of the errors in all the various steps in performing an absolute calibration at millimeter wavelengths, we conclude that such measurements should have an absolute uncertainty of less than about 7 percent.[23]

[22] Ulich, B.L., Davis, J.H., Rhodes, P.J., and Hollis, J.M. 1980, IEEE Trans. Antenas Propagation, in press.
[23] Ulich, B.L. and Haas, R.W. 1976, Astrophys. J. Suppl., 30, 247.

III. Applications

A. Studies of the Atmospheres of the Planets

Not only does the earth's atmosphere contain molecules with microwave transitions but so do the atmospheres of several other planets. In addition to oxygen and water vapor, molecules of carbon monoxide, carbon dioxide, ammonia, and hydrogen affect the microwave opacity in various planetary atmospheres. In general the transition probabilities and/or abundance of these molecules are sufficiently small so that a high opacity is reached only in the deep atmosphere where pressure broadening has smeared the individual rotational transitions into a single broad absorption band. Therefore we cannot use spectrometric techniques to look at individual line profiles, measure velocities, etc., but merely use moderate bandwidth continuum radiometry at several wavelengths to look at the general band structure. Analysis of the measured temperature across the band gives us a profile of the temperature distribution with depth in the planetary atmosphere. To evaluate it, we consider the transfer equation of radiation through that planet's atmosphere which is identical to that through the earth's (equation 7) except that T_o is now the brightness temperature of the surface of the planet and κ_ν is the absorption coefficient of the materials in its atmosphere.

In the center of the molecular band where the absorption coefficient is greatest we reach a large optical depth in a short path length so that in the center we measure the temperature of the high atmosphere whereas in the wings, with the lower absorption coefficient, we receive radiation from deeper down. The tropospheres of all the planets are heated from below by convection and so the outward decrease in temperature produces an absorption band with the lowest brightness in the center. Figure 3 [24] shows the profile of Jupiter's

[24] Tomasko, D., Dickel, J.R., and Goodman, G.C. 1974, Bull. American Astron. Soc., 6, 377.

thermal emission at microwave frequencies where the absorption is caused by an inversion transition of the ammonia molecule centered at a frequency of 23.7 GHz (or a wavelength of 1.23 cm). On the short wavelength side there is overlap with pressure-induced dipole absorption by the hydrogen molecule.[25] The observations are represented in the figure by dots with their error bars and the solid lines represent the brightness temperature expected for models of Jupiter's atmosphere which is almost pure hydrogen but with trace amounts of methane (0.3% by number of molecules) and the ammonia abundances given. The different materials not only affect the microwave opacity but also control the temperature gradient in the atmosphere which has a value of -2°/km The effective planetary temperature was 130 K.

Infrared measurements have indicated that above the troposphere, Jupiter has a stratosphere where the temperature rises again. Several attempts have been made to detect narrow emission lines of ammonia from this region but with negative results.[26,27] It has been possible to conclude that the relative abundance of ammonia in the stratosphere is less than 1/100 of that in the lower atmosphere. Apparently the ammonia has been frozen out in a cloud layer and does not rise above it.

The one molecular line which has been seen at sufficiently low pressure in planetary atmospheres to require actual spectrometric techniques and give some detailed information is the 115 GHz J=1→0 transition of carbon monoxide in the upper atmospheres of Venus and Mars.[28,29] These data allow us to probe

[25] Goodman, G.C. 1969, Ph.D. thesis, University of Illinois.

[26] Gulkis, S., Klein, M.J. and Poynter, R.L. 1974, in Exploration of the Planetary System-IAU Symposium #65, ed. by A. Woszcyyk and C. Iwaniszewski, p. 367.

[27] Dickel, J.R. 1976, Icarus, 29, 283.

[28] Kakar, R.K., Waters, J.W. and Wilson, W.J. 1976, Science, 191, 379.

[29] ____. 1977, Science, 196, 1090.

the chemistry and dynamics in a high altitude range which is not accessible to direct study by other means. At this high frequency the overall required bandwidth is quite large and the spectrometer consists of a series of narrow bandwidth filters tuned to adjacent frequencies in the intermediate-frequency stage of the receiver after the signal has been mixed down from the original high frequency. The responses of the individual filters can be calibrated by observing a source of continuum radiation which should produce the same response in each channel.

B. Planets Without Atmospheres

Microwave radiometry can also give us important information about the surface materials of bodies without atmospheres. Ever since the first radiometric observations of our nearest planetary neighbor, the moon, in 1945[30] we have been acquiring very detailed information on the thermal and dielectric properties of the surface materials of the planets. The solid surface receives heat from incoming solar radiation which is transported downward into the planet by conduction. At a given point the input of heat necessary to raise the temperature a given amount is proportional to $(\rho s/k)^{1/2}$ where ρ is the density, s the specific heat of the material, and k the thermal conductivity, but the conductivity also enters to carry the heat away from the region so the final temperature is governed by a quantity $(k\rho s)^{1/2}$ which is called the thermal inertia. It measures the effective resistance of a medium to heating.

Because the planets spin, they will alternately be exposed to the incoming solar radiation and to cold sky so that the heat flow actually reverses periodically and a thermal wave is set up in the surface layers. This has a

[30] Dicke, R.H. and Beringer, R. 1956, Astrophys. J., 103, 375.

wavelength of

$$L_{thermal} = (Pk/\rho s\pi)^{1/2} \quad (8)$$

where P is the spin period of the object and the other symbols are as defined above. This variation in temperature has an interesting illustration in the planet Mercury which, because of its very elliptical orbit around the sun and its tidally locked spin period of exactly 2/3 its orbital period, has a permanent difference in average solar input at various longitudes. The resultant brightness curves, shown in Figure 4,[31] are thus different at different longitudes.

The thermal parameters can also vary with depth below the planetary surface and to relate them to the observed brightness requires a knowledge of the depth, ℓ, from which the radio-emission arises. This given by

$$\ell = (2\pi\varepsilon^{1/2}\tan\Delta)^{-1} \quad (9)$$

where ε is the dielectric constant and $\tan\Delta$ is a quantity called the loss tangent of the material which is given by

$$\tan\Delta = 2\sigma\lambda/c\varepsilon \quad (10)$$

where σ is the electrical conductivity. The loss tangent essentially causes a phase change in the wave as it propagates which produces self interference or an effective absorption. If the material is layered there will also be a reflection and change in emissivity at each interface which depend upon the

[31]Klein, M.J., 1970, Radio Science, 5, 397.

dielectric constant. With appropriate values for the various parameters at each depth the equation of radiative transfer can be integrated outward to determine the emergent intensity at the planetary surface for comparison with the data at several wavelengths. Such analyses have recently been applied to several satellites and asteroids as well as the terrestrial planets. In general we find that they require layered surfaces with a coating of dust, having low thermal inertia, overlying more compacted material.[32,33] On the moon, the availability of insitu data coupled with the very high resolution available from radio interferometry have allowed considerably more sophisticated analysis such as the derivation of actual heat flow rates and conductivity in the surface layers rather than just mean thermal inertia parameters[7].

C. Bodies with Both a (Radio) Visible Surface and an Atmosphere.

The planet Venus has a very thick atmosphere, but carbon dioxide, the major constituent, has only a very small radio opacity. The wing of its smeared rotational bands is evident at short wavelengths so that the effective altitude at which the temperature is measured lies up in the cooler atmosphere, but at a wavelength of 6 cm we see through the atmosphere to the 750 K solid surface of the planet (Figure 5).[34] This spectrum, reveals an additional phenomenon which has never been explained, however: at longer wavelengths, beyond about 15 cm, the brightness temperature drops again. This feature has been further confirmed observationally[35,36] so the effect is real but we know of no material which absorbs in that spectral range. Refraction in the atmosphere

[32]Morrison, D.D. and Klein, M.J. 1970, Astrophys. J., 160, 325.
[33]Dickel, J.R. 1979, in Asteroids, ed. by T. Gehrels (Tucson: Univ. of Arizona Press), 212.
[34]Warnock, W.W. and Dickel, J.R. 1972, Icarus, 17, 682.
[35]Condon, J.J., Jauncey, D.L. and Yerbury, M.J., 1973, Astrophys. J., 183, 1075.
[36]Muhleman, D.D., Berge, G.L. and Orton, G.S. 1973, Astrophys. J., 183, 1081.

or an ionosphere are also insufficient to explain this peculiar effect which still defies understanding.

Another interesting feature of Venus is the lack of any detectable diurnal temperature variation at the surface.[37,38] Although its rotation period with respect to the sun is very slow, about 120 earth-days, the tremendous heat capacity of an atmosphere of CO_2 -- almost 100 times as dense as the earth's atmosphere, does not allow significant temperature changes.

D. Aperture Synthesis Maps of Jupiter's Radiation Belts.

An interesting application of aperture synthesis has recently been applied to observations of Jupiter. Although it takes 12 hours to accumulate the data for one map, the planet rotates in slightly less than 10 hours, so it is not possible to fully map features at a particular longitude on Jupiter in a single session. To overcome this, de Pater[39] observed the planet for 12 hours on each of six successive days and then performed a massive sorting of the data based upon the comensurability of the earth's and Jupiter's rotation periods to obtain an identical spatial frequency coverage for separate maps every 15° in Jovian rotation angle. Figure 6 shows four of the twenty-four such maps obtained by this procedure at a wavelength of 21 cm. The twenty-four frames have been combined into a movie showing the rotation of the planet. In this case most of the emission is synchrotron radiation from relativistic electrons trapped in Jupiter's magnetosphere and the observed changes can be attributed to the varying aspect of the complex magnetic field which we view as the planet rotates and also the bunching of particles caused by Jupiter's satellites and other conditions.

[37] Dickel, J.R., Warnock, W.W. and Medd, W.J. 1968, Nature 220, 1183.
[38] Morrison, D.D. 1969, Science, 163, 815.
[39] de Pater, I. 1980, Astron. and Astrophys., 88, 175.

IV. Concluding Remarks

All the standard techniques of radio astronomy are necessary for studying the many aspects of the planets and, because of their peculiar nature, several additional considerations become important. Their various motions, for example, affect the procedures adopted for both on-off and aperture synthesis observations. The high pressures found in some planetary atmosphere significantly alter standard spectrometric techniques.

As equipment improves at millimeter wavelengths and aperture synthesis techniques become more refined, many new data should continue to become available to help us understand the exciting variety of objects in the solar system. Sensitive radiometry at both centimeter and millimeter wavelengths of a much larger sample of asteroids and satellites is currently in progress and planned. This will give us the opportunity to establish similarities and differences in characteristics between the various classes of objects and see how they relate to other bodies.

The opportunities of aperture synthesis observations are ever expanding. The recently completed Very Large Array of Radio Telescopes is already being used for observations of Venus, Jupiter (its disk, radiation belts, and satellites), Saturn plus its amazing ring system, Titan, Uranus and several asteroids. Plans to observe Neptune and other lesser bodies are in the works. These observations allow the opportunity of seeing features on the larger objects and recording the actual sizes and shapes of the smaller ones. For example, the observations of Saturn allow us to not only measure the brightness changes between the center of the disk and the edges caused by opacity in the atmosphere but also to see the absorption by the rings in front of the disk and their emission outside. The separate rings can also be recognized. As these and similar observations are completed we are becoming able to characterize the radio emission from other real and understandable worlds rather than mere point sources of emission.

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John R. Dickel was born in New York and educated at Yale (BS in physics 1960) and the University of Michigan (Ph.D. in astronomy 1964). He then went to the University of Illinois where he has been on the faculty of the Astronomy Department ever since. He began his research activities in planetary radio astronomy in 1956 while an undergraduate student and continues to work about half time in this area. His other research activities include radio studies of supernova remnants and the dynamics of galaxies. He has observed extensively with most of the world's major radio telescopes and has published over 75 research papers in professional journal. He is a member of the American Astronomical Society, the International Astronomical Union, Sigma Xi, and URSI.

Figure Captions

1. A schematic observing procedure for an on-off measurement of Saturn's satellite Saturn to remove the effect of background radiation and spurious responses from Saturn itself. The circles indicate the half-power response width of the antenna and the numbers next to the tracks of the planetary motion are dates in March 1977.

2. Geometry of a simple interferometer with 2 antennas A and B separated by a distance d.

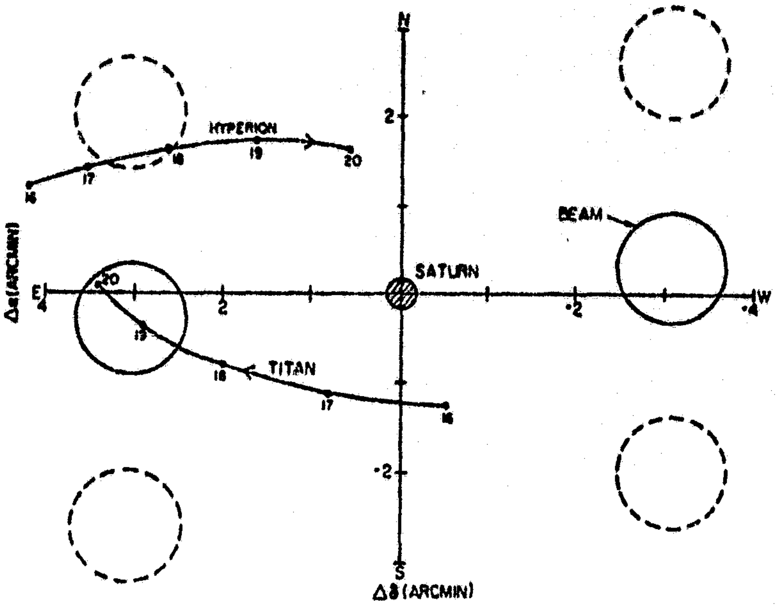
3. The observed microwave spectrum of the disk of Jupiter compared with calculated models of Jupiter's atmosphere for several different abundances of ammonia (reference 19).

4. The variation in the microwave brightness temperature for several different longitudes on Mercury as a function of solar illumination (from reference 25).

5. The observed microwave spectrum of Venus illustrating absorption by its atmosphere at the shortest wavelengths, emission from the planetary surface beginning at a wavelength of about 6 cm and then an unexplained decrease in brightness at wavelengths longer than about 15 cm (reference 28).

6. Maps of the non-thermal radio emission from Jupiter at a wavelength of 21 cm. The circle represents the visible disk of the planet. The longitude of the observed central meridian of Jupiter is shown in the upper left of each

frame. The left hand side shows the total intensity and the right shows the circularly polarized emission which varies as we view the magnetic field at different inclinations with Jupiter's rotation. The solid contours represent right-hand and the dashed contours left-hand polarization (reference 33).



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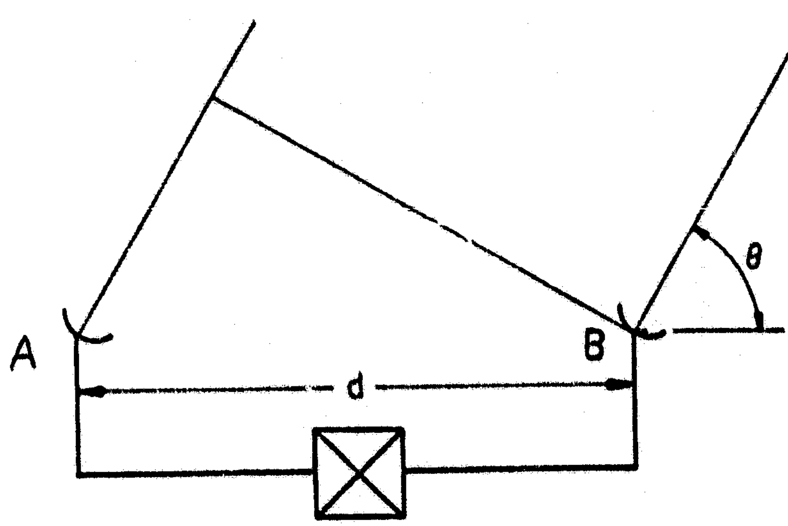
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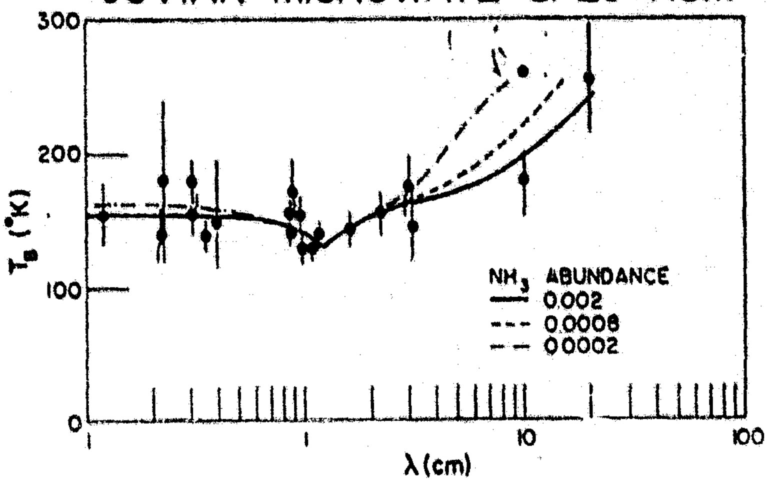
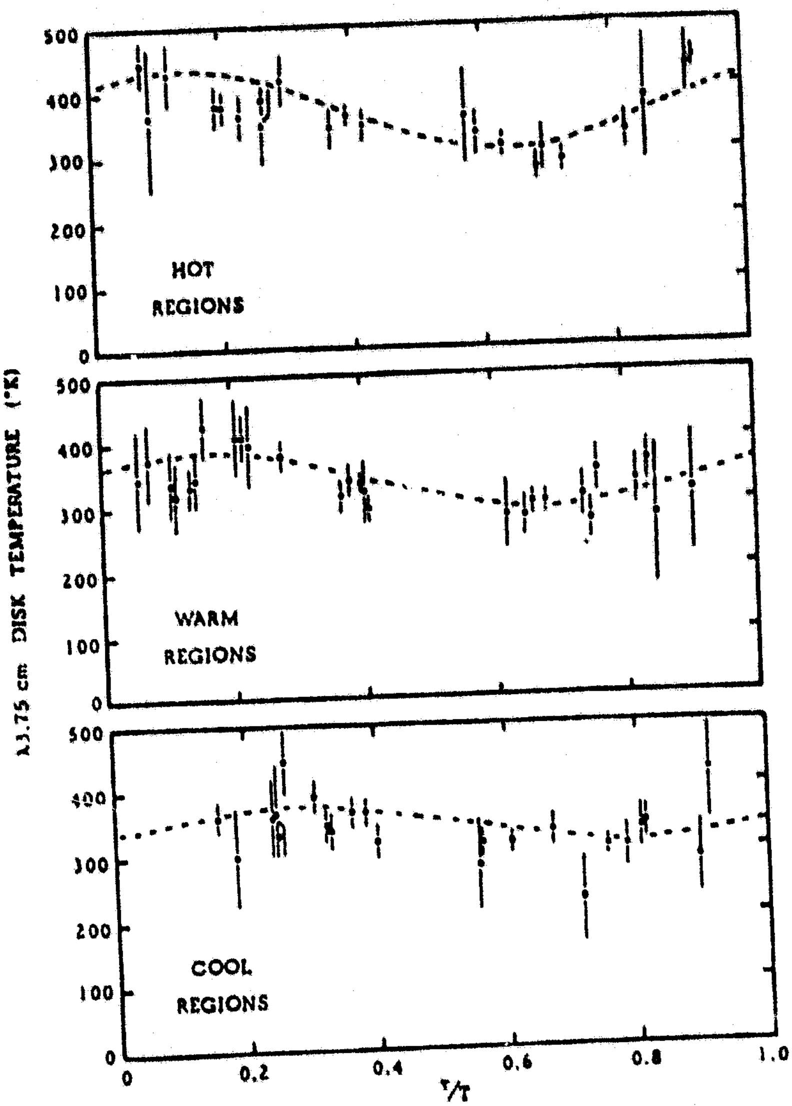
JOVIAN MICROWAVE SPECTRUM





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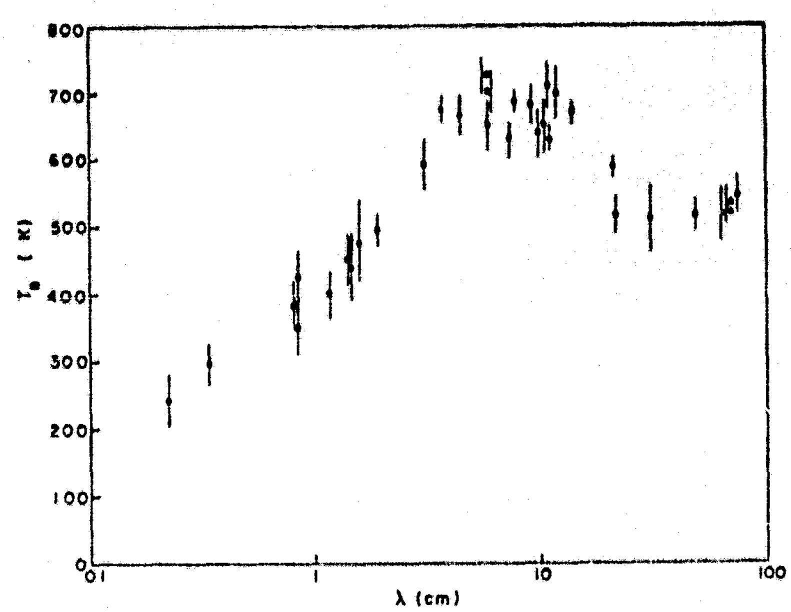

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