II Session: JUPITER, AS OBSERVED AT SHORT RADIO WAVES

Jupiter, as Observed at Short Radio Wavelengths

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The history of our knowledge of the microwave emission from Jupiter is reviewed briefly, highlighting only what appear to the reviewer to be the significant advances. The Van Allen belt emission has a constant flux density, and polarization from 200 Mc/s to 3000 Mc/s, but probably decreases at frequencies above 3000 Mc/s. The radiation from the disk corresponds to near infrared temperatures at wavelengths of a few centimeters, but may increase at longer wavelengths, reaching twice this value at 10 cm. The rocking of the plane of polarization and the beaming of the radiation are discussed. The present state of knowledge is reached with the presentation of a preliminary map by Berge showing the distribution of brightness over the radio source, and a comparison of this map with preliminary model calculations by Ortwein, Chang, and Davis. This comparison shows that there are two Van Allen belts having very different electron pitch angle distributions.

1. Discovery

The long-wavelength burst radiation from Jupiter, was, as Douglas [1964] has taught us, discovered serendipitously. By contrast our knowledge of the microwave radiation is mainly the result of systematic studies, although this is not to say that there have not been plenty of surprises.

In the first series of observations of microwave emission from the planets, which were made by Mayer, McCullough, and Sloanaker [1958a, b] at the Naval Research Laboratory in 1956, radio emission from Jupiter was measured at a wavelength of 3.15 cm. The equivalent disk temperature of 145 ± 26 °K was in reasonable agreement with the infrared temperature of 130 °K [Menzel, Coblentz, and Lampland, 1926] and so excited no comment. However, when 2 years later Sloanaker [1959] extended observations of the emission to a wavelength of 10 cm, he detected Jupiter much more easily than he expected. The measured flux density corresponded to a disk temperature of 600 °K. This result was reported at the 1958 Paris Symposium on Radio Astronomy, and when the significance of the result had been appreciated many radio observatories began searching for emission at longer wavelengths, so that a year later detection of Jupiter emission out to a wavelength of 68 cm had been reported [Drake and Hvatum, 1959; Epstein, 1959; McClain, 1959; Roberts and Stanley, 1959]. The longest wavelength reported to date is 169 cm, where Gower [1963] has successfully measured the emission.

2. The Spectrum of the Microwave Emission

Figure 1 shows the spectrum of the emission. Over the decimetric range the flux density is, within the errors, constant, the total emission (the sum of two orthogonal polarizations) being $6.7 \pm 1.0 \times 10^{-26}$ $\mathrm{Wm^{-2}(c/s)^{-1}}$ at the standard distance of 4.04 A.U. In the centimetric range the thermal emission from the disk becomes appreciable. It is equal to the nonthermal component at a frequency ~ 5000 Mc/s (6 cm) and becomes increasingly dominant at higher frequencies. It is difficult to determine the nonthermal contribution in this range, both because it is a small part of the total emission, and because the intensity of the thermal component cannot be predicted with sufficient accuracy. In figure 1 the contribution expected from a uniformly bright disk at a temperature of 130 °K—the infrared temperature—is indicated by the length of the arrows. However more detailed theories of atmospheric absorption predict slightly different effective temperatures [Field, 1959; Giordmaine, 1960; Thornton and Welch, 1963]. At the highest frequencies it would certainly be possible to attribute all the radiation to thermal emission.

Observationally the thermal and nonthermal components could be separated by studying the angular distribution. At a wavelength of 10.4 cm, Berge [1964, 1965] has evidence that the disk component is about twice that expected on the basis of the infrared temperature.

It should be mentioned that the *apparent* flux density at the longer decimetric wavelengths underwent some rather violent excursions. At a wavelength of 68 cm Drake and Hvatum [1960] initially measured a flux density of 9×10^{-26} $\mathrm{Wm^{-2}(c/s)^{-1}}$ in May 1959, but a few months later found a figure of only $2 \pm 2 \times 10^{-26}$ $\mathrm{Wm^{-2}(c/s)^{-1}}$. Similarly in March 1960 at a wavelength of 74 cm, Long and Elsmore [1960] reported the flux density was less than 2×10^{-26} $\mathrm{Wm^{-2}(c/s)^{-1}}$. It now seems likely that these apparent variations were due to confusion problems. Figure 2 illustrates how serious these problems are at the longer wavelengths. This figure shows a series of six scans made at a wavelength of 1 m. Each of the scans was made with a different polarization, and alternate scans are in the

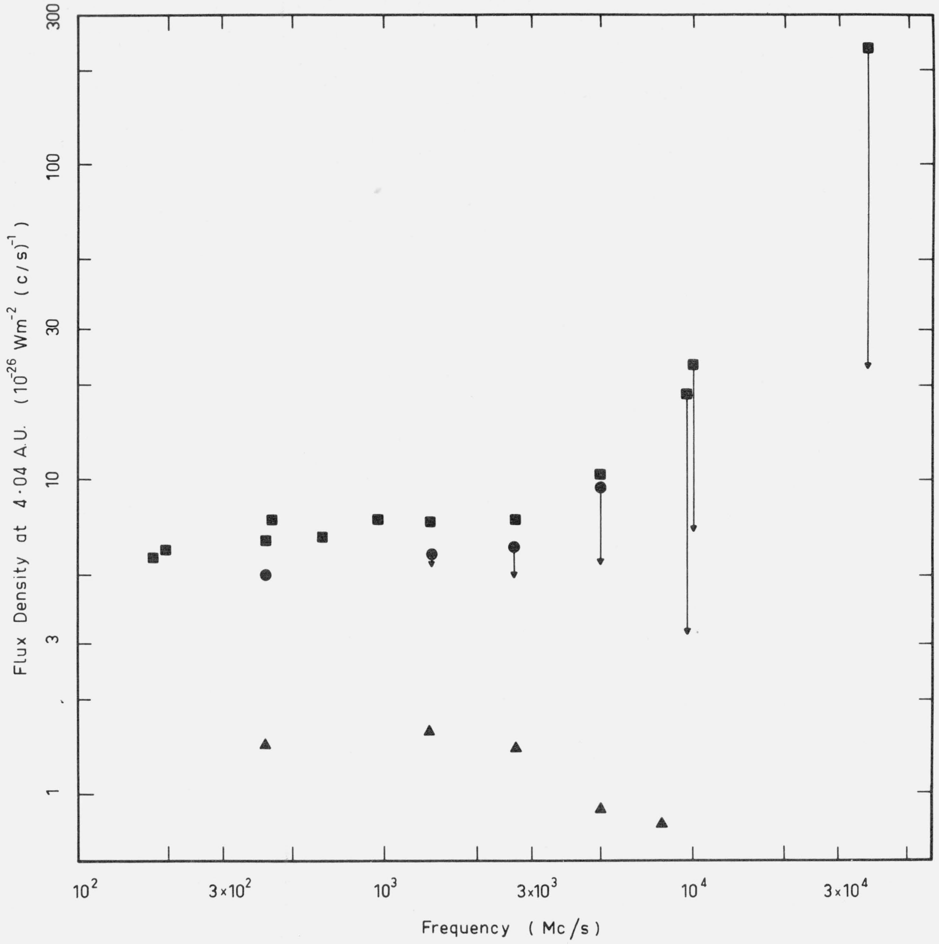

FIGURE 1. *The spectrum of the microwave emission from Jupiter at a distance of 4.04 A.U.*

The total flux density is shown by squares, the unpolarized flux density by circles, and the polarized flux density by triangles. The length of the arrows indicates the contribution which would be made by the thermal emission from the disk if it were uniformly bright at a temperature of 130 °K.

The points at 408 Mc/s, 960 Mc/s, 1410 Mc/s, 2650 Mc/s, and 5000 Mc/s [Roberts and Komesaroff, 1965] and at 620 Mc/s [Roberts and Ekers, 1965] are on a uniform flux density scale and refer to the intensity in the Jovomagnetic equator. Other points are from Thronton and Welch [1963] (37,000 Mc/s), Gol'nev, Lipovka, and Pariiskii [1964] (10,000 Mc/s), Mayer [1961] (mean of NRL values at wavelengths near 3.1 cm), Haddock and Dickel [1963] (8000 Mc/s), Kazes [1964], and Tiberi [1965] (430 Mc/s), Kazes [1964] (195 Mc/s), and Gower [1963] (178 Mc/s).

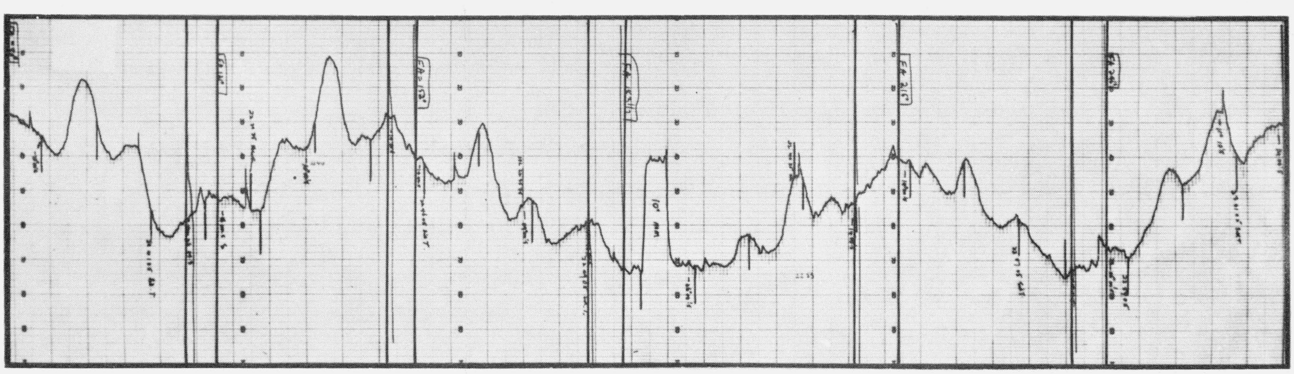

FIGURE 2. *Scans across Jupiter at a wavelength of 1 m.*

The polarization of successive scans differs by + 30°of position angle; alternate scans are in the opposite sense. A noise lamp calibration appears at the start of the fourth scan. Notice how the confusion problem is made worse by the polarization of the background; e.g., compare scans 1 and 5 [Roberts and Komesaroff, 1965].

opposite sense. The largest peak on each scan is in fact due to Jupiter, but clearly the irregularities in the background can cause serious errors in estimates of the flux density. The situation is further complicated by the polarization of the background; e.g., compare scans 1 and 5.

In principle this difficulty can be overcome by measuring the same part of the sky with the same instrument after Jupiter has moved away. This has been done in only about half the observations reported to date, and even when this is done the subtraction process tends to increase the errors considerably.

3. Polarization

The discovery of the excess decimetric emission from Jupiter came in the same year as the discovery of the Van Allen belt surrounding the Earth. It was natural, therefore, for Drake and Hvatum [1959] to suggest that the Jupiter radiation might be emission from electrons spiraling in a radiation belt surrounding that planet. This idea was developed by several authors [Roberts and Stanley, 1959; Field, 1959, 1960, 1961; Chang and Davis, 1962] and Field's prediction of the polarization properties of the emission spurred Radhakrishnan and Roberts [1960] to search for linear polarization. At a wavelength of 31 cm these authors found that the radiation was 20 to 30 percent linearly polarized with the E-vector approximately in the equatorial plane of the planet.

Later observations have shown that the polarization of the extrathermal component is essentially constant over the range from 300 Mc/s (1 m) to 2650 Mc/s (11.3 cm) (fig. 1). Over this range the polarized component is $\simeq 1.5\times10^{-26}$ Wm^{-2} (c/s)$^{-1}$ and the degree of polarization of the extrathermal emission, 0.22. At higher frequencies there is evidence that the polarized component decreases (fig. 1) and by 8000 Mc/s (3.75 cm) amounts to only 0.8×10^{-26} Wm^{-2} (c/s)$^{-1}$. As indicated earlier it is not clear whether the total extrathermal emission falls off in this way, or whether the degree of polarization is decreasing.[1]

The discovery of substantial linear polarization certainly supported the theory that magnetic bremsstrahlung was the source of the radiation. The constancy of the polarization over a wide range of frequencies is consistent with synchrotron, but not cyclotron, emission [Field, 1961; Roberts, 1963]. Chang and Davis [1962] have shown that mirroring electrons trapped in a dipole field will emit synchrotron radiation with 22 percent linear polarization provided the electrons mirror at suitable distances from the magnetic equator, i.e., provided the electrons at the equator are in suitable, relatively flat, helices.

The constancy of the intensity across the frequency spectrum would be explained if the electrons had a differential energy spectrum $\propto E^{-1}$. This is very much flatter than the E^{-5} observed in the Earth's Van Allen belt. The spectrum could also arise with a steeper energy distribution if the higher energy electrons were preferentially trapped in shells closer to the planet, where the magnetic field is greater. In fact, the known details of the spectrum are consistent with the radiation being that of monoenergetic electrons with a critical frequency $\sim 3\times10^3$ Mc/s.

3.1. Rocking of the Plane of Polarization

In 1961 Morris and Berge [1962] discovered that the direction of polarization was not constant, but that as the planet revolved the direction rocked through nearly $\pm$ 10° from a mean value almost perpendicular to the axis of rotation. The direction of polarization of synchrotron emission is determined by the direction of the magnetic field. Hence Morris and Berge suggested that the magnetic poles on Jupiter did not coincide with the poles of the rotational axis, but, as on the Earth, were displaced some 10° from the rotational axis. As the planet rotates, the mean direction of the magnetic field as seen from the Earth rocks first to one side and then to the other of the rotational axis. With this simple observation Morris and Berge were able to locate the magnetic poles on Jupiter. The most recent measurements put the pole in the northern hemisphere at a System III longitude of 193° $\pm$ 8°, and displaced 10.0°$\pm$0.5° from the axis of rotation [Roberts and Komesaroff, 1965]. The quoted errors on the longitude of the pole arise from uncertainties of interpretation, as will be made clear below.

Figure 3 shows the rocking of the plane of polarization as recorded with the Australian CSIRO 210-ft telescope at wavelengths of 11.3 cm and 21 cm [Roberts and Komesaroff, 1964]. Notice that the curve is not sinusoidal. There is an asymmetry which is due mainly to a second harmonic term, amounting to 7 percent in the 11.3-cm data and 15 percent in the 21-cm data. At longer wavelengths variable Faraday rotation in the Earth's ionosphere makes it difficult to define this curve precisely.

It seems most likely that this departure from a sinusoidal form indicates some departure from symmetry in the magnetic field. In other words, the variations from a centered dipole field which were discussed earlier in this conference in connection with the decametric bursts, are still producing detectable effects as far out as the Van Allen belts. The alternative of variable shadowing of the emitting areas by the planet itself [Warwick, 1964] now seems unlikely. For a belt three times the size of the planet theoretical estimates place the shadowing at only $\sim$ 6 percent [Thorne, 1964; Ortwein, Chang, and Davis, 1964], and furthermore the shadowed areas are uniformly polarized. Of course, differential shadowing could be important if there were appreciable radiation from an asymmetrically placed belt closer to the planet.

By observing the rocking of the plane of polarization the rotation period of the magnetic field of Jupiter can be determined. Plots such as those of figure 3, in which data taken over a period $\sim$ 1 week are plotted against System III longitude, form such clearly defined curves that it seems that the rotation period must be close to System III. More accuracy is ob-

[1] Note that in figure 7 of Roberts and Komesaroff [1965] the polarized intensity at 5000 Mc/s is incorrectly plotted at twice the value stated in the text.

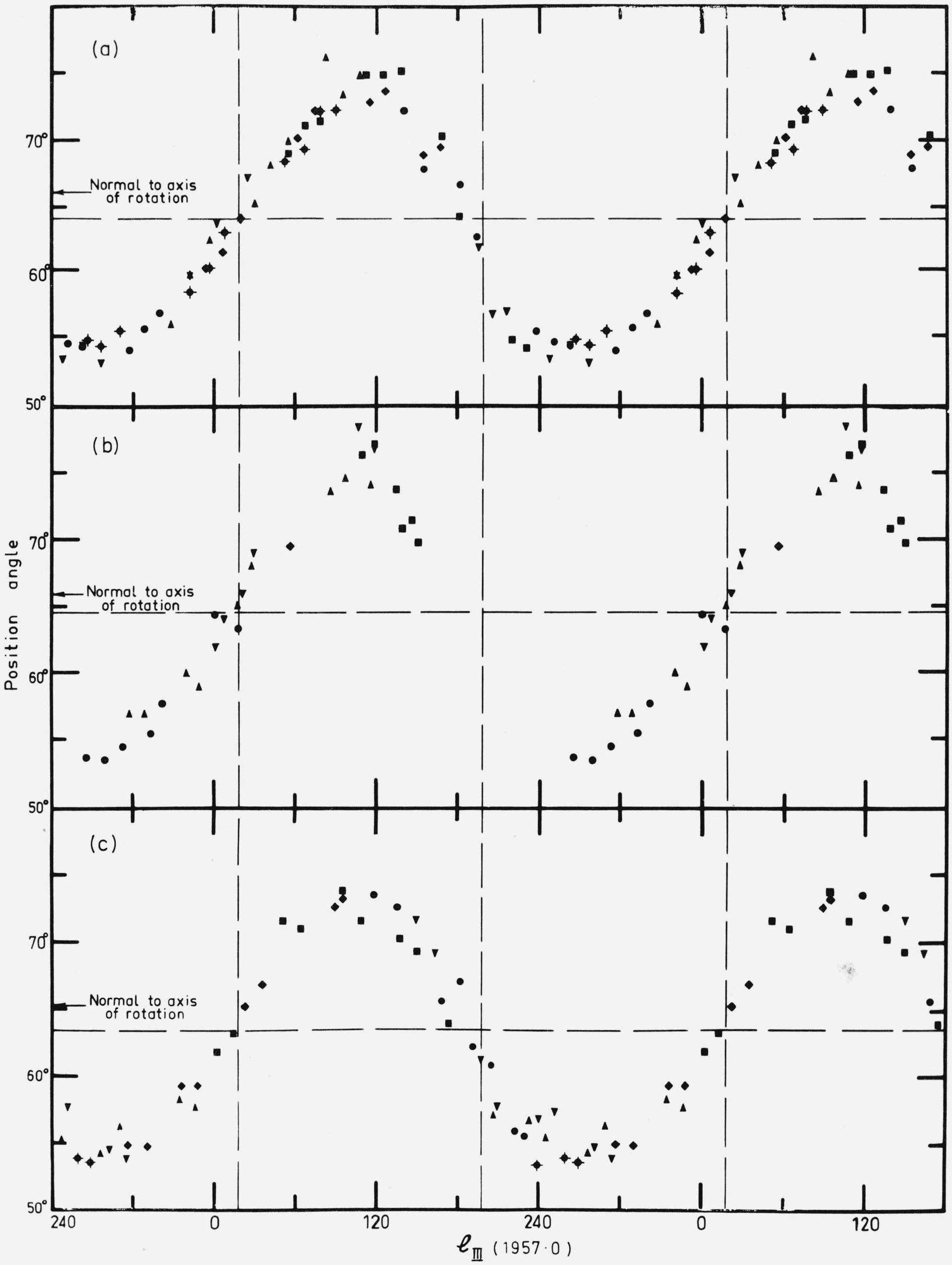

FIGURE 3. *Position angle of the maximum electric vector of the received Jovian radiation as a function of IAU System III longitude.*

(a) 21 cm, 1963 August; (b) 21 cm, 1962 August-September; (c) 11.3 cm, 1963 November. To assist in the comparison of the shapes and symmetries of these curves and those in figure 4, dashed lines are shown (i) at the position angle midway between the maxima and minima of the curves, and (ii) at longitudes 18° and 198°, the longitudes of approximate symmetry of the total intensity curves (fig. 4). The different observing days are distinguished by different symbols [Roberts and Komesaroff, 1964].

tained by comparing the two sets of 21-cm observations shown in figure 3 which were taken a year apart (1962 August-September and 1963 August). This comparison suggests that the mean rotation period between 1962 August and 1963 August coincided with the IAU System III (1957.0) within ± 0.5 sec [Roberts and Komesaroff, 1964].

4. Variation of Intensity

A variation of the total intensity as the planet rotates has been reported by several authors [McClain, 1959; Morris and Berge, 1962; Gary, 1963; Rose, Bologna, and Sloanaker, 1963; Bash et al., 1964; Roberts and Komesaroff, 1964, 1965; Tiberi, 1965; Roberts and Ekers, 1965]. In some of these observations only one plane of polarization was recorded so that the effects of the rocking of the plane of polarization and the variations of the total intensity cannot be uniquely separated. Figure 4 shows observations made at Parkes in which at least two orthogonal polarizations were recorded [Roberts and Komesaroff, 1965; Roberts and Ekers, 1965]. The results at wavelengths of 11.3 cm, 21 cm, and 48 cm are all very similar. The total intensity has two approximately equal maxima per revolution, while the minimum near $l_{III}=198°$ is somewhat lower than the minimum near $l_{III}=18°$.

At 74 cm much less variation was recorded. Such a change over a wavelength range of 3/2 is inherently unlikely. Furthermore, at the nearby wavelength of 70 cm Tiberi [1965], working at Arecibo, has found a variation with rotation. The present discussion will therefore be confined to the 11.3-cm, 21-cm, and 48-cm results.

There is also evidence for a small variation of the degree of polarization with rotation. The maximum degree of polarization of the Van Allen belt radiation is approximately 0.22 and it drops to approximately 0.19 near longitude 170° [Roberts and Komesaroff, 1965].

There were persistent reports in the literature of variations in the intensity of Jovian decimetric emission over longer periods of time, and indeed of a correlation of these variations with solar activity [Drake and Hvatum, 1960; Sloanaker and Boland, 1961; McClain, Nichols, and Waak, 1962; Roberts, 1962a, b; Roberts and Huguenin, 1963]. In the experience of the present author the variations found for Jupiter have never been greater than those found for other radio sources observed with the same signal/noise or signal/confusion ratio. The constancy of the radiation is illustrated by the two sets of 11.3-cm data and the two sets of 21-cm data in figure 4. The differences of up to 4 percent between these data appear to be within the errors. This agreement between data recorded at times separated by a year, and also the small scatter of the points about a mean curve in the data with the best signal/noise (11.3 cm, 1964 November, and 21 cm, 1963 August) show that the effect on the total intensity of anything other than the rotation of the planet (e.g., the position of Io) must be very small indeed. Bash et al., [1964] also set a very low limit to long-term changes in intensity, and Dickel [1965] has similarly failed to find any effect of Io.

In fact, the variation of the total intensity with rotation is sufficiently constant so that it provides an accurate method of determining the rate of rotation of the Jovian magnetic field. The System III longitudes of the minima in the two sets of 11.3-cm data in figure 4 agree to within $\pm 7°$ and fix the mean rotation period over the year 1963 November to 1964 November as coincident with the IAU System III within ± 0.8 sec.

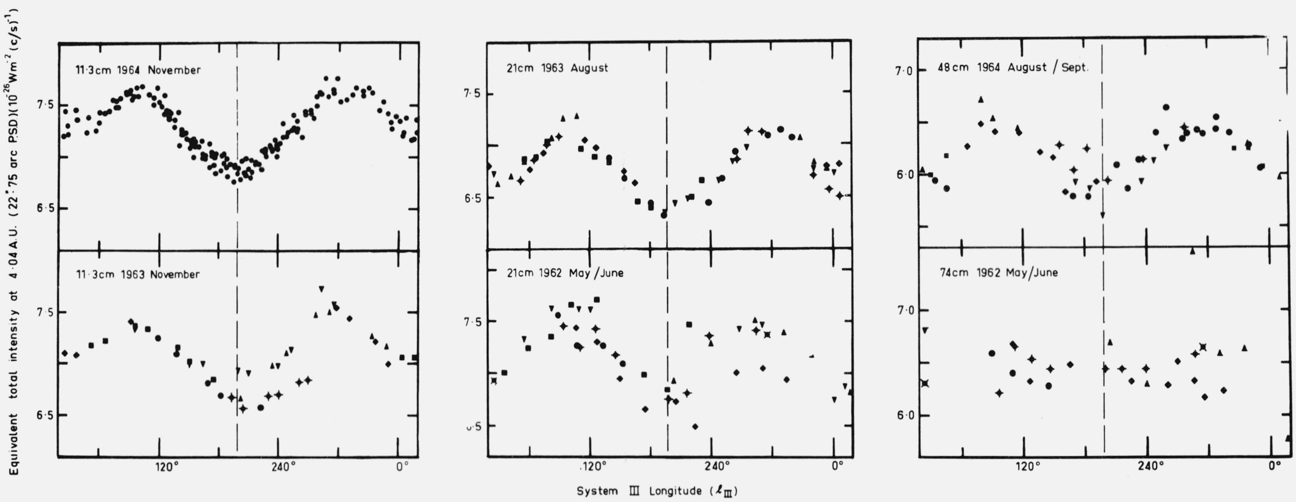

FIGURE 4. *Variation of the total flux density as Jupiter revolves.*

The flux densities have been normalized to a distance of 4.04 A.U. In all except the 1964 November 11.3-cm data, different observing days are distinguished by different symbols. The 74-cm observations were made simultaneously with (some of) the 1962 May–June 21-cm observations, using cross-polarized feeds. From Roberts and Komesaroff [1965], and Roberts and Ekers [1965].

4.1. Interpretation as Beaming

To explain the variation of the total intensity (and the degree of polarization) as the planet rotates, it has been supposed that the radiation is beamed towards the magnetic equator [Gary, 1963; Bash et al., 1964; Roberts and Komesaroff, 1964]. When such beaming is combined with the tilt of the magnetic axis to the rotational axis, and the present tilt of the north rotational pole towards the Earth, the qualitative features of the observations are reproduced.

If the emission were symmetric about the magnetic axis and the magnetic equator, the total intensity at the Earth would depend only on the Jovomagnetic latitude of the Earth, ϕ. However if the data of figure 4 are replotted as a function of magnetic latitude as in figure 5, it is seen that this is not true. When the Earth is at northern magnetic latitudes (circles in fig. 5) the intensity decreases approximately as $\cos^{4.5}\phi$, but at southern magnetic latitudes (squares) it decreases more rapidly, approximately as $\cos^{10}\phi$. In other words, the minimum near $l_{\mathrm{III}} = 18°$ is relatively deeper than would be expected. Furthermore, the 1964 11.3-cm data (which has the best signal/noise) suggests an even more complex variation.

This qualitative disagreement with the symmetric model is not altered by small changes in the parameters adopted—unless one is prepared to change the tilt of the axis of rotation! Roberts and Komesaroff [1964, 1965] therefore conclude that this is additional evidence for departures from a dipole field in the Van Allen belt. As in the case of the asymmetries in the direction of polarization curve, the effect seems to be less at 11.3 cm than at longer wavelengths.

From data such as those in figure 5, Roberts and Komesaroff have sought to determine the distribution of pitch angles of the electrons in the Van Allen belt, using the theory given by Thorne [1963] for the dipole case. It is obviously unsatisfactory to use a theory for a dipole field when there are such obvious departures

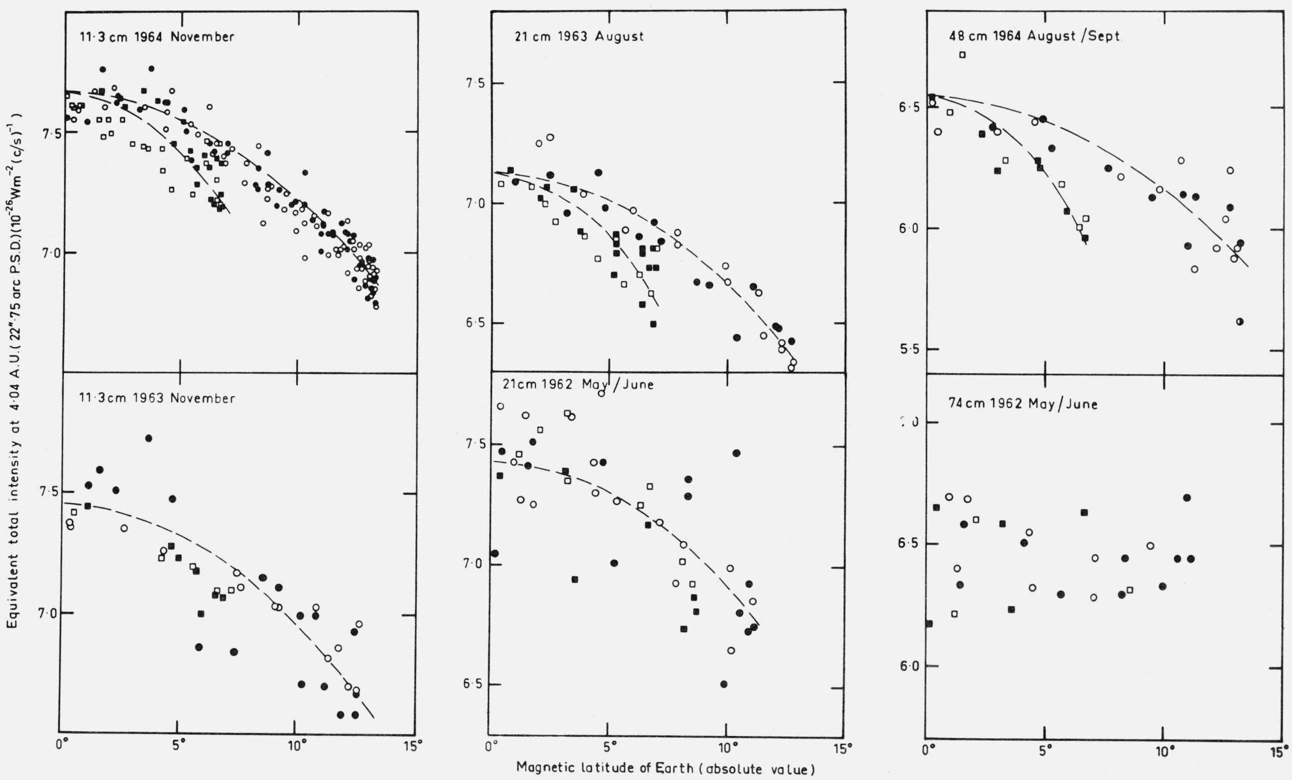

FIGURE 5. *The data of figure 4 replotted as a function of the Jovomagnetic latitude of the Earth, assuming the Jovian magnetic axis is inclined 10.0° to the axis of rotation with the pole in the northern hemisphere at a System III longitude of 198°.*

Points for northern magnetic latitudes are shown by circles, those for southern latitudes by squares; for longitudes 18° → 198° the symbols are open, and for 198° → 360° → 18° the symbols are filled.

The quadratic curves shown, when interpreted as parts of curves of the form $\cos^n\phi$, have the following equations:

11.3 cm 1964 November $I = 7.67 \cos^4\phi$ (Northern latitudes)
$I = 7.67 \cos^9\phi$ (Southern latitudes)
1963 November $I = 7.45 \cos^{4.5}\phi$
21 cm 1963 August $I = 7.13 \cos^{4.5}\phi$ (Northern latitudes)
$I = 7.13 \cos^{10}\phi$ (Southern latitudes)
1962 Aug/Sept. $I = 7.43 \cos^{4.5}\phi$
48 cm 1964 Aug/Sept. $I = 6.55 \cos^4\phi$ (Northern latitudes)
$I = 6.55 \cos^{14}\phi$ (Southern latitudes)

[Roberts and Komesaroff, 1965; Roberts and Ekers, 1965.]

from symmetry, and it is to be hoped that the theory for nondipolar cases will be developed soon. Using the simple theory, Roberts and Komesaroff showed that the beaming observed at northern magnetic latitudes for both the total intensity and the degree of polarization could be reproduced with a distribution of pitch angles made up of two terms, one corresponding to a group of electrons having a distribution of pitch angles peaked sharply near 90° (i.e., in very flat helices), and the other group having a much wider distribution of pitch angles. It will be seen later that the brightness distribution measured by Berge also indicates the presence of two such groups of electrons, and shows that they are in two separate belts.

5. Shape and Location of the Radio Source

One obvious method of testing the Van Allen belt theory is to measure the angular size of the Jovian emitting area. Using the Caltech interferometer, Radhakrishnan and Roberts [1960] showed that the E-W angular extent of the source at 31 cm was several times the diameter of the planet. This same instrument was used later by Morris and Berge [1962] to measure both the E-W and N-S angular sizes at 21 cm and 31 cm, and has now been used by Berge [1964, 1965] to produce a complete map of the brightness and polarization over the source at wavelengths of 10.4 cm and 21.2 cm. This is an important step forward, and a comparison of these maps with theoretical predications should give a great deal of information about the Van Allen belt.

Berge will give details of these observations later in the session, but figure 6 shows a preliminary map of the brightness distribution at 10.4 cm, which illustrates the detail that is provided by these observations. It is very interesting to compare this with a preliminary theoretical map of the brightness distribution for a thin shell of electrons trapped in a dipole field (fig. 7). The latter map is drawn from calculations by Ortwein, Chang, and Davis [1964]. Comparison of the theoretical map and the observed map suggests that there are two belts, one with a radius of about 3½ times the radius of Jupiter, in which the electrons have pitch angles as steep as those in the theoretical model, and a second belt with a smaller radius (about twice that of the planet) in which the electrons are in very flat helices, and hence are confined near the magnetic equator. The comparison of the details of the theoretical and observed distributions—e.g., the polarization in different regions—provides a further test of the model, and it is to be hoped that Berge will discuss such matters later. One aspect that merits immediate comment is that the radiation from the inner belt in which the electrons are in flat helices will be highly beamed and could presumably account for the variation of the total intensity as the planet rotates.

Two lunar occultations of the Jovian radio source have been recorded [Roberts and Komesaroff, 1965; Clarke and Roberts, 1965]. While, in principle, lunar occultations can provide fine details of the distribution of brightness over the source, in practice the Jovian source is so weak that this is not possible. The occultation results confirm the broad details derived from interferometry, and suggest that the shape of the source does not change appreciably over the wavelength range from 21 cm to 74 cm. Indeed the agreement between the occultation curves recorded by Clarke and Roberts at 21 cm and at 48 cm is quite remarkable.

At centimetric wavelengths, however, the situation is less clear. Korol'kov, Pariiskii, and Timofeeva

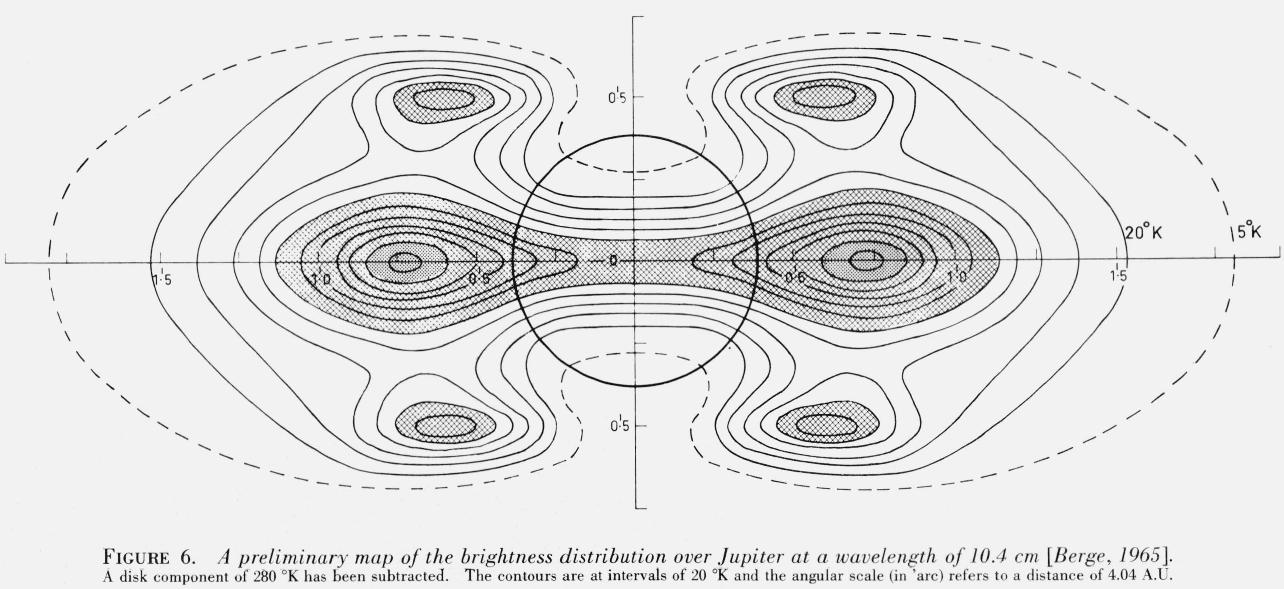

FIGURE 6. *A preliminary map of the brightness distribution over Jupiter at a wavelength of 10.4 cm* [*Berge, 1965*]. A disk component of 280 °K has been subtracted. The contours are at intervals of 20 °K and the angular scale (in 'arc) refers to a distance of 4.04 A.U.

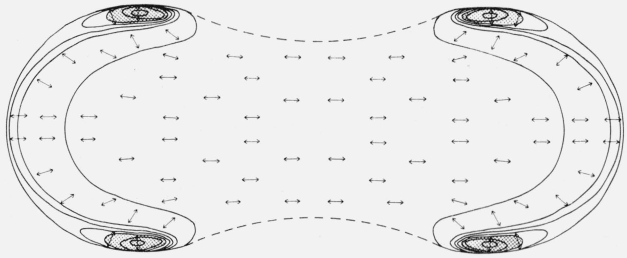

FIGURE 7. *The distribution of brightness (total intensity) of synchrotron emission from electrons trapped in a thin shell in a dipole field, viewed normally to the dipole axis.*
From preliminary calculations by Ortwein et al., [1964]. The electrons have a differential energy distribution $\propto E^{-1}$, and the pitch angles at the magnetic equator are distributed uniformly over the range $\sin \alpha \geqslant 0.4$

[1964] and Gol'nev, Lipovka, and Pariiskii [1964] have used the Pulkova fan-beam variable-profile antenna to measure the angular size of the source at wavelengths of 3.02 cm and 6.5 cm. They find that 95 percent of the 3.02-cm radiation comes from a region < 1.1 times the diameter of the planet, while at 6.5 cm the broadening of the beam is the same as would be produced by a Gaussian source with sigma only 1¼ times the diameter of the planet. If the thermal contribution is that of a uniformly bright disk at a temperature ~ 130 °K, Gol'nev, Lipovka, and Pariiskii show that the angular extent of the Van Allen belt radiation must decrease rapidly at wavelengths shorter than 10 cm—to 1.3 ± 0.2 diam at 6.5 cm, and to practical coincidence with the disk at 3.02 cm.

On the other hand Korol'kov, Pariiskii, and Timofeeva [1964] suggest that the intensity of the Van Allen belt radiation drops sharply between 10 cm and 3 cm, as is also suggested by the plots of the polarized intensity in figure 1. If there is such a sharp decrease in the belt emission, and if the disk temperature is greater than 130 °K (as suggested by Berge at 10 cm and by Korol'kov at 3.02 cm), then the evidence for a changing angular size of the Van Allen belt source is much less compelling. In a private communication Pariiskii has indicated that the 6.5-cm data would be consistent with the belt being the same shape as observed at 10 cm by Berge, provided the disk temperature is 295° ± 25°. Further observations, including a study of the angular distribution of the polarized component at 6.5 cm, should clarify the situation.

5.1. The Location of the Radio Source in Relation to the Planet

In the course of the 10.4-cm interferometry discussed above, Berge and Morris [1964] found what appeared to be an elegant method of locating the Van Allen belt relative to the planet. At an E-W baseline of 1860 wavelengths and with the feeds of both aerials linearly polarized parallel to the axis of rotation of the planet, the received intensity was at its first minimum. Berge and Morris believed this residual was entirely thermal radiation from the disk. At the same baseline, but with the feeds cross polarized at ±45° to the axis of rotation, the accepted radiation was thought to be typical of the Van Allen belt radiation. By measuring the relative phase of the interferometer fringes recorded with these two systems, they hoped to measure the position of the Van Allen belt source relative to the planetary disk.

As shown in figure 8a the relative phase of the fringes varied systematically as the planet rotated, and led Berge and Morris to infer that the centroid of the Van Allen belt emission was eccentric to the planet. However, when Roberts and Ekers [1965] used a pencil-beam instrument to make direct observations of the position of Jupiter relative to a nearby radio source they found that any movement of the Jovian radio centroid was much less than that inferred by Berge and Morris (fig. 8b). Roberts and Ekers place the

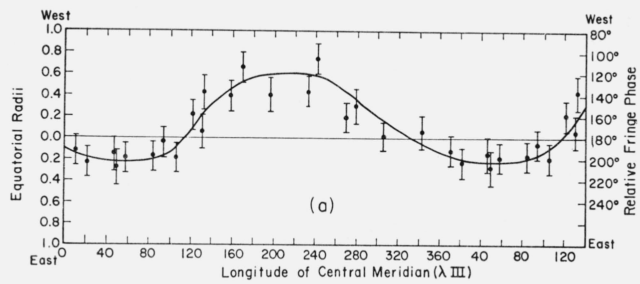

FIGURE 8a. *The measurements by Berge and Morris [1964] of the relative phase of the fringes observed with an interferometer with cross-polarized and parallel polarized feeds.*
The scale of equatorial radii is relevant for their suggested interpretation in terms of a wobbling of the apparent position of the whole Van Allen belt.

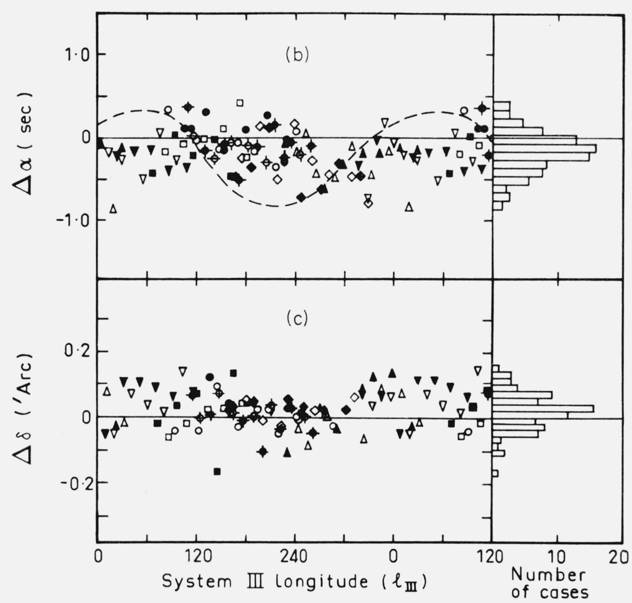

FIGURE 8b, c. *Measurements by Roberts and Ekers [1965] of the position of the centroid of the Jovian radio source relative to the ephemeris position of the planet.*
The dashed curve in (b) shows the movement expected if the explanation given by Berge and Morris for their observations were correct.

radio centroid as within 0.15 radii of the axis of rotation. Evidently there is some other explanation of the results of Berge and Morris. I understand that Berge will suggest that they result from the presence of a small component of circular polarization—which may be an even more important discovery than an eccentric location for the Van Allen belt.

The comparison source used by Roberts and Ekers in their position studies was later occulted by the Moon, so that its position is now known with an accuracy of a few seconds of arc [Clarke, 1965]. Hence the mean centroid of the Jupiter source can be located on an absolute scale and is found to coincide with the ephemeris position within ± 0.1 radii in right ascension and ± 0.3 radii in declination.

6. Conclusion

Further understanding of the Van Allen belt decimetric radiation seems to require theoretical computations of the synchrotron emission from electrons trapped in nondipolar fields. There are now three lines of evidence showing the importance of nondipolar terms in the Jovian field: the longitude dependence of the decametric burst activity, and the asymmetries in the longitude dependence of both the direction of polarization and the total intensity of the decimetric radiation. There have already been efforts to determine the nondipolar term from the burst radiation [Ellis and McCulloch, 1963]. It would seem desirable to compute the synchrotron emission for this model, or alternatively for a dipolar field perturbed by a second weaker dipole near the planetary surface. For the nondipolar models, as well as for the dipolar case, computations are needed of the two-dimensional distributions of intensity and polarization for comparison with observed maps such as those of Berge [1965].

The strength of the disk component of the radiation is another matter requiring study, particularly since it can influence conclusions about the synchrotron component at wavelengths shorter than 10 cm. Berge suggests that at 10.4 cm the disk radiation is twice that expected on the basis of the infrared temperature. Such a result is already known in the case of Venus, and further study of the Jovian case may possibly clarify the Venusian situation.

Finally, the great unknown is the strength of the magnetic field. From the substantial circular polarization of the decametric bursts it seems that at some point the field strength must be $\gtrsim 10$ G. On the other hand, since the polarization characteristics indicate that the decimetric emission is synchrotron and not cyclotron emission, the magnetic field *in the belt* must be $\lesssim 50$ G. Finally, the constancy of the decimetric radiation implies strong magnetic control against interplanetary disturbances, suggesting a field strength in the belt that is greater than that in the Earth's belt. Field strengths in the belt of ~ 1 G have been suggested [Chang and Davis, 1962; Warwick, 1963].

If the field is as great as this, then electrons with energies of only a few million electron volts will radiate in the decimetric range. For such low-energy electrons the ER approximations in synchrotron theory may be inadequate in some details, in particular, as Westfold [1964] has commented, as regards circular polarization. If Berge and Morris have indeed discovered circular polarization in the synchrotron emission, this may provide a means of determining the strength of the magnetic field in the Van Allen belt.

The author thanks all those who were good enough to make information available in advance of publication.

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Discussion Following Roberts' Paper

F. Drake: Although your decimeter rotation period fits the System III period to within $0^s.5$, isn't it now inconsistent with the decameter period, which has recently been changing?

Answer: The decimeter measurements, made 2 years ago, might not disagree with the decameter period observed then if one takes account of the uncertainties involved.

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An Interferometric Study of Jupiter at 10 and 21 cm

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An interferometric study of Jupiter's decimeter radio emission has recently been carried out at the Owens Valley Radio Observatory. Using the two 90-ft paraboloids as an interference polarimeter, observations have been made with various east-west spacings ranging from 300 to 4700λ at 10.4 cm and 300 to 2300λ at 21.2 cm and also with some critical north-south spacings at 10.4 cm. Berge and Morris [1964] and Berge [1965] have presented some preliminary results of this study.

Figures 1 and 2 illustrate the east-west interferometer response at 10.4 cm, as a function of baseline, for different orientation combinations of the linearly polarized feed horns. The plotted points are the fringe amplitudes and relative fringe phases respectively. The data are for a 90° range of longitude of the central meridian of Jupiter (System III) centered on $l_{\text{III}} = 20°$. The response functions (called visibility functions) vary with l_{III} because of the beaming effect as Jupiter rotates and also because the Jovian source changes its orientation with respect to the interferometer baseline as Jupiter rotates. Both of these effects are a result of the difference of 10° between the directions of the magnetic and rotational axes. It is because of these changes than the data have been segregated roughly according to l_{III}.

At the time of the observations, the position angle measured from north through east in the sky, of Jupiter's rotational axis was 335°. The position angle of the east-west baseline projected onto the sky was always nearly 90°, even at large hour angles.

Moffet [1962] has discussed the theory of visibility functions for unpolarized sources when the feed horns are identical. Morris, Radhakrishnan, and Seielstad [1964] have generalized the results to include nonidentical feeds for studying the polarization distribution over the face of a radio source. The normalized complex visibility function is

$$\beta(s, p) = V(s, p)e^{i\Phi(s, p)}$$