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AN ANALYSIS OF JUPITER DATA FROM THE RAE-1 SATELLITE

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Final Report, covering the period July 1, 1973 -Sept. 30, 1974.

NASA Grant No. NGR 10-005-176.

Principal Investigator: Thomas D. Carr

A. RESULTS OBTAINED

Appendix 1, which is the preprint of a paper submitted for publication in Astrophysical Journal (Letters), presents (a) background information regarding low frequency observations of Jupiter's radio bursts, (b) the methods used by the Principal Investigator and Mr. Michael D. Desch (graduate student) in identifying and analyzing Jupiter radio emission events in the RAE-1 satellite data under the terms of NASA Grant No. 10-005-176, and (c) results. The results have exceeded initial expectations. Not only have Jupiter bursts been positively identified at frequencies down to 450 KHz, but the following contributions to the knowledge of Jovian radio phenomena have been made:

a) The first clear-cut demonstration of an effect by the Jovian satellite Europa and the manner in which the effect varies with frequency.

b) Measurement of histograms of emission occurrence probability as functions of Jovian central meridian longitude and the orbital phase of Io (as well as that of Europa) at frequencies from 4700 KHz down to 700 KHz.

c) The first determination of Jupiter's low-frequency spectrum down to 450 KHz, revealing a well-defined maximum at 8 MHz.

This information will provide much-needed new constraints on the many theories which are being proposed to account for the mechanism of emission of Jupiter's radio bursts and the influences of the Jovian satellites upon it. The information will also be of great value in the design of instrumentation and the planning of experiments for the investigation of the previously inaccessible low-frequency region of Jupiter's radio spectrum on the forthcoming Mariner Jupiter-Saturn 1977 spacecraft missions.

B. TRAVEL

The following trips were made in connection with this grant:

a) To Goddard Space Flight Center
   T. D. Carr, August 15-31, 1973
   M. D. Desch, August 15- September 17, 1973

b) M. D. Desch to Winston-Salem, North Carolina
   November 9-11, 1973, to present paper.

c) T. D. Carr and M. D. Desch to Palo Alto, California
   April 1-7, 1974, to present papers.

C. PAPERS PRESENTED OR TO BE PRESENTED

The following papers on preliminary results obtained during the course of this work were presented:

a) "Positive Identification of Jupiter Bursts at Frequencies below the Ionospheric Cutoff as Detected by the RAE-1 Satellite" by M. D. Desch and T. D. Carr. Presented by M. D. Desch at the 1973 Meeting of the Southeastern Section of the American Physical Society, Winston-Salem, North Carolina, November 10, 1973.

Abstract published in Bulletin of the American Physical Society, 19, 701 (May 1974). Copy of abstract in Appendix 2a of this report.

b) "Decametric and Hectometric Observations of Jupiter from the RAE-1 Satellite" by M. D. Desch and T. D. Carr. Presented by M. D. Desch at the 1974 Meeting of the Division of Planetary Sciences, American Astronomical Society, at Palo Alto, Calif. on April 3, 1974. Abstract in press in Bulletin American Astronomical Society. Copy of abstract in Appendix 2b of this report. Other papers were also presented by Desch and Carr at the same meeting on the results of ground-based observations of Jupiter's radio emission.

Upon the invitation of Dr. Thomas W. Thompson, Chairman of the Special Session on Radio and Radar Observations from Spacecraft, USNC/URSI-IEEE Meeting to be held in Boulder, Colorado, October 14-17, 1974, the following paper will be presented by T. D. Carr or M. D. Desch:

"Decametric and Hectometric Observations of Jupiter from the RAE-1 Satellite".

A copy of the abstract of this forthcoming paper is given in Appendix 2c of this report.

D. RECOMMENDATIONS REGARDING UNREDUCED RAE-1 JUPITER DATA

The highly successful results of this investigation have been obtained from only a portion of the available RAE-1 data -- from the 4700, 3930, 2200, 1300, 900, 700, and 450 KHz data for a 3-month period in 1969. Although the reading of the microfilmed records has proven to be considerably slower than the computer-search method originally planned, the visual method is much more satisfactory for the lower frequencies and provides a surprising amount of information. We believe that there is more to be learned from the RAE-1 data which has not yet been reduced. We recommend the reading and analysis of the following additional portions of the RAE-1 data, using the methods which we have developed:

a) The 6550 KHz data for the same 3-month interval in 1969.

b) Data at 6550, 4700, 3930, 2200, 1300, 900, 700, and 450 KHz for two additional months in 1969 (any more than two additional months would put Jupiter and the sun in the antenna beam at the same time).

c) Data at the same 8 frequencies for a period of about 5 months in 1970.

d) Data at the same 8 frequencies for a 5-month period in 1971, or as much of it as is usable.

After 1969, the RAE-1 radiometers began to deteriorate progressively. However, in spite of unexpected level changes, dirty relay contact noise and other glitches characteristic of aging satellites, much of the 1970 data is good, and a considerable amount of the 1971 data can probably be salvaged. We plan to submit a proposal for the continuation of this work.

The NASA Technical Officer for this grant is D. R. Hallenbeck, Physics and Astronomy Programs/SG.

APPENDIX 1.

DECAMETRIC AND HECTOMETRIC OBSERVATIONS OF JUPITER FROM THE RAE-1 SATELLITE

by

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Running Title: RAE-1 OBSERVATIONS OF JUPITER
AT LOW FREQUENCIES

ABSTRACT

Analysis of RAE-1 satellite data has revealed the presence of radio bursts from Jupiter in the frequency range from 4700 KHz to 450 KHz. Strong correlations with Io were found at 4700, 3930, and 2200 KHz while an equally strong Europa effect was observed at 1300, 900, and 700 KHz. Jupiter's radio spectrum was extended to the lower frequencies.

I. INTRODUCTION

Although Jupiter's burst emission at decameter wavelengths has been monitored extensively from ground-based observatories during the 18 years which have elapsed since its discovery, the lower frequency portion of its spectrum has been largely unobservable because of the opacity of the terrestrial ionosphere. While it has been possible to make scattered observations in the 4 to 10 MHz range during years of minimum solar activity (Carr _et al_. 1964; McCulloch and Ellis 1966; Dulk and Clark 1966; Carr and Gulkis 1969; Zabriskie 1970), results obtained at these frequencies are rather inconclusive. Systematic synoptic monitoring has been confined to frequencies between about 15 MHz and the upper cutoff frequency of the emission itself, about 40 MHz.

The Radio Astronomy Explorer 1 (RAE-1) satellite has made possible studies of astronomical phenomena at frequencies well below those accessible to ground based installations (Alexander 1970). The satellite carries two gravity gradient stablized 229 m-long V antennas, one beamed at the zenith and the other at the nadir. Each antenna is connected to a Ryle-Vonberg (RV) receiver, providing separate upper V (sky) and lower V (earth) channels at each of 9 frequencies between 450 and 9180 KHz. The use of two antennas makes it possible to distinguish between radiation arriving from above and terrestrial interference from below (Weber _et al_. 1971). Although there are other detection systems on the RAE-1 satellite, we have employed the data from the V antenna-RV receiver system exclusively in this analysis.

II. DATA SELECTION AND REDUCTION

The RAE-1 data stored at the Goddard Space Flight Center exists in the form of digital data on magnetic tapes and also analog-converted transcriptions of it on microfilm. An extensive preliminary inspection of the microfilmed data revealed the presence of a number of usually small bursts which were apparently of Jovian origin, together with a large number of solar Type III bursts and considerable amounts of powerful terrestrial interference. This interference consisted of noise from thunderstorm activity and from conglomerates of ground-based radio transmissions. Fortunately, the terrestrial interference could be easily recognized, and often was completely absent for a substantial fraction of each orbit of the satellite.

The data on which the results of this paper are based were recorded during the 1969 Jovian apparition, before the radiometers had begun to show signs of degradation. A three month period centered on Jovian opposition was chosen in order to minimize contamination from Type III solar bursts. Approximately 700 orbital passes of the antenna beam across Jupiter occurred during this time. At 1300 KHz the half-power beamwidth of the V antenna was 180°, corresponding to 1.9 hours of satellite travel time. The total amount of interference-free monitoring time at this frequency was 700 hours.

In order to make an unbiased decision concerning the presence or absence of Jovian activity, a computer was instructed to search the data on magnetic tape for "upper V only" events, which would supposedly be of extraterrestrial origin. Only those events which were at least 3 db above the galactic background level were considered significant. Superimposing 700 oribital epochs, we obtained from the 4700 and 3930 KHz data the histograms presented in Figure 1, in which the probability of occurrence of such events is plotted as a function of satellite orbital phase from Jupiter transit. The two significant peaks at both frequencies occur at 0° and 180° orbital phase, corresponding respectively to the positions of Jupiter and the sun. Unfortunately, this method of computer selection of Jovian events was not satisfactory at the lower frequencies. Below 3930 KHz independent variations of the upper V and lower V background levels would sometimes cause the computer to count events which by visual inspection were obviously not Jovian.

It was therefore decided to read the lower frequency data visually. To facilitate reading, both channels of all the RV radiometer data were rephotographed on microfilm using an improved format. The vertical scale (antenna temperature) was expanded by a factor of two, and the horizontal scale (RAE-1 orbital phase) was realigned at every orbital pass so that Jupiter transit would appear in the middle of each frame. As a result, the relatively weak Jupiter bursts could be more easily identified and more quickly measured. Figure 1 also shows the histogram for the 2200 KHz data read visually from microfilm. The Jupiter and solar peaks are even more distinct here than at 4700 and 3930 KHz. Broadening of the two peaks in comparison with those obtained at the higher frequencies is due to the decrease in directivity of the V antenna with increasing wavelength.

III. RESULTS

Following the successful identification of Jupiter activity using automatic computer and visual search techniques, we plotted histograms indicating the relative probability of occurrence as functions of the System III longitude of the central meridian, the phase of Io, and the phase of Europa, respectively. Since the durations of individual Jovian storms was less than the time encompassed by individual histogram bars, the data was weighted in proportion to storm durations in calculating relative occurrence probability. Except where noted otherwise, the histograms have been smoothed by calculating a 3-point running mean in which the points have respective weights of 2/9, 5/9, and 2/9. Figure 2 shows the variation in the normalized occurrence probability with respect to Jupiter's System III (1957.0) longitude. The 4700 KHz histogram is in general agreement with the intensity profile of McCulloch and Ellis (1966) at the same frequency. The most prominent features are also in good accord with data obtained in Chile at 5000 KHz in 1962 (Lebo 1964). In making these comparisons the 3.3° per year drift in System III (1957.0) longitude has been taken into account (Carr 1971). A particularly interesting feature of most of these histograms is the prominent peak lying between the positions occupied by Sources A and B at the higher decametric frequencies. It is perhaps significant that the meridian toward which Jupiter's north magnetic pole is tipped lies in the same vicinity. The position of the peak changes from a System III (1957.0) longitude of 195° at 2200 KHz to 150° at 900 KHz.

It should be noted that the results at 450 KHz are less reliable than those at higher frequencies due to the interference resulting from resonances in the terrestrial plasma adjacent to the RAE-1 antennas. As a consequence, interference-free observing time at 450 KHz was reduced by an order of magnitude below that at the higher frequencies.

While the System III rotation phase profiles bear little resemblance to those observed at the higher decametric frequencies, the situation is very different for the Io effect. As can be seen in Figure 3, the Jupiter activity is found to be highly correlated with the phase of Io (departure from superior geocentric conjunction). The pronounced peaks near 90° and 240° which are observed from the ground at 15 MHz and above are also prominent in the RAE-1 measurements at 4700, 3930, and 2200 KHz. On the other hand, the Io effect in ground-based measurements below 15 MHz appears to be very slight (Dulk and Clark 1966, Register 1968). It is not known whether this indicates a) a relaxation of the Io effect between 4.7 and 15 MHz, b) ground based results at the lower frequencies having been subject to more severe contamination from interference than was realized, or c) some other effect.

The dependence of activity on Io phase can be seen to have decreased slightly at 2200 KHz (Figure 3) and to have almost disappeared at 1300, 900, and 700 KHz. (There was insufficent data at 450 KHz for a significant histogram in this case.) However, when the variation in activity at these three lowest frequencies is examined with respect to the phase of Europa, a striking dependence is found. There is a sharp peak in activity when Europa is near 190° from superior geocentric conjunction. The modulation is most pronounced at 1300 KHz. The appearance of peaks in the Europa phase histograms at 4700, 3930, and 2200 KHz are artifacts due to the coupled motions of Io and Europa. Because the period of Europa is almost exactly twice that of Io any correlation with Io phase will appear also as a correlation with Europa phase at two positions separated by 180°. The lack of any well defined Io effect at 1300, 900, and 700 KHz, however, permits the isolation of the Io and Europa influences. A periodogram (autocorrelation) analysis of the 1300 KHz data produced only two highly significant peaks, one occurring at the rotational period of Jupiter and the other at Europa's synodic orbital period. No significant spectral power appeared at Io's period. This result further supports our contention that Europa, independently of Io, modulates Jupiter's activity at frequencies below about 2 MHz.

It is of interest to note that Goldreich and Lynden-Bell (1969) predicted a strong dependence of Jupiter activity below 5 MHz on Europa's phase. The particular geometry of the Jupiter-Europa-earth alignment indicated by the peak in Figure 3, however, is highly suggestive of magnetic field-aligned propagation of radiation along ducts of enhanced ionization (Carr _et_ _al_. 1965). This is in contrast to the model developed by Goldreich and Lynden-Bell to explain the favored Io phases of 90° and 240°.

A number of rather comprehensive searches for evidence of the modulation of Jovian emission by satellites other than Io have previously been made (Duncan 1966; Bigg 1966; Tiainen 1967; Wilson _et_ _al_. 1968; Register 1968; Kaiser and Alexander 1973). With only one exception, both individual and joint effects among Jupiter's five innermost satellites have been found to be of zero or marginal significance. The exception was the result of Tiainen, based on an analysis of the 7 to 15 MHz Boulder dynamic spectra, in which he found a statistically significant joint correlation of Jovian activity with respect to the phases of Io and Europa. The favored Europa phase found by Tiainen was also near 190°. No attempt was made in the present study to find correlations with the phases of the two Galilean satellites having the longest periods because the observations did not span a sufficiently long interval.

For many years, one of the major questions concerning Jupiter's decametric radiation has been whether or not its flux density continues to increase with a decrease in frequency below 10 MHz, and if so, at what point the spectrum peaks. Figure 4 appears to provide the answer. Here the spectrum of peak flux densities is displayed from 27 MHz down to 450 KHz, all the lower frequency points having been obtained from the RAE-1 results. Each of the RAE-1 points is the average of the peak flux densities of the 5 strongest Jupiter storms; they are seen to merge very well with the ground-based data taken from Carr _et al_. (1964). The uncertainty in the RAE-1 points, about ±30%, is due primarily to the uncertainty in the directivity of the V antenna at each frequency. The directivity data was provided by J. K. Alexander (private communication). The maximum in Jupiter's peak flux density spectrum occurs at about 8 MHz, and the curve is down by a factor of 10 from the peak at 1 MHz and at 21 MHz. The spectral indices are roughly -5 and +1.5 at the high and low frequency ends, respectively. If it is assumed that the radiation is emitted close to the electron gyrofrequency, the magnetic field must be between 0.4 and 7 gauss in the principal emitting region, with most of the rediation produced where the field is about 3 gauss. On the other hand, if the radiation occurs at the upper hybrid frequency (Smith and Wu 1974), the field values are somewhat less. In either case, the fact that the peak of the spectrum occurs at 1/5 the upper cutoff frequency (40 MHz) suggests that the field at the location of the strongest emission is very roughly 1/5 the intensity of that at the planetary surface, and that this location is at about 1.7 radii from the center of the magnetic dipole (assuming an inverse-cube variation of field with distance).

We express our appreciation for the cooperation extended by the Radio Astronomy Branch, Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center. In particular, we wish to thank J. K. Alexander and M. L. Kaiser for their indispensable assistance in the initial phase of this project.

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FIGURE CAPTIONS

FIGURE 1. Occurrence probability of 'upper V only' events as a function of RAE-1 orbital phase. Individual peaks in the probability of reception due to radio bursts from both Jupiter and the sun are clearly visible.

Figure 2. Variation in the normalized occurrence probability of Jupiter activity as a function of the System III longitude.

Figure 3. Variation in the normalized occurrence probability of Jupiter activity as a function of the geocentric phase of Io and Europa. The upper four pairs of histograms have been smoothed as indicated in the text; the lower three are unsmoothed but the histogram bars are 40° wide instead of 20°.

Figure 4. Peak flux density spectrum of Jupiter combining ground based and RAE-1 satellite data from 27 MHz to 450 KHz. The ground based data is from Carr _et al_. (1964).

gure 1 (Desch & Carr)

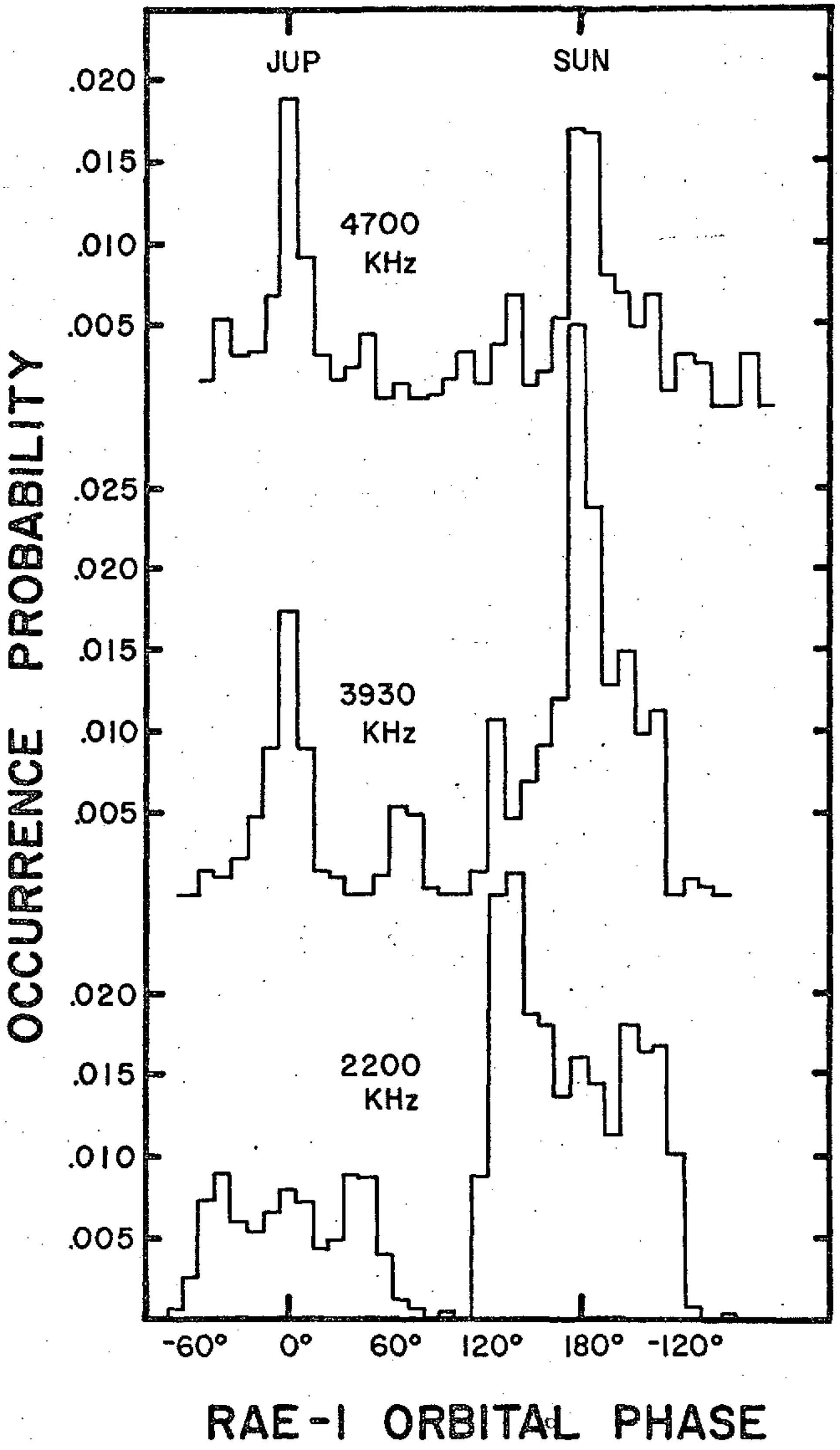

Figure 1 (Desch & Carr)

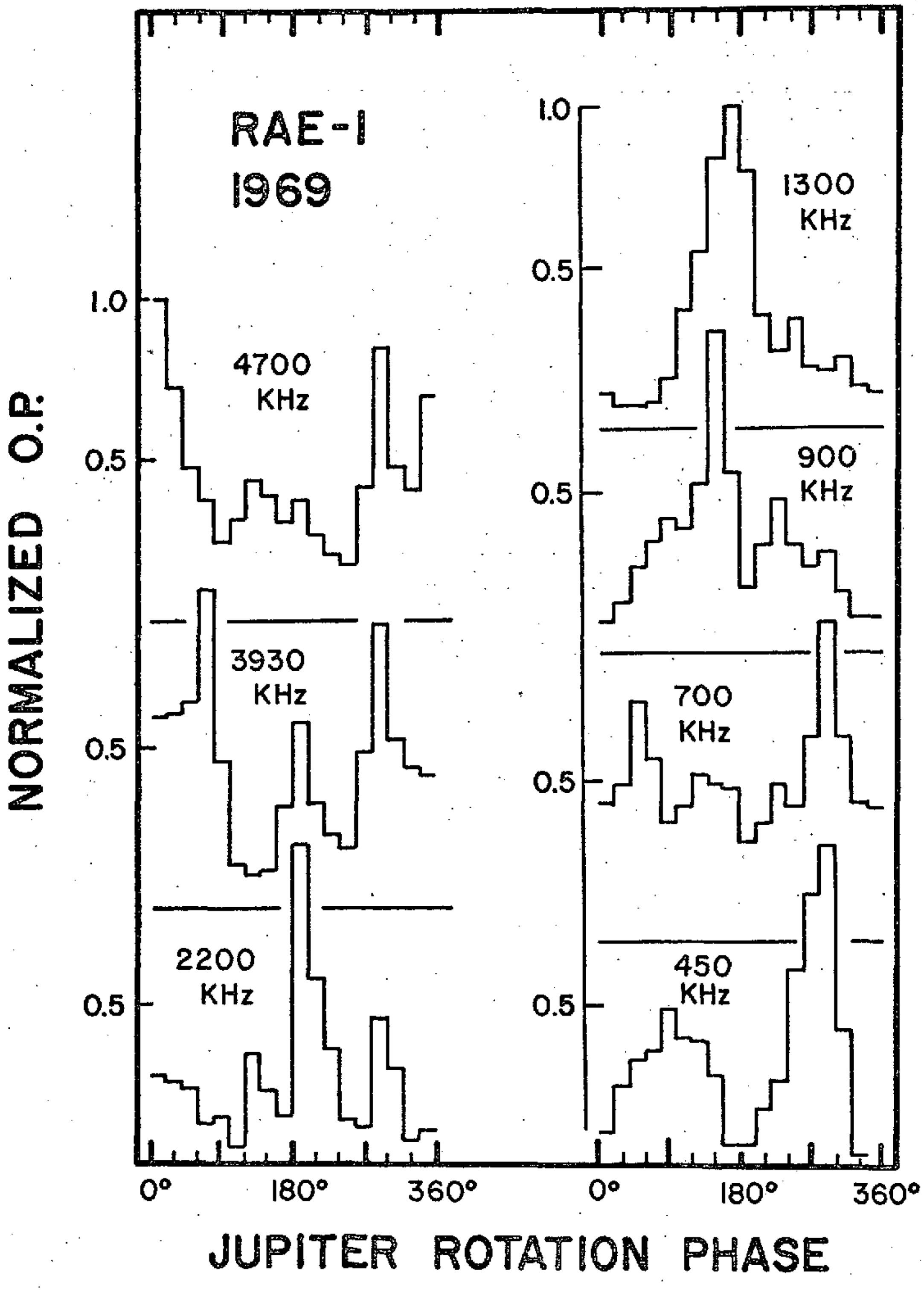

Figure 2 (Desch & Carr)

Figure 3 (Desch & Carr)

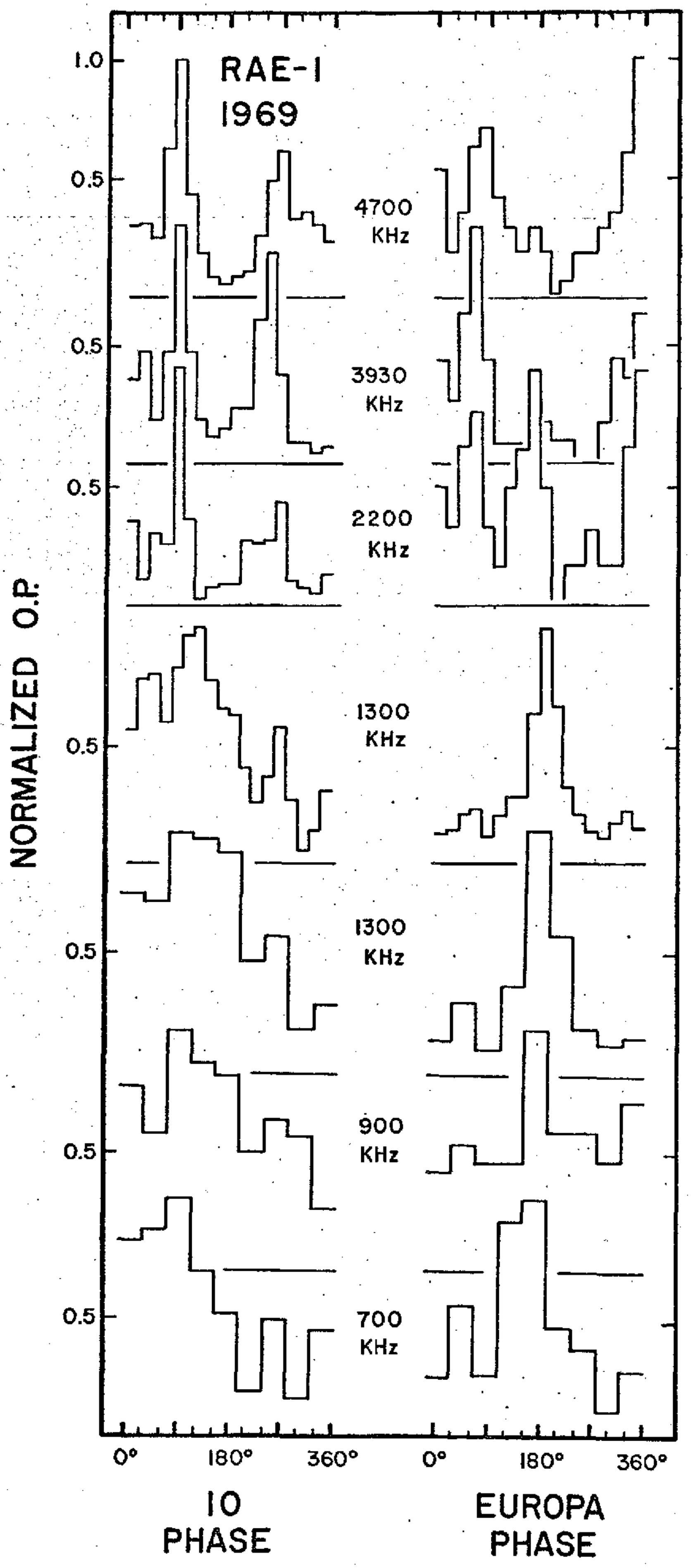

Figure 3 (Desch & Carr)

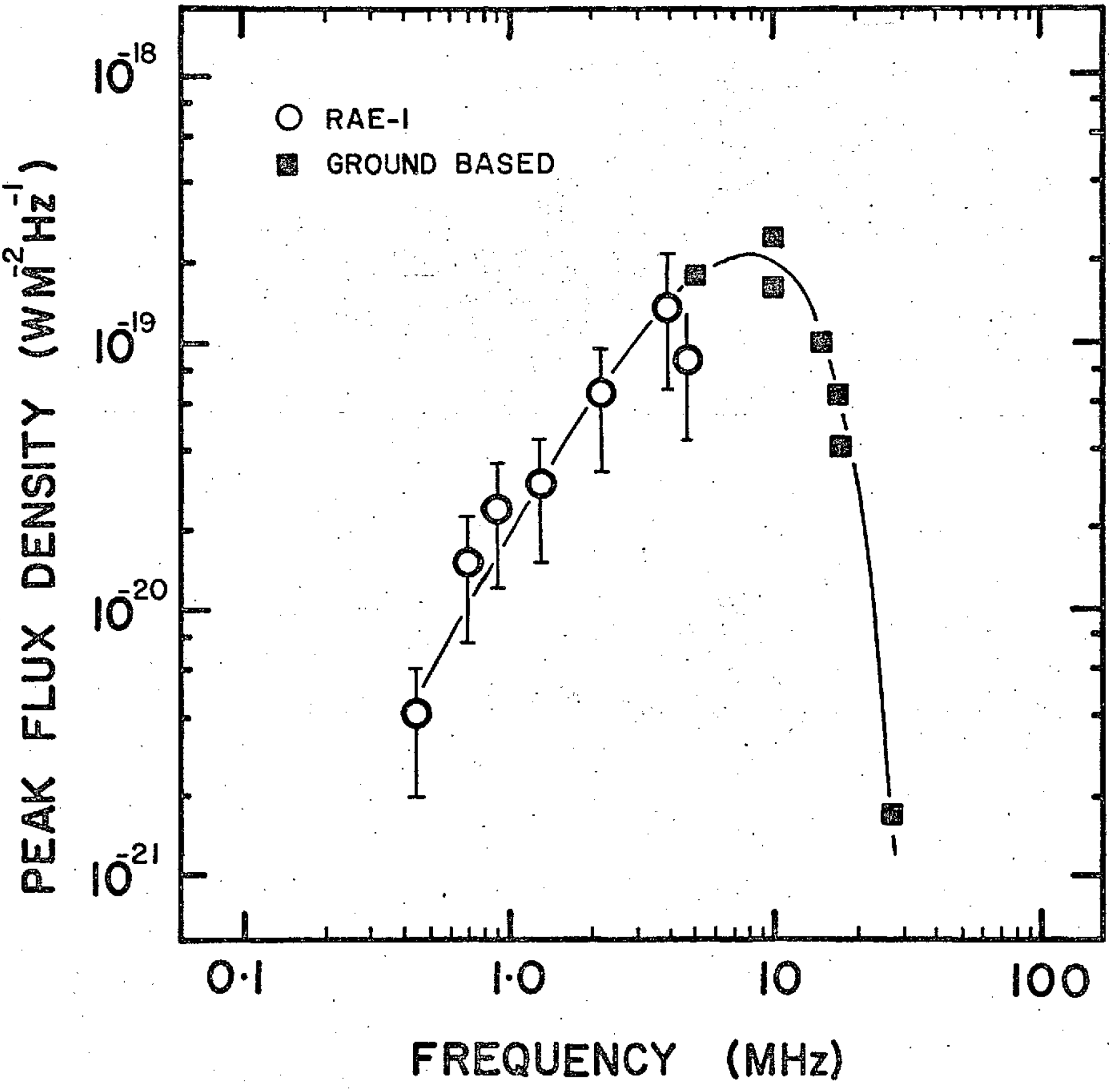

Figure 4 (Desch & Carr)

APPENDIX 2

a) From Bulletin of the American Physical Society, 19, 701 (May 1974):

ED4. Positive Identification of Jupiter Bursts at Frequencies below the Ionospheric Cutoff as Detected by the RAE-1 Satellite.* M.D. DESCH and T.D. CARR, University of Florida-- An extensive analysis of data detected by the RAE-1 earth-orbiting radio astronomy satellite shows an increase in the number of events for times when the satellite antenna beam sweeps across Jupiter. Observing periods were chosen which would minimize the contamination of the data by Type 3 solar events which have previously masked the weaker Jovian radiation. Complete results will be presented at 4700 KHz and 3930 KHz and preliminary results at a number of lower frequencies. The analysis will include an examination of the flux densities and the Jupiter-Io System morphology of the bursts.

*Work supported by NASA Grant NGR 10-005-176.

b) Abstract from program of the 1974 meeting of the Division of Planetary Sciences, American Astronomical Society, Palo Alto, Calif., April 3, 1974 (also in press in Bulletin American Astronomical Society):

Decametric and Hectometric Observations of Jupiter from the RAE-1 Satellite. Michael D. Desch and Thomas D. Carr, University of Florida, Gainesville, Florida.-- An extensive analysis of data detected by the RAE-1 earth-orbiting radio astronomy satellite will be presented at seven frequencies extending from 4700 KHz down to 450 KHz. Observing periods were chosen which would minimize contamination from Type 3 solar bursts, resulting in approximately 700 hours of monitoring during the 1969 apparition of the planet. One and two dimensional plots of Jupiter rotation and Io orbital phase will be compared with the higher frequency earth based data. Positive identification of a significant number of Jupiter bursts has permitted extension of the planet's flux spectrum down at least as far as 900 KHz. Also to be discussed is the possible influence of the satellite Europa on the occurrence of Jupiter activity at certain frequencies as predicted by Goldreich and Lynden-Bell (1969, Astrophys. J. 156, 59).

This research was supported by NASA under grant NGR 10 005-176.

APPENDIX 2 (continued)

c) Abstract of paper to be presented at USNC/URSI-IEEE meeting in Boulder, Colo., Oct. 14-17, 1974:

DECAMETRIC AND HECTOMETRIC OBSERVATIONS OF JUPITER FROM THE RAE-1 SATELLITE.

M. D. Desch and T. D. Carr. Department of Physics and Astronomy, University of Florida, Gainesville, Florida 32603.

An analysis of data from the Radio Astronomy Explorer 1 (RAE-1) satellite at 8 frequencies between 4700 and 450 KHz, inclusive, revealed the presence of bursts from Jupiter as well as from the sun. There was a strong correlation of occurrence probability of the Jovian bursts with the System III longitude of the central meridian, but the longitude histograms showed little resemblence to those characteristic of the higher decametric frequencies. A pronounced dependence of occurrence probability on the phase of Io was apparent at 4700, 3930, and 2200 KHz, and an equally strong Europa effect was discovered at 1300, 900, and 700 KHz. The active phases of Io were near 90° and 240° from superior geocentric conjunction as in the case of the higher frequencies, but the favored Europa phase is 190°, suggestive of initial propagation along field-aligned ducts. The spectrum of Jupiter's peak burst flux densities was extended from 4700 KHz down to 450 KHz, revealing a well-defined maximum at 8 MHz. We suggest that Jupiter's most intense burst emission arises from a region about 1.7 radii from the magnetic dipole center, where the field is about 1/5 that at the planetary surface.