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M. L. KAISER

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A LOW-FREQUENCY RADIO SURVEY OF THE PLANETS WITH RAE-2

M.L. Kaiser
Planetary Sciences Branch
Laboratory for Extraterrestrial Physics
Goddard Space Flight Center
Greenbelt, Maryland 20771

ABSTRACT

Over one thousand occultations of each planet in the solar system have occurred during the period from mid-1973 through mid-1976 as seen from the lunar orbiting Radio Astronomy Explorer-2 (RAE-2) spacecraft. These occultations have been examined for evidence of planetary radio emissions in the 0.025 to 13.1 MHz band. Only Jupiter and the earth have given positive results. Lack of detection of emission from the other planets can mean that either they do not emit radio noise in this band or the flux level of their emissions and/or its occurrence rate are too low to be detected by RAE-2.

Non-thermal radio emission of natural origin has previously been detected from four planets in the solar system. Radio noise from Jupiter has been measured for two decades by ground-based instruments operating above 5 MHz and emission extending to ~ 0.5 MHz has been measured with earth-orbiting spacecraft (see review by Carr and Desch, 1976). Brown (1975, 1976) has announced the discovery of emission from Saturn near 1 MHz, and possibly from Uranus near 0.5 MHz. Kaiser and Stone (1975) have shown that the earth must also appear in this list as an astronomical object because it is a powerful non-thermal emitter near ~0.3 MHz when observed by spacecraft from above the ionosphere.

Until in situ measurements were made by Pioneers 10 and 11, the Jovian non-thermal radio emission was the only direct evidence that Jupiter possessed a magnetic field and magnetosphere. The terrestrial kilometer-wavelength radiation (TKR) is strongly related to the magnetosphere (see Alexander and Kaiser, 1976 and references therein) and based on their Jovian-like radio emissions, Saturn and Uranus by analogy would also be expected to possess magnetospheres. Thus, it seems that planetary magnetic fields and radio emission appear together. Similarly, Mercury, with its recently detected magnetic field (Ness et al., 1976), Venus with its possible magnetic field (Russell, 1976), Mars with its 64γ surface field (Dolginov et al., 1976), and Neptune with its predicted magnetic field (Kennel and Maggs, 1976) must be considered as viable, although perhaps less likely, candidates for radio emission. The dense and turbulent atmosphere of Venus might also be an emitter of noise analogous to the earth's thunderstorm noise which can be detected from above the ionosphere at frequencies greater than the ionospheric critical frequency (Herman et al., 1973). Thus with the possible exception of Pluto, there seem to be reasons to search for radio emission from every planet in the solar system.

Now in hand are nearly three years of data from the lunar-orbiting Radio Astronomy Explorer-2 spacecraft. As seen from RAE-2, the moon appears as a disk 76^o across with an apparent limb motion of $\sim$ 1.6^o/min (222 min orbit) relative to the celestial background. Over the course of three years (July, 1973 to May, 1976) each planet has been occulted literally thousands of times by the moon. With the aide of a large-scale digital computer, each planet, with the exception of Pluto, has been studied in an effort to confirm or detect radio emissions below 13 MHz with an occultation "stacking" technique. In this report the results of this initial search for emissions are presented.

MEASUREMENT TECHNIQUE

a) Instrumentation

A detailed description of the RAE-2 spacecraft has been given by Alexander et al. (1975) so only the instrumentation relevant to the current investigation will be briefly described. The major RAE-2 antennas are two oppositely-directed V-antennas. The entire configuration resembles a giant X with the lower V always pointed at the moon while the upper V scans the celestial sphere. The lower V-antenna was used in this study because it more nearly "points" toward a source at the lunar limb than does the upper V. For the period from July 1973 until November 1974, the lower V antenna elements were each extended 183m. After November 1974 they were extended to their full length of 229m. Connected to the lower V-antenna is a total-power receiver sweeping the 0.025 to 13.1 MHz band in 32 discrete channels every 7.68 seconds. Each channel has a bandwidth of 20 kHz and a post-detection time constant of 6 ms. The total dynamic range is 50-60 dB and the telemetry digitization step size is typically 1/4 dB.

b) Occultation Analysis Scheme

RAE-2 is in an 1100 km circular orbit inclined 60 degrees to the lunar equator. The 222 min orbital period coupled with the receiver sampling rate results in approximately one measurement per frequency channel every 12 minutes of arc of sky coverage. At 1 MHz, the scale size of the Fresnel diffraction pattern of a point source is also ~ 12 minutes of arc, thus a simple on-off type of occultation analysis was used in this study.

A crude form of pattern recognition was used to "stack" successive occultations in order to enhance the signal-to-noise ratio. The method involved simply averaging the received power at each observing frequency for a few minutes just prior to and just after the predicted geometrical disappearance or reappearance. The average received power during the unocculted portion minus the average received power during the occulted portion ($\equiv \delta$) was subsequently saved for each disappearance/reappearance in the one-bit form of +1 or -1. If no source were visible, the sum of these differences after a large number N of disappearances/reappearances would be $\approx \pm\sqrt{N}$, analogous to the random walk problem solved by Chandrasekhar (1943). If, however, a source was indeed present, the sum of the differences would be positive and larger than $\sqrt{N}$. The particular computer code used in this study not only calculated $S \equiv \sum \delta/\sqrt{N}$ for each frequency, but also produced a listing of all occultation events where three or more consecutive channels had a +1 and an unocculted-to-occulted intensity ratio of $\geq$ 1/2 dB which is the smallest difference visible to the unaided eye on intensity versus time plots. The plots of the events in this listing were then visually scanned in order to verify that actual occultations of planetary emission had been detected because visual identification of at least a few occultations coupled with statistical detection at several consecutive frequencies was deemed absolutely necessary before claiming a planet to be a radio source.

c) Operational Difficulties

A number of difficulties both anticipated and unanticipated were encountered during the analysis which altered to some degree the scheme outlined in the previous section.

It was expected that scattering in the interplanetary medium would play an important role in this frequency range. Erickson (1966) estimated the minimum apparent angular size of a distant point source at low frequencies by scaling proportional to λ^2 from high frequency observations. Figure 1 shows a rough guide adapted from his calculations at various solar elongation angles. The effect on detection of weak sources having sizes several degrees in diameter is to make the occultation so gradual as to be virtually undetectable. For the outer planets, observations near opposition appear to be the most likely and perhaps the only time to detect any emission below 1-2 MHz. For Mercury and Venus only those times near inferior conjunction hold any promise at all, and even then possible confusion with nearly simultaneous solar radio source occultations could further reduce the available observing time.

The problem of nearly simultaneous occultations is not restricted to the sun. With the moon covering ~ 11% of the sky at any instant, nearly simultaneous occultation disappearances or reappearances of more than one planet can be fairly commonplace. The occultations of the earth often interfere with the other planets because the earth is very intense and the earth's immersions and emersions are relatively long (several minutes). Thus, the computer code was amended to delete all occasions for a given planet when either the sun or any other planet was within 3^{o} of the lunar limb (5^{o} for the earth) at that same instant. This restriction reduced the total number of useable occultations by about 30% for each planet.

Although lunar occultations are a very powerful method of detection of discrete sources, it is extremely difficult to obtain quantitative spectral information from any occultation viewed by RAE-2. To convert the difference between the "unocculted" received power and the "occulted" received power into absolute flux requires a detailed knowledge of both the antenna pattern (with a 76° "hole" in its center), and its orientation with respect to the source. Only the gross properties of the RAE-2 V-antenna, such as front-to-back ratio (to perhaps ± 2 dB accuracy) and approximate angular size of the main beam (to perhaps a few degrees accuracy) are known at some of the 32 observing frequencies. Furthermore, the antenna beam orientation can only be obtained to an accuracy of several degrees at any instant. For sources such as planets, the problem of determining the average spectra is compounded because, based on the four planets already observed, their emissions are only observed sporadically and are often bursty when observed. Thus, in this study no attempt was made to determine detailed spectral information.

A temporary problem existed for the three or four frequency channels in the 1-2 MHz band caused by the less than full extension of the lower-V-antennas prior to November, 1974. The short antennas caused galactic background noise to fall in an insensitive section of the receiver response curve at these frequencies because the higher shunt capacitance of the partially extended antennas reduced the amount of power delivered to the receivers. The effect was to produce a rather large number of "false alarms" in this band. After full antenna extension on November 6, 1974, this problem disappeared because the lower shunt capacitance and longer antenna length produced higher voltage levels at the receiver.

RESULTS

Figure 2 shows the approximate dates during which each planet underwent repeated occultations. The length of each occultation session is governed primarily by the movement of the planets themselves for Mercury out to Jupiter and by RAE-2 orbital precession for the outer planets. The spots marked N and F for each planet are for the nearest (inferior conjunction or opposition) and farthest points from the earth. The total number of occultations over the ~ 3 years is about 2700 ($\pm$ 500) for each planet of which perhaps half are "useable". The results for each planet are summarized in the following subsections.

a) Mercury

The result of stacking six separate 3-month occultation sessions is negative. At no frequency in the band from 75 kHz to 13 MHz did the sum-of-differences analysis yield any promise of detection of Mercury.

The solar wind electron density in the vicinity of Mercury is approximately 9 times that at the earth. The corresponding solar wind plasma frequency, below which emission cannot propagate to earth, is about 75 kHz. At frequencies below 3 MHz, interplanetary scattering would be severe even at inferior conjunction.

The surface polar magnetic field strength on Mercury can be estimated from Ness et al. (1976) to be ~ 700γ (dipole field) corresponding to an electron gyrofrequency at the surface of only 20 kHz. It is conceivable that a population of trapped particles with maximum energies of several hundred keV could produce detectable synchrotron emission. However, Simpson et al. (1974b) found no evidence for radiation belts although they did measure substantial transient electron events with energies of 300 keV. Hence the negative results for Mercury are not unexpected.

b) Venus

At Venus, the solar wind plasma frequency is ~ 35 kHz, so nearly the entire frequency range of RAE-2 was utilized, however throughout the entire RAE-2 band, Venus produced negative results. The expectation of any ionospheric or magnetospheric emission was extremely low for Venus. Russell's (1976) reinterpretation of Venera-4 data indicates a possible Venusian surface field of 30γ (1 kHz electron gyrofrequency). Simpson et al. (1974a) found no energetic electrons other than those associated with the bow shock,

c) Earth

The earth, while not a subject of this particular investigation, has been studied in considerable detail with RAE-2 (see Alexander and Kaiser, 1976 and references therein). The earth emits radiation which can be detected by RAE-2 in three different frequency bands. Above ~ 3 MHz (depending on the ionospheric critical frequency) emissions generated at ground level such as thunderstorm noise and man-made broadcasts are nearly always detected when RAE-2 is over the night side of earth (near full moon). These emissions generally appear less than 10 dB above galactic background, but, on occasion have been seen as strong as 40 dB above background.

By far the most intense emission, TKR, occurs in the 100-600 kHz region of the spectrum. This emission is apparently associated with energetic particle precipitation in the auroral zones and is most pronounced in the pre-midnight sector. At the frequency of maximum power of ~ 300 kHz, emissions from the night side of earth often saturate the RAE-2 receivers at > 50 dB above galactic background.

The third component, low-level continuum radiation below 100 kHz, has been studied by Gurnett and Frank (1976) and is associated with low energy (1-30 keV) electrons in the outer radiation zones. The flux level of this continuum radiation increases with decreasing frequency to a value of $> 10^{-19}$ W m^{-2} Hz^{-1} at 30 kHz. The solar wind plasma stops propagation of this noise outside the magnetosphere below 20 kHz.

d) Mars

Dolginov et al. (1976) have found evidence for a Martian magnetic field, but the surface electron gyrofrequency is only ~ 3 kHz, well below the solar wind plasma frequency. RAE-2 observed no emission from Mars with the occultation technique and Brown (1976) detected no Martian emissions with the IMP-6 spacecraft.

e) Jupiter

Occultations of Jupiter were clearly and unambiguously detected. This was expected since the planet had been easily observed with the RAE-1 and IMP-6 spacecrafts. The statistical analysis gave an $S \cong 10$ response to the 3-5 MHz region. The 3.93 MHz channel was the most detectable frequency with approximately 2/3 of all events producing a +1. Visual confirmation of the Jovian occultations is exemplified in figure 3. In the top panel, a dynamic spectral display is shown with increasing darkness proportional to increasing intensity. The lower panels are relative intensity versus time displays of individual channels from the upper panel. The occultation can be seen on all channels above 1.45 MHz, and possibly on a few channels below 1 MHz. The lack of detection between 1.45 and 1 MHz may be due to the antenna length problem discussed earlier.

The low frequency limit of detection appears to be controlled by interplanetary scattering. An increase in the averaging time before and after immersion and emersion increases the values of S for the channels below 1 MHz. At 360 kHz, for example, a processing "window" corresponding to five degrees of limb motion ($\sim$ 5 min) is needed to obtain an $S > 2$. Five degrees is roughly the scattered source size at 360 kHz suggested by figure 1. At still lower frequencies, interference from the TKR places statistical detections in doubt. No unambiguous visual occultations have been seen below about 360 kHz.

f) <u>Saturn</u>

It was hoped that Brown's (1975) announcement of Saturn emission near 1 MHz could be verified by RAE-2. The opposition passage of Saturn occurred after full antennna extension so that the 1-2 MHz band was operating nominally. The values of S for the channels immediately surrounding 1 MHz do not exceed 1 except at 1.03 MHz where $S = 1.84$.

Visual inspection of high-resolution intensity versus time plots for every predicted Saturn occultation also failed to produce one single unambiguous event.

Brown estimated the occurrence rate of Saturn's emission to be less than 5% of Jupiter's. Additionally, his twelve candidate events are only 1 to 10 minutes in duration, thus, it is quite possible that RAE-2 has simply "missed" Saturn.

g) Uranus

Kennel and Maggs (1976) have prediced that Uranus should emit radio bursts near 0.85 MHz with a peak power flux of 10^{-21} W m^{-2} Hz^{-1}, some 16 dB below the cosmic background noise. Brown (1976) has tentatively identified six short (< 3 min) events in the IMP-6 data originating from the direction of Uranus although he found a peak flux density at 0.5 MHz an order of magnitude above the Kennel and Maggs estimate.

No Uranus bursts were observed in this study, however the lack of detection of emission from Uranus by RAE-2 does not resolve the apparent conflict between the Kennel and Maggs prediction and Brown's observations. The Kennel and Maggs predicted flux level is well below the detection capability of RAE-2. However, Brown's very low occurrence rate and extremely short duration bursts could simply mean Uranus did not emit during a disappearance or reappearance.

As mentioned by Brown, Uranus and the earth were separated by only a few degrees at the times of his six events, e.g. for the May 3, 1971 event, the line-of-sight from IMP-6 to uranus passed within 6 to 7 earth radii of the earth, well within the region of TKR emission (Alexander and Kaiser, 1976).

Additionally, at the time of the May 3, 1971 event Venus and Uranus were only one degree apart in IMP-6 spin coordinates.

h) Neptune

The Kennel and Maggs (1976) prediction of bursts from Neptune at 0.7 MHz would also be some 16 dB below the cosmic background level. These bursts could not and were not detected by RAE-2.

SUMMARY

Nearly three years of occultation data from the lunar orbiting RAE-2 spacecraft have been examined for evidence of radio emission from all the solar system planets except Pluto. A lack of detection with the occultation technique used in this study does not imply that a planet is radio quiet. Indeed, all the planets could emit sporadic radio bursts at times when they are not being occulted. The negative results of this particular survey can only be interpreted as an indication that either none of the planets (excluding the earth and Jupiter) emit radio noise more than 5-10% of the time or their radio emissions are too weak to be detected with RAE-2.

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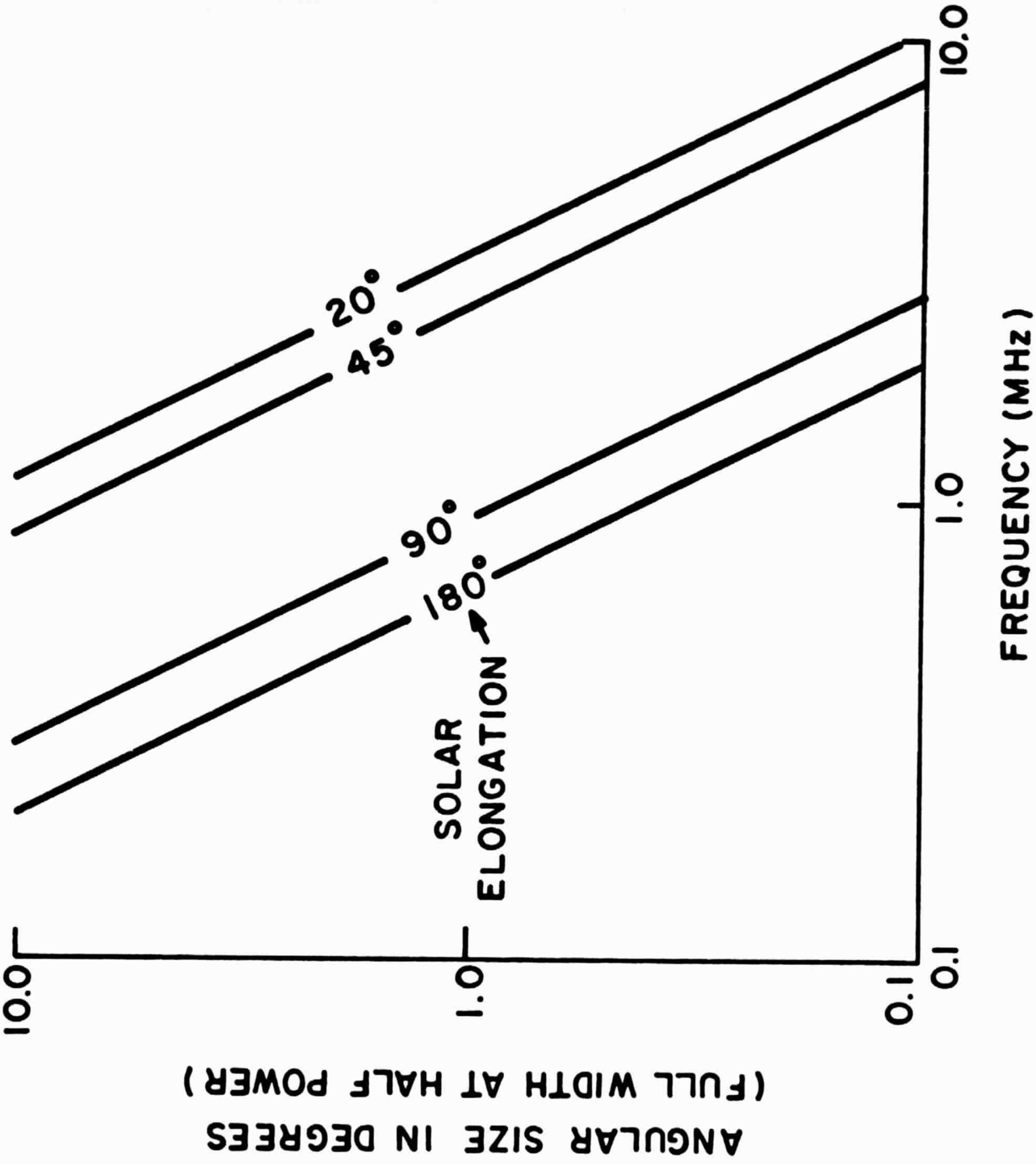
FIGURE CAPTIONS

Figure 1 - The approximate source size (for a point source) due to interplanetary scattering as a function of observing frequency for various solar elongations (after Erickson, 1966).

Figure 2 - The periods during which occultations of the various planets occurred for the first 2½ - 3 years of the RAE-2. The arrow heads marked N and F for each planet are for nearest and farthest distance to Earth. The N and F points for Mercury were not included because they occur every 58 days.

Figure 3 - The top panel shows a dynamic spectrum centered on the time of a predicted occultation of Jupiter. Increasing intensity is indicated by increasing darkness. The bottom panels are relative intensity vs. time displays of some individual channels from the top panel.



20°
45°
90°
180°
SOLAR ELONGATION
FREQUENCY (MHz)
0.1
1.0
10.0
ANGULAR SIZE IN DEGREES
(FULL WIDTH AT HALF POWER)

Figure 1

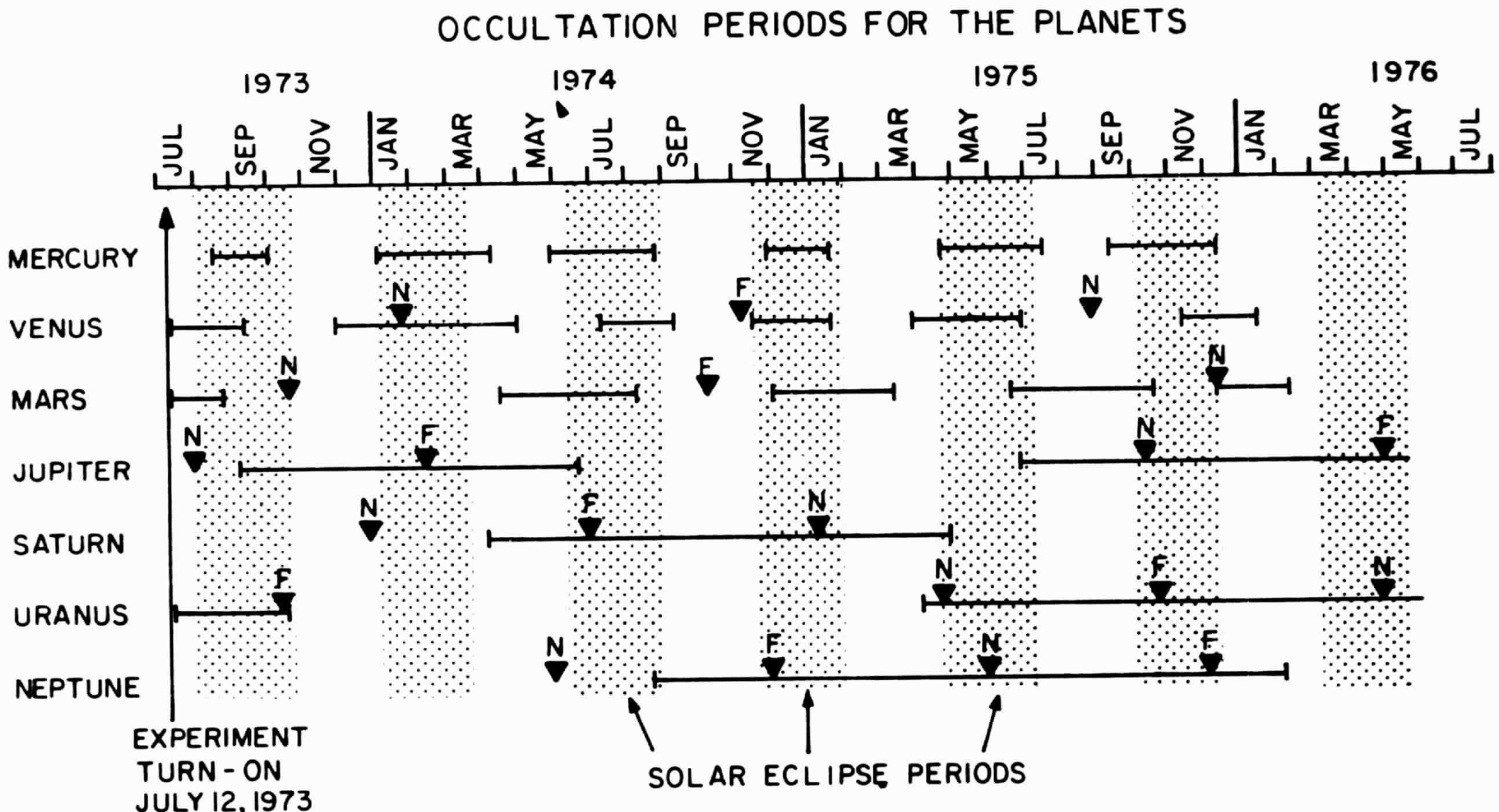

OCCULTATION PERIODS FOR THE PLANETS
1973
1974
1975
1976
JUL
SEP
NOV
JAN
MAR
MAY
JUL
SEP
NOV
JAN
MAR
MAY
JUL
SEP
NOV
JAN
MAR
MAY
JUL
MERCURY
VENUS
MARS
JUPITER
SATURN
URANUS
NEPTUNE
N
F
EXPERIMENT
TURN-ON
JULY 12, 1973
SOLAR ECLIPSE PERIODS

Figure 2

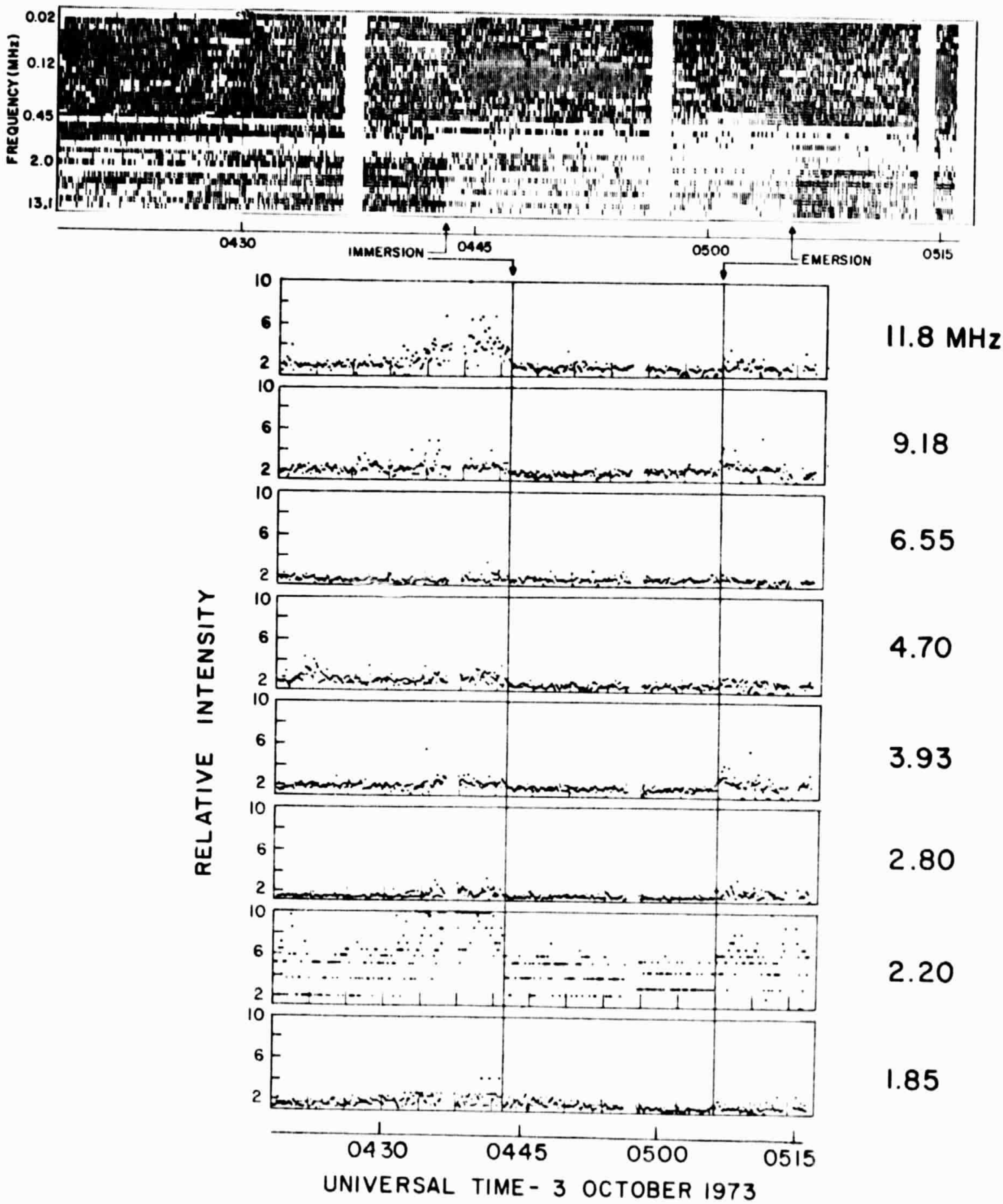

0.02
0.12
0.45
2.0
13.1
FREQUENCY (MHz)
0430
IMMERSION
0445
0500
EMERSION
0515
RELATIVE INTENSITY
11.8 MHz
9.18
6.55
4.70
3.93
2.80
2.20
1.85
0430
0445
0500
0515
UNIVERSAL TIME - 3 OCTOBER 1973

Figure 3