AN INVESTIGATION INTO SOME ASPECTS OF JOVIAN DECAMETRIC RADIATION.

by

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Except where it is clear from the text that I am describing the work of others, or where it is obvious that I am making a survey of existing knowledge on the subject of the present study, the work described in this thesis is my own.

G. Hill

CONTENTS.

ABSTRACT.

This thesis describes observations of the fine structure in Jovian decametric radiation made at Grahamstown during the 1967-68 apparition. It was found that pulses with duration less than 0.5 milliseconds were common during fine structure storms. The restrictions placed on the source for different theories of origin of the short pulses are discussed.

The variation of the probability of occurrence from year to year is analysed on the assumption that the radiation is found in directions fixed with respect to the planet's magnetic field. It is concluded that there is a factor other than the declination of Earth and the Io effect which controls the probability of occurrence. A detailed analysis suggests a beam width of 3° in latitude at Jupiter but further work is necessary to check this.

ACKNOWLEDGMENTS.

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I.E. HILL.

1. REVIEW OF PREVIOUS KNOWLEDGE OF JUPITER'S DECAMETRIC RADIATION.

Since the discovery that Jupiter was a source of intense decametric radiation (Burke & Franklin 1955a, 1955b) much work has been done on this radiation in both theoretical and observational fields. This chapter is intended to provide a brief summary of this work.

1-1. Observations of Jovian decametric radiation.

The decametric radiation from Jupiter has a very irregular nature with time structure on a number of different scales. "Storms" lasting for a few hours are the most obvious feature and are related to the rotation of the planet on its axis. The surface of Jupiter is covered by dense clouds which rotate with the planet and which completely hide the surface of the planet. The observed rotation rates for clouds in the equatorial and mid-latitude regions are different and features in these regions are referred to the longitude systems I and II respectively. The rotation rate for the decametric radiation was found to be different from both of these (Shain 1956) and in 1962 a third longitude system was adopted. System III longitude was defined as coinciding with system II at 0000 UT on the 1st January, 1957, and as having a period of 9 h 55 min 29.37 s (Douglas 1964). Since 1962 there has been some doubt about the accuracy of this period with some suggestions of a change of about 1 sec in 1961 (Douglas & Smith 1963, Smith et al

1965). It has also been suggested that the period should be 9 h 55 min 29.67 s and that the change in rotation rate is due to a cyclic movement of the sources (Gulkis & Carr 1966).

Radiation is received more frequently when certain ranges of system III longitude lie on the central meridian of Jupiter. Plots of the dependence of probability of emission on central meridian longitude show three peaks called A, B and C sources as shown in figure 2-6. The position and width of the sources has been found to vary considerably with frequency of observation. At low frequencies the radiation probability is largely independent of longitude but shows a marked power distribution with longitude (Ellis 1962a, McCulloch & Ellis 1966). At higher frequencies the radiation is predominantly from B source (Gruber 1967).

The frequency range over which storms have been received is very limited. The highest frequency reported is 43 MHz with a single aural record. (Kraus 1958). Low frequency emission is difficult to detect because of interference but activity has been recorded regularly at 4.8 MHz (Ellis 1962a). Activity is most likely at about 18 MHz and the probability falls off rapidly with increasing frequency. A spectograph operating at Boulder, Colorado over the range 8 - 41 MHz has been used since 1960 for observations of Jupiter. (Lee and Warwick 1964). Warwick (1962, 1963) has shown that spectral characteristics are fixed in longitude and are reproducible over a period of years.

Bigg (1964) found that the probability of a Jupiter storm occurring depended strongly on the position of Jupiter's second satellite, Io. Three dimensional plots of central meridian longitude and Io departure from superior geocentric conjunction against probability show that for Io positions between 70° and 110° and central meridian longitudes between 90° and 185° there is a high probability peak. There is a second broader and lower peak for longitudes in the range 200° to 280° and Io positions in the range 210° to 260°. The majority of B source activity is Io related. The Io control is more noticeable for high frequency activity (Gruber 1967, Duncan 1966). Dulk (1967) has shown that Jupiter's other satellites have no effect on the decametric radiation.

The radiation probability is found to vary from year to year and showed a clear minimum in 1958-59. Data are insufficient but indicate an approximately 11 year cycle in activity. Carr (1958) and Carr, Smith, Bollhagen, Six and Chatterton (1961) suggest that the probability anti-correlates with the smoothed sunspot number which has a period of 11.1 years while Gulkis and Carr (1966) point out that a correlation with Jupiter's position in its orbit is more likely. In particular activity seems to correlate with the declination of earth as seen from Jupiter. This has an 11.9 year period. This probability variation will be discussed in more detail in Chapter 4.

Many observers have tried to find a short term correlation between Jupiter activity and solar activity of various kinds. The most promising correlation is that found by Warwick (1963) (see also Roberts 1963) between solar continuum and Jupiter storms which extended above 30 MHz in the following few days. All other correlations are probably statistically insignificant.

Individual storms contain time structure on a finer scale still. Bursts of activity tend to form groups containing several bursts or pulses and lasting for tens of seconds to minutes. It is found that these groups of pulses do not correlate over a long baseline and are probably of ionospheric origin. (Gardner & Shain 1958, Smith et al 1960, Douglas & Smith 1967). These groups are made up of pulses of various lengths from several seconds to milliseconds with pulses of the order of a second being the most common. Pulses with duration longer than 0.2 seconds will be called normal pulses and the rest will be called short pulses. The normal pulses are found to be correlated over long baselines at times, although it is necessary to allow for delays between the arrival times at the ends of the baseline. (Smith et al 1960). These pulses must be part of the Jovian radiation incident on the ionosphere and are probably due to interplanetary scintillations (Douglas & Smith 1967).

The short pulses were reported in earlier studies by Gallet (1961), Kraus (1958) and Douglas and Smith (1961), but did not attract much attention. Short pulses tended to clump together in groups of 3 or more pulses although occasional isolated pulses were reported. Riihimaa (1964b) obtained spectographic records of these short pulses and found that they tended to drift in frequency. He estimated a duration of about 5 msecs on average for the pulses. In 1965 Slee and Higgins found that the millisecond structure was simultaneous over a 200 km baseline in contrast with delays of up to one second observed with normal pulses. This pointed to an origin for the short pulses which was different from that of the normal pulses. Since 1965 the short pulses have attracted more attention. Recent work has shown that the pulses have components on a submillisecond scale and are well correlated over long baselines. It seems likely that some subdivision of the short pulses into two types as shown in table 2.1 (Baart, Barrow and Lee 1966) would represent a real division between pulses which are merely short normal pulses and pulses on a millisecond or sub-millisecond scale. The latter appear to have a different origin. Chapters 2 and 3 of this thesis deal with these millisecond scale pulses.

The radiation from Jupiter usually shows a definite polarization and many polarization studies have been made. Observations in both northern and southern hemispheres show that the radiation is largely right hand circularly or elliptically polarized.

The higher frequencies show only right hand polarization with left hand bursts becoming more common with decreasing frequency. Several observers report radiation with a random linear polarization. (Sherrill 1965).

1-2. Theories of Jovian Decametric Radiation.

There have been several attempts to explain the origin of the decametric radiation theoretically. The earlier suggestions of lightning flashes or volcanic stimulation of the ionosphere were soon discarded and attention was focused on methods of generation by particles streaming through the ionosphere or magnetosphere. Only two theories have been developed sufficiently to provide a mechanism which is capable of describing the observed longitude distributions and frequency dependence. A third theory describes the longitude and frequency dependence well and includes the Io effect as an integral part of it, but as yet it lacks a developed generation mechanism.

The most fully developed theory is that of Ellis (1962b, 1963, 1965) and Ellis and McCulloch (1963). They suggest that the radiation is due to Doppler shifted cyclotron radiation generated in the magnetospheric plasma by an electron stream travelling through the plasma along the magnetic field lines. It is assumed that the plasma frequency is always less than the cyclotron frequency because the plasma density is controlled to a large extent by the magnetic field intensity. The radiation is assumed to be generated in the extra-ordinary mode. Under these conditions only the Doppler shifted radiation propagating with a component in the direction of the electron stream can escape the plasma. (See Appendix B).

Radiation is possible for streams moving toward the planet or for streams moving away from the planet after reflection at the mirror point. In the former case radiation will be beamed towards the planet and reflected outwards at the appropriate extra-ordinary mode reflection level. In either case Fung (1966) has shown that the radiation at a particular frequency will be concentrated on the surface of a cone co-axial with the magnetic field lines. The angular width of the cone increases with decreasing frequency. Using as an example the possible generation of whistlers in the magnetosphere by this method, they assume that the radiation will only take place from field lines with a high magnetic latitude. Activity will only be observed when the cone of radiation is swept over the Earth. By using a magnetic field model with the dipole axis inclined with respect to the rotational axis and with suitable dip anomalies, they obtained a good fit to the observed longitude - frequency profile.

In particular this model predicts a fine structure due to individual bunches of electrons within a stream. This fine structure will appear as bursts of activity drifting in frequency over a short range of frequencies determined by the cone intersecting Earth. The drift rate would be in the range 30 to 50 MHz/sec for the magnetospheric properties assumed and would be a drift from low to high frequencies with time (positive drift) for bunches moving towards the planet and a negative drift for bunches moving away from the planet.

In addition the probability of radiation being received at earth must be strongly dependent on the magnetic declination of Earth with respect of Jupiter, i.e. on the angle between the magnetic equatorial plane of Jupiter and the line joining Earth and Jupiter.

The second theory is that due to Warwick (1961, 1963), who suggested that the radiation originates close to the planet in the ionosphere. It is assumed that the main radiation belt lies between 2 and 3 Jovian radii from the centre of a dipole magnetic field. A localized disturbance in this belt causes fast electrons to be precipitated down the field lines into the ionosphere. Those electrons with velocities greater than the phase velocity for propagation in the plasma generate Čerenkov radiation in the extra-ordinary mode below the gyrofrequency. The wave which is most strongly generated has a phase velocity near the velocity of the electrons and a frequency just greater than the plasma frequency.

Warwick assumes that the radiation is confined to within 10° of the field line and is beamed ahead of the precipitated electrons. The radiation is reflected by a denser part of the ionosphere or by the surface of the planet and emerges beamed in the direction of the field lines. In a manner similar to that of the Ellis and McCulloch theory the longitude and frequency profiles observed on Earth are caused by these beams being swept across Earth by the rotation of Jupiter. To obtain the observed profiles it was necessary to displace the dipole relative to the rotational axis of Jupiter, relative to the equatorial plane and relative to the 200° system III plane which remains parallel to the dipole axis. The extent of the displacements required is one of the weak points of theory and accurate decimetric observations such as Branson (1968) have made it unlikely that displacements of the magnitude required are present.

The theory makes no specific predictions about fine structure but again the probability of receiving emission will depend on the magnetic declination of Earth.

Gledhill (1967a, 1967b) has proposed that the radiation is generated in the vicinity of Io. The theory provides a model of Jupiter's magnetosphere which is capable of explaining some of the observed properties of the radiation from Jupiter rather than providing a detailed theory of the emission mechanism. It is assumed that Jupiter's magnetosphere co-rotates with the planet. The high rotation rate of Jupiter causes the plasma in the magnetosphere to concentrate at those points of the field lines furthest from the axis of rotation giving rise to a disc shaped magnetosphere. The magnetic dipole axis is assumed to be inclined to the rotational axis and the dipole is displaced 0.4 radii north of the equatorial plane. The magnetic field intensity is chosen to give a maximum plasma frequency of 40 MHz at Io's orbit.

It is proposed that radiation is generated by Io at the local plasma frequency as Io passes through the plasma. This model give a good fit to the spectra observed from the sources of radiation as well as explaining the Io effect in a rather more satisfactory way than other theories.

These three are by no means the only theories proposed to explain Jovian decametric radiation but are representative of theories placing the source in each of the three regions; the ionosphere, the magnetosphere or at Io and are the most detailed theories for each of these regions.

2. MILLISECOND STRUCTURE IN JOVIAN DECAMETRIC RADIATION.

In the previous chapter it was seen that several observers have reported a component in the time structure of Jovian decametric radiation with a time scale of less than 50 msecs. It is this structure which is the subject of this chapter and which constituted the bulk of the research work I have done during the past two years.

The first section summarizes those properties of the millisecond or "spitting" component of the radiation which were known at the commencement of the programme and outlines the aims of the programme. This is followed in the second section by a description of the equipment used in the study of the millisecond structure and of the form of the permanent records made of such activity. In the third section the observing programme and the identification of the radiation received with a Jovian origin is discussed. The final section deals with the results obtained from these observations.

2.1. Previous observations of millisecond time structure in Jovian decametric radiation.

The "bursty" nature of the Jovian decametric radiation has been mentioned in the first chapter. In accordance with the NASA "Recommendations for Standardization of Reporting Procedures" as quoted by Baart et al (Baart, Barrow and Lee 1966) the names and classifications given in 2-1 will be used to identify burst types and for convenience the name I-pulses assigned to bursts lasting less than 50 milliseconds in the above paper will be adopted throughout this chapter.

The properties of these millisecond bursts or I-pulses can be summarized as follows:

Over a loudspeaker they are heard as sharp clicks rather like terrestrial static. They may occur singly or more often in groups of two or three pulses following closely upon each other and may be received with normal bursts, superimposed on normal bursts or entirely independently of normal bursts. Measurements of the durations of the pulses at one frequency vary from 0.5 milliseconds to 50 milliseconds. Spitting storms are far more common from B and C sources than from A source and exhibit the usual dependence on Io position with the peak at 90^{o} S.C.C. relatively larger than for normal storms as a result of the greater likelihood of B source being active. The spitting pulses are usually elliptically polarized, as are normal bursts, and both right hand and left hand polarized pulses are obtained. Swept frequency receivers with a high repetition rate show that the pulses are narrow banded and at times appear to drift in frequency towards lower frequencies.

	PULSE LENGTHS	CLASSIFICATION
L	Greater than 2 secs.	Long
N	0.2 - 2 secs.	Normal
S	0.05 - 0.2 secs.	Short
I	Less than 0.05 secs.	I-pulses

Table 2.1 Classification of pulses.

The aim of this study was firstly to confirm those characteristics of the I-pulses which were already known and secondly to obtain accurate measurements of the duration of the I-pulses. It was hoped that an accurate knowledge of the pulse lengths would yield information on possible mechanisms for the generation of these pulses. Till recently there had been few attempts at measuring the durations of these pulses accurately and most of the measurements which had been made were done by measurement of analogue records made during noise storms. Disadvantages of this kind of measurement are the limitations placed on the minimum pulse length measurable by the necessity for reasonably economical chart speeds and by the inertia of the mechanical components. When analogue records are obtained by photographing traces on an oscilloscope screen more accurate measurements are possible but continuous records are impossible and tedious measurements of pulse durations are still necessary.

To eliminate some of the drudgery involved in these measurements and to decrease the lower limit imposed by mechanical systems on measurable pulse lengths, it was decided to construct an electronic device capable of measuring the durations of pulses automatically.

2-2. Equipment.

The antennae and receivers used during the I-pulse experiment were used simultaneously for routine fixed frequency observations of Jupiter's decametric radiation by the Rhodes University physics department. Observations were made at 16, 18, 20 and 22 MHz in the period from the 8th November, 1967, till the 10th June, 1968, although not all frequencies were used throughout this period.

The antenna used at each frequency consisted of two four element Yagi's mounted on the same beam but with elements mutually perpendicular to each other and to the beam. The antenna was fixed in elevation but rotatable in azimuth. The main lobe of the beam pattern was about 90^{o} in width. With this arrangement Jupiter could be kept in the beam of the antenna for up to eight or nine hours a day with rotation of the antenna only necessary at hourly intervals.

The antenna yielded two perpendicular plane polarized components of the incident radiation which were converted to two circularly polarized components of opposite sense using a hybrid ring method as illustrated in fig. 2-2, (see for example Barrow 1962). After preamplification by a broad band amplifier each of the two circular components was fed to a standard communications receiver (Trio 9R - 59) with an output signal

Fig 2.1 Crossed Yagi antennae at the observatory site.

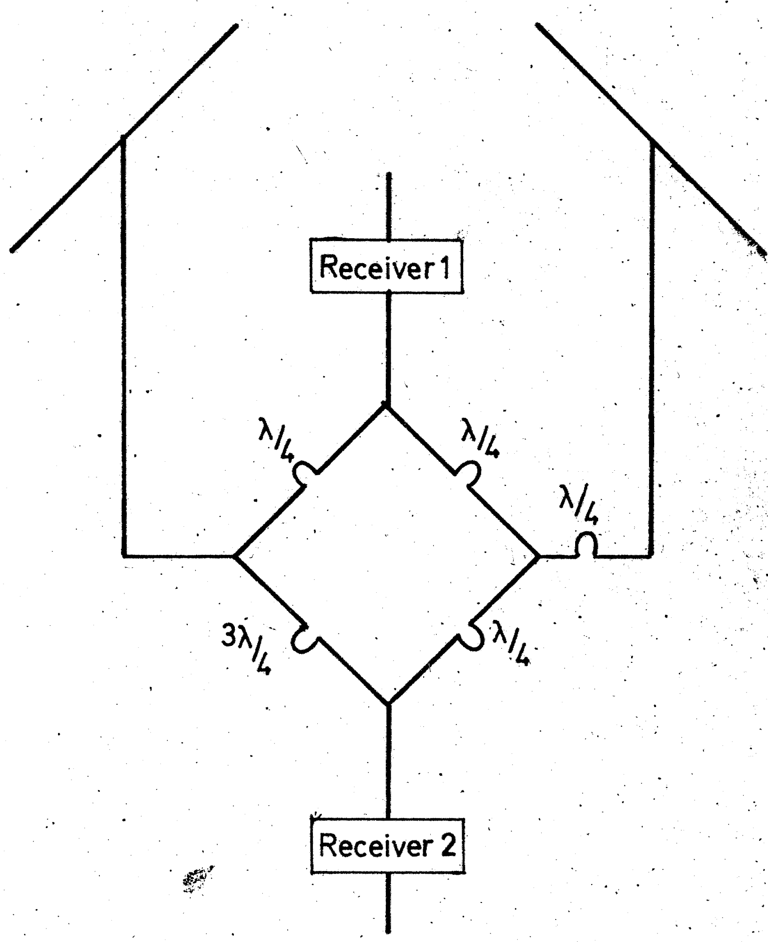


Fig 2.2 The hybrid ring system used to obtain left and right handed circular polarizations.

taken from the detector. This left the audio stages free for monitoring purposes. An eight track variable speed pen recorder was used to record two polarizations at each of the four frequencies used (when all were in operation) as a part of the routine observation programme. The chart speed when I-pulse storms were in progress was 250 mm/min with a nominal time constant FOR THE RECORDER AMPLIFIER of 0.1 seconds. The shortest pulse length measurable from a chart under these conditions would be 0.2 seconds and so I-pulses could not be measured.

A block diagram of the pulse measuring equipment is shown in fig. 2-3 and a detailed circuit diagram in fig. 2-4. The basic idea was to square the I-pulses from the detector of the receiver and use them to gate a sweep generator. The sweep's peak height could then be used as a measure of pulse length. The circuit converts a time interval to a voltage which is easily measurable.

In order to be able to set the minimum level for identification of a pulse as Jovian radiation with some degree of precision it is necessary that the peak amplitude of the pulse be much greater than the uncertainty in the selection level. As the uncertainty in the selection level was determined by the hysteresis of the Schmitt used for squaring the pulse and was in practice of the same order of magnitude as the r.m.s. sky noise level a fairly high gain voltage amplifier was necessary.

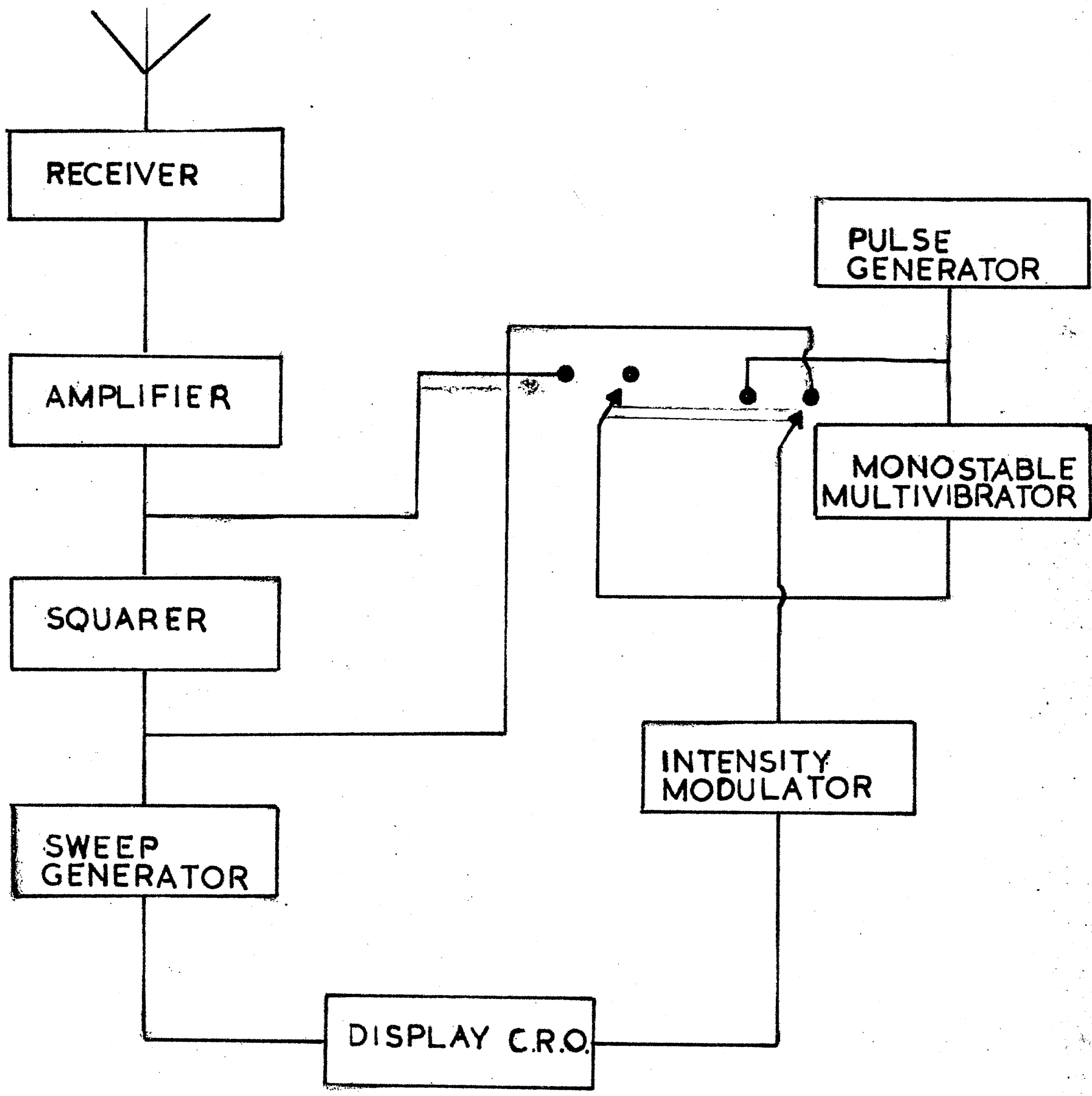


Fig 2.3 Block Diagram of Equipment.

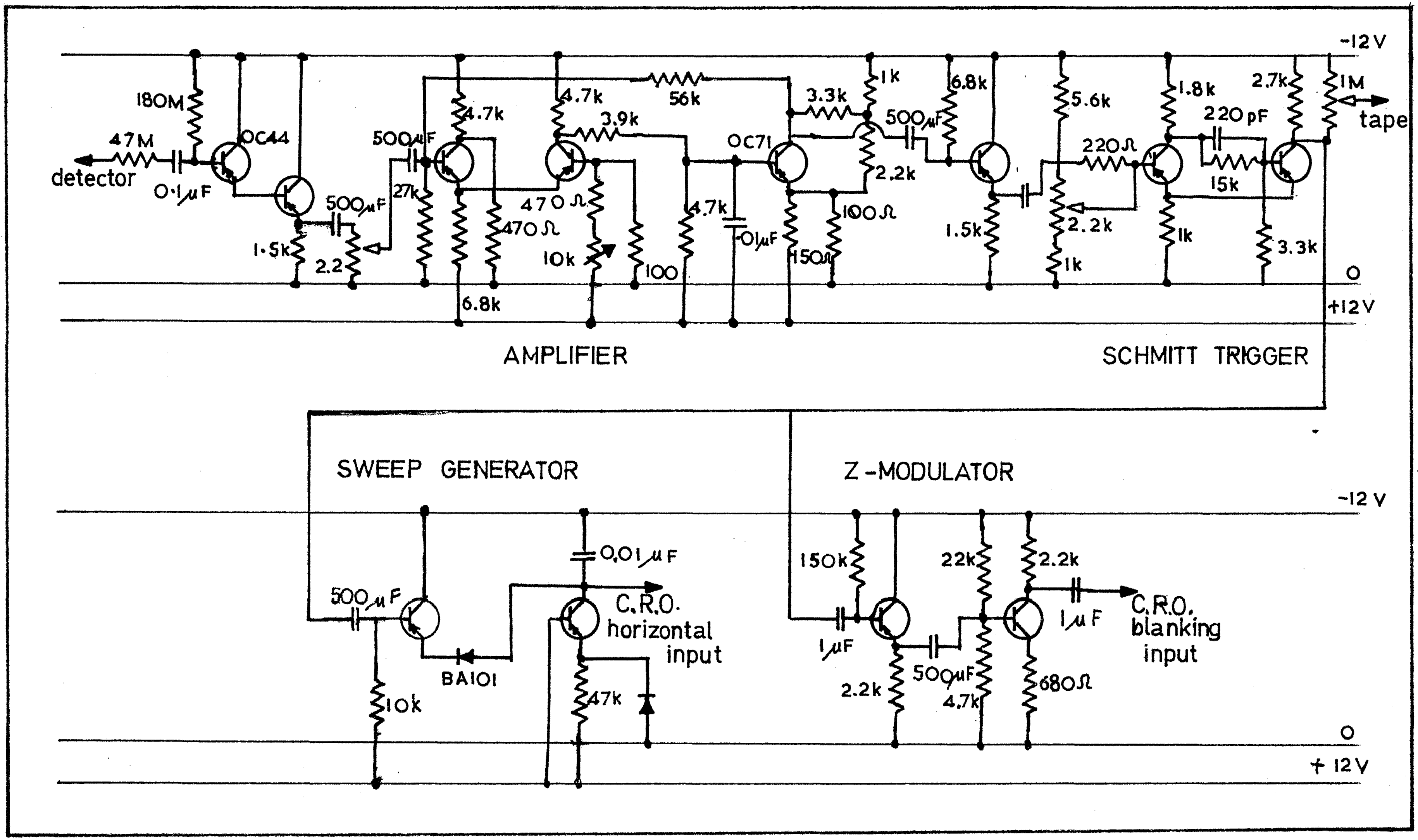


Fig 2.4 Circuit Diagram

From records of pulse length observations available at the time the apparatus was designed, it was expected that pulses would have lengths down to about 1 msec. and this was used to determine the bandwidth necessary for the pulse amplifiers. Fourier synthesis of a square pulse shows that for an amplifier to pass a pulse of duration T with satisfactory accuracy, the amplifier must have a bandwidth of at least $^{2}/_{T}$ and preferably greater. It was later found that pulses with shorter duration were common and it was necessary to modify the amplifying stages.

At the other end of the spectrum the amplifier had to have a lower cut-off sufficiently low to prevent droop of pulses with durations of tens of milliseconds but on the other hand it would be advantageous if short and normal bursts were not passed by the amplifier. The circuit used consisted of a Darlington pair to match the amplifier to the detector of the receiver followed by a difference amplifier with capacitative coupling between the two. The low frequency cut-off was then determined almost exclusively by the value of the coupling capacitor.

The pulse squarer which followed the amplifier was a simple Schmitt trigger. The triggering level was set by means of a potentiometer which was calibrated in terms of the r.m.s. noise voltage which would just fail to trigger it. The selection level was obtained by measuring the r.m.s. noise voltage at the input to the

Schmitt and setting the potentiometer to three times this value. By this means only those pulses which had an amplitude greater then three times the r.m.s. noise level were measured and thus regarded as having Jovian origin. This did not eliminate terrestrial static pulses but, as these are usually wide-band pulses in contrast with the narrowbanded pulses of Jovian origin, it is possible to eliminate them by comparison of records obtained at frequencies differing by a few MHz. For this reason two identical pulse measurers were built and operated at frequencies separated by 2 MHz. This method was only used for the earlier observations, thereafter it was realised that the site of the observatory was sufficiently quiet and free from static to make such precautions unnecessary. Measurements were then made of pulse durations in the two circularly polarized components of the radio noise at the same frequency.

The switching time of the transistors did not place any restriction on the minimum pulse length measurable as even using audio frequency transistors it was considerably less than 0.1 milliseconds.

The sweep generator used was of the constant current type: a constant current through a transistor T_1 connected in the common base configuration is used to charge a capacitor. The current remains constant as it is determined only by the potential drop across the emitter resistor and this potential is very nearly the positive supply voltage since the emitter-base voltage is small in comparison. In the quiescent state the capacitor is shorted by a second transistor T_2 which carries all the current passing through T_1. The positive gate pulse from the Schmitt carries the base of T_2 positive thus cutting T_2 off. The capacitor then charges until the gate is removed and T_2 returns to the conducting state. As T_2 starts conducting it discharges the capacitor. The sweep generated in this way was applied directly to the horizontal plates of an oscilloscope. There was no vertical input to the oscilloscope so the display on the screen consisted of a single horizontal line for each I-pulse received. The length of the line was proportional to the duration of the pulse.

The square pulse from the Schmitt was amplified and used to intensity modulate the display on the oscilloscope. This ensured that only the sweeps were visible, the flyback and delay before the next sweep were blanked out. This display was filmed using a camera which moved the film vertically past the screen at about 1½" per minute. The film when processed had a series of parallel lines across it representing the durations of individual pulses.

In addition to the photographic record, the pulses from the Schmitt were recorded on magnetic tape using a Thermionic Products T3000 data recorder. Only one camera and oscilloscope were available so only one of the channels could be recorded directly on film, the other had to be recorded on tape. As the photographic recording proved a fickle process, both channels were recorded on magnetic tape and were later recovered and photographically recorded by the process above. The output from the recorder was inverted and fed directly to the Schmitt which then provided suitable gate pulses for the sweep generator.

To interpret the photographic record it was necessary that it be calibrated suitably in terms of pulse length. A synchronous motor was used to fire a relay once a minute. The relay performed two tasks in order to produce the desired calibrations. The intensity modulation voltage to the oscilloscope was switched from the squared pulses from the Schmitt to a 2 kHz square wave signal from a Phillips PM5710 pulse generator. The output of the pulse generator was also used to trigger a monostable multivibrator, the output of which was switched into the input of the squaring Schmitt to provide regular long sweeps during the period the relay was closed. As the modulating pulses were fixed relative to the start of each sweep the calibration marks appeared as band across the film.

A specimen record including calibration marks is shown in fig. 2-5. THE CALIBRATION MARKS ARE THE PEAKS IN INTENSITY IN THE VERTICAL BAND ON THE RIGHT.

Even though the D.C. horizontal input to the oscilloscope was used the zero point drifted horizontally when the rapidly repeated sweeps used during calibration were applied. This was corrected during analysis of the records by measuring the shift in zero position and moving the calibration marks by exactly this amount.

2-3. Observing procedures.

The Jovian decametric radiation observation programme carried out by the Rhodes University physics department during the 1967-68 apparition ran from 8th November, 1967 till 10th July, 1968, with observations being made on most nights when conditions were favourable. Table 2-2 lists the frequencies and polarizations at which observations were made and the periods during which these channels were operational. All records during this period have been examined for evidence of I-pulse storms. The pulse duration experiment was carried out from mid November until mid June, 1968, with a break during February for extensive modifications to the circuitry. These included an increase in the bandwidth of the amplifier and a complete revision of the method of calibration. For these

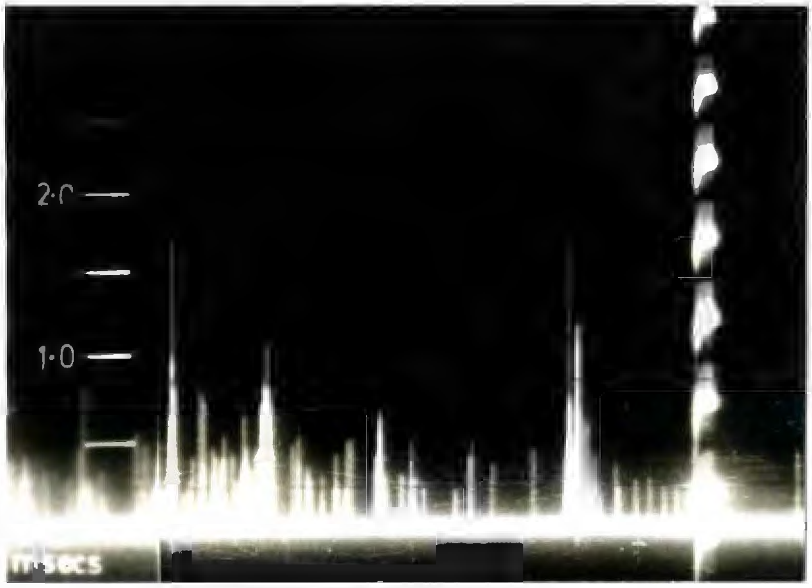


Fig.2.5. An example of the records obtained from the pulse measuring apparatus with calibration marks included. Time runs from left to right across the figure.

FREQUENCY	OBSERVING PERIOD	
	FROM	TILL
16MHz Total Power	8th November, 1967	12th January, 1968
16MHz Circularly polarized components	16th January, 1968	10th July, 1968
18MHz Total Power	19th January, 1968 25th March, 1968	6th March, 1968 13th June, 1968
18MHz Circularly polarized components	8th November, 1967	17th January, 1968
20MHz Circularly polarized components	19th January, 1968	10th July, 1968
22MHz Total Power	17th June, 1968	10th July, 1968
22MHz Circularly polarized components	8th November, 1967	16th June, 1968

TABLE 2-2. OBSERVING PERIODS AT VARIOUS FREQUENCIES.

reasons only results of the pulse measurement experiment since March have been analysed. The apparatus was not in use every night during this period as it proved too difficult for one observer to run both the routine observations and the additional experiments. Normally the apparatus was in use only on those nights when from the orientation of Jupiter and the position of Io it was most likely that spitting activity would occur. These favourable nights were determined with the aid of prediction charts. (See appendix A).

The watch each night lasted for that part of the 7 to 8 hour period, centred on the local transit time of Jupiter, which fell between 8 p.m. and 7 a.m. As the observatory is situated in a valley and as Jupiter had a declination of between $+10^{\circ}$ and $+12^{\circ}$ during most of the apparition, Jupiter was only visible for about 8 hours a day and observations were not usually made during the period immediately after it had risen and immediately before it set. Observations during daylight hours are not worthwhile at decametric wavelengths due to the large amount of terrestrial static present.

During all observation periods the audio outputs of the receivers were monitored aurally by an observer for any sign of Jupiter activity. At the beginning of each watch the pulse experiment apparatus was checked to ensure that it was in working order; in particular the display on the oscilloscope, the recording level on the data recorder, and the calibration mark system were checked. When this had been done the triggering level was set by measuring the r.m.s. noise voltage at the monitor terminals and setting the triggering level accordingly. This level was checked at regular intervals throughout the watch. When spitting Jupiter activity was suspected the pen recorder chart was switched to 50 mm/sec and the time constant reduced. When the activity was positively identified as containing spitting pulses of Jovian origin the chart was run at 250 mm/sec and the oscilloscope recording camera and the data recorder were started. This was continued until I-pulse activity had ended.

At the end of each watch the receiving system for each channel was calibrated to obtain an indication of the gain of any one of the channels relative to any other channel. The antenna input to the preamplifiers was replaced by a white noise signal generated by a D.C. current flowing through a microwave diode. Each channel was calibrated for two different diode currents. The zero input position of the pen was included with the calibrations.

There are several other sources of radio noise which could be mistaken for Jupiter I-pulse activity and so the following checks were made to determine whether or not the noise was of Jovian origin. The observer monitored the audio outputs of the receivers and noted on the pen recorder chart any interference of obviously terrestrial origin. If possible the receiver was retuned to an interference free frequency. Powerline noise, distant stations and lightning flashes could be identified by their characteristic sound and were eliminated by this means before analysis of the records. To help ensure that the receivers were tuned to a frequency clear of any distant stations the B.F.O. of the receiver was switched on while retuning. Before any radio noise was identified as coming from Jupiter the receiver was tuned over a few hundred kilohertz; only if the noise could not be tuned out was it taken as being of Jovian origin. In addition Jupiter had to be in the beam of the antenna before positive identification was made. In cases of doubt the antenna was directed at right angles to the Earth-Jupiter line. If the noise originated from the planet then it should disappear as the antenna is rotated. A further condition which had to be fulfilled before the pulses were recorded as being of Jovian origin was that they had to have an amplitude greater than three times the r.m.s. sky noise level. As mentioned earlier, in the pulse measurement experiment this was determined by the triggering level. Although any one pulse during a storm will exhibit a narrow bandwidth, activity is typically observed over a range of at least a few megahertz. Activity over two or more different frequencies was used as a guide in identifying noise storms as coming from Jupiter but lack of such activity did not necessarily exclude a Jovian origin for the noise.

During analysis of the pen records, any pulses which appeared simultaneously over a bandwidth of 4 MHz or greater were disregarded. Before an analysis of the photographic records was made, the pen record for that time interval was studied for any sign of interference, and if an appreciable amount of interference was found that section of the photographic record was ignored during the analysis or, if it were possible to identify on the photographic record from the pulse measurer, the interference pulses marked on the paper chart, only those pulses were ignored. This was generally only possible where a single static pulse occurred during a break in I-pulse activity.

2-4. Analysis of Records and Results.

Table 2-3 lists all the Jovian decametric storms recorded during the observation period which contain I-pulse activity. The times after the date in the table are the Universal Time of start and end of each event as

DATE	START	END	CENTRAL MERIDIAN LONGITUDE	IO POSITION	CERTAINTY
24th Nov., 1967	0100	0230	147-201	93-105	3
30th Nov., 1967	0130	0155	348- 3	237-241	3
30th Nov., 1967	0212	0306	13- 46	244-251	3
1st Dec., 1967	0146	0303	148-195	83- 94	3
22nd Dec., 1967	0321	0430	128-169	49- 58	2½
1st Jan., 1968	2210	2332	157-205	83- 93	3
1st Jan., 1968	2337	2344	208-211	95- 96	2
3/4th Jan., 1968	2331	0019	146-176	142-149	3
4th Jan., 1968	2240	2317	266-287	338-340	1
8th Jan., 1968	2248	2350	152-191	73- 82	3
27th Jan., 1968	2239	2303	128-147	339-343	2
28th Jan., 1968	2226	2319	273-306	181-188	2
31st Jan., 1968	0038	0104	293-312	247-252	3
31st Jan., 1968	2202	2325	350- 42	69- 81	3
8th Feb., 1968	0223	0307	123-150	92-98	2
9/10th Feb. 1968	2332	0120	321- 28	114-130	2
14th Feb., 1968	0313	0335	338-352	239-242	3
15th Feb., 1968	0317	0337	131-143	85-88	3
25th Feb., 1968	2019	2147	94-151	105-118	2½
3rd Mar., 1968	2236	2338	153-189	108-117	2½
10th Mar., 1968	2304	2320	143-155	98-100	2
16/17th Mar. 1968	2224	0043	302- 27	234-254	3
25th Mar., 1968	0010	0049	134-155	79- 84	3
3rd Apr., 1968	2009	2026	52- 64	279-282	1
8th Apr., 1968	2006	2037	84-102	217-221	3
25th Apr., 1968	2026	2143	134-180	79- 89	3
24th May, 1968	1825	1835	104-110	202-203	2
26th May, 1968	1751	1826	24- 45	243-249	3
27th May, 1968	1724	1809	156-184	82- 89	2½

TABLE 2-3 DETAILS OF I-PULSE EVENTS.

determined by examination of the pen records and rejection of all short pulses not of Jovian origin and all Jupiter activity not containing I-pulses. The following two columns give the system III central meridian longitude and the departure of Io from superior geocentric conjunction at the beginning and end of each event. Both these values are not accurate~~ly correct~~ but the central meridian longitude will lie within 3° of the value quoted and the Io position within 1° of the quoted value. Accurate values were used where necessary. The final column gives an indication of the certainty, on a scale of 1 to 3, with which the pulses of millisecond duration during the storm can be identified as Jovian I-pulses. The value 3 was assigned to those storms where, in the opinion of the investigator, the pulses were certainly part of the Jovian radiation. The following criteria were used to judge this certainty.

(i) The pulses were associated with Jupiter activity of any kind on a different frequency.

(ii) The pulses did not have a wide bandwidth, but had a bandwidth of less than 2MHz.

(iii) The pulses did not have the appearance of any known terrestrial interference.

(iv) The pulses could be expected to exhibit some kind of circular polarization.

(v) The pulses had an amplitude greater than three times the r.m.s. sky noise level.

Of these conditions only (ii) and (v) had to be satisfied for the event to be included in table 2-3. In cases where other conditions were not satisfied the events were assigned to one of the remaining categories using the general guides below.

Those events with a likelihood of 2, contained pulses which were very probably of Jovian origin but which did not satisfy all the five requirements listed above. Some storms in this category contained pulses which would have been classified as 3 if they had been isolated but which were accompanied by a large amount of terrestrial interference making identification difficult. The remaining category contains storms where there is a fifty-fifty chance of the event being due to Jupiter.

In the few cases where the certainty changed during the course of an event, the events were assigned half integral values.

Fig. 2-6 shows the dependence of what, for convenience, is called the probability of occurrence on the central meridian longitude in system III. This is not in fact a true probability but is more accurately that fraction of the number of five minute intervals in each 15° range of longitude during which any Jupiter activity was received. The shaded histogram shows the dependence of the above probability on longitude considering only those five minute periods where I-pulse

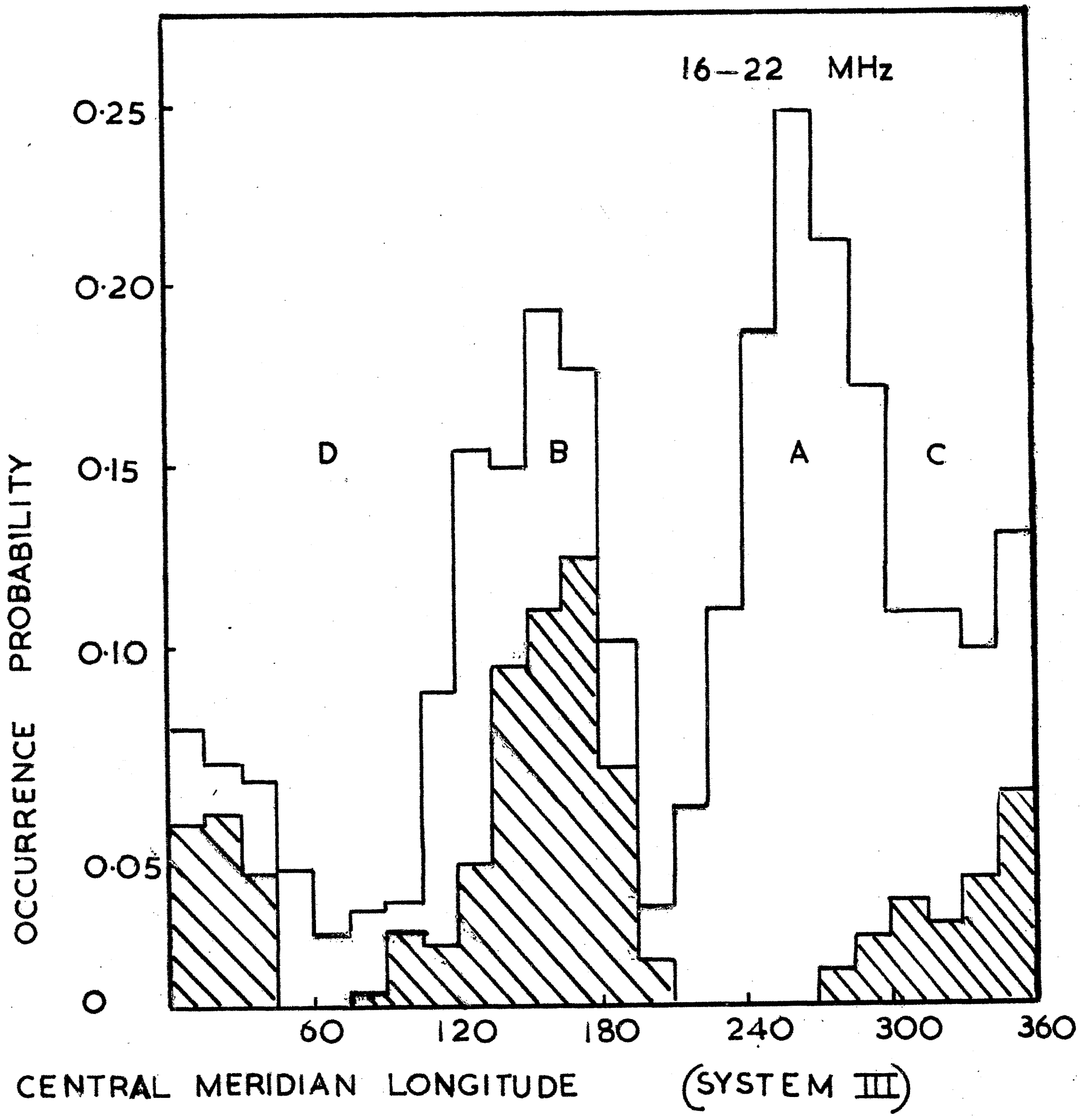


Fig. 2.6 Total and S-burst Activity Distributions with Central Meridian Longitude of Jupiter.

activity was present. The three sources A, B and C are all evident in the total probability histogram with C appearing as an extension of A source as a result of the large longitude step. An unusual feature of this distribution is the high probability of B source activity. ~~relative to A and C sources~~. Previous fixed frequency observations in the same frequency range have shown that B usually has about the same probability as C with A being more active than both. No explanation can be offered for the difference between the usual distributions and the distribution obtained during 1967-68. The I-pulse activity shows the usual kind of distribution with most of the activity being due to B source with a second peak at C source. (Olsson and Smith 1966). The complete lack of I-pulse activity from A source is unusual.

A histogram has also been drawn up relating the form of probability described above and the departure of Io from superior geocentric conjunction for only those intervals containing I-pulse activity. This is shown in fig. 2-7. This histogram has no unusual features but shows peaks at 90° and 240° (Bigg 1963) as is usually the case.

These two correlations of I-pulse activity with events on and near Jupiter show that the pulses must be

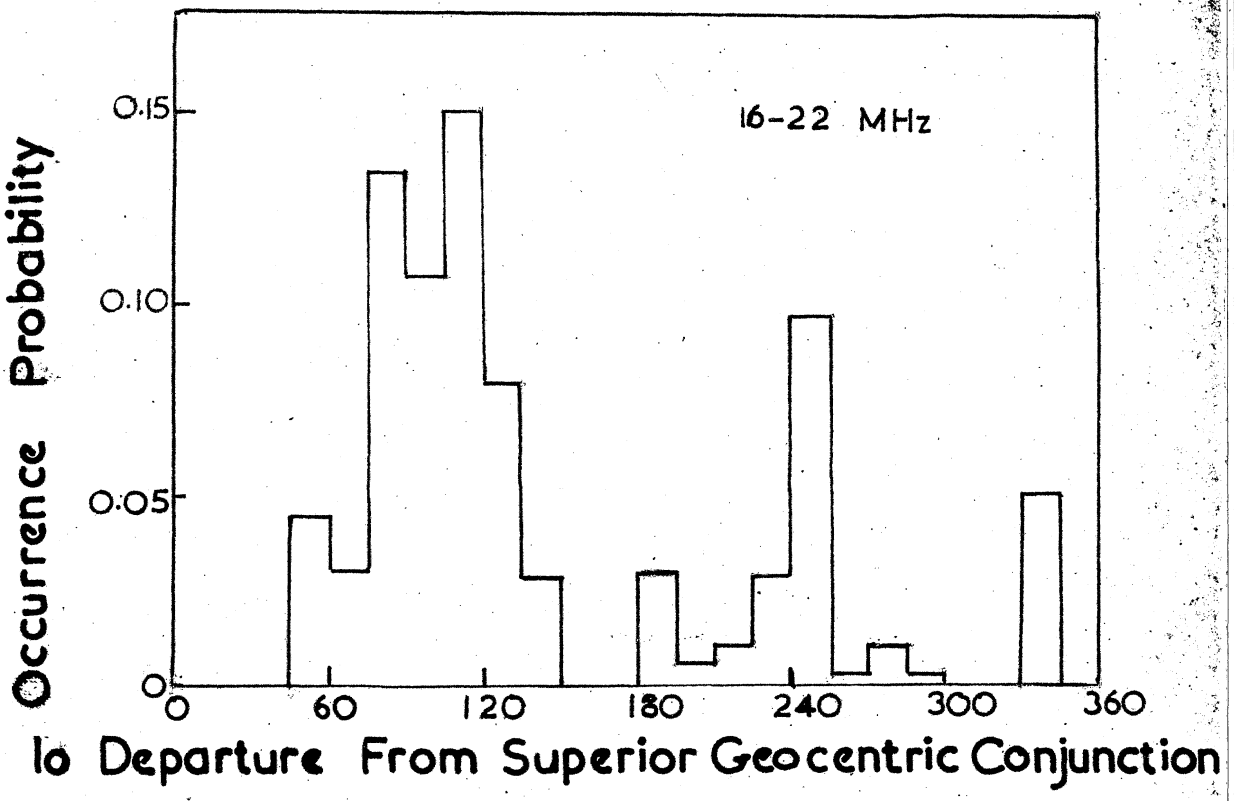


Fig 2.7 I-Pulse Activity Distribution with IO Position.

associated with Jupiter and not with terrestrial sources.

Before commenting on the records obtained from the pen recorder during I-pulse activity it would be well to clarify what the trace represents. As mentioned earlier the time constant when I-pulse activity was present was nominally 0.1 seconds which is a factor of 100 greater than the duration of a 1 millisecond pulse. If it is assumed that the I-pulse is a square pulse and that the pen follows an exponential curve when a step voltage is applied, the deflection y of the pen after a time t will be

$$y = y_o \left(1 - e^{-\frac{t}{\tau}}\right)$$

where y_o is the amplitude the pen would attain after a long time and τ is the time constant of the system. The maximum deflection produced by a pulse of duration T would be

$$y = y_o \left(1 - e^{-\frac{T}{\tau}}\right)$$

and if $\tau \gg T$ as is the case here the exponential can be replaced by

$$e^{-\frac{T}{\tau}} = 1 - \frac{T}{\tau}$$

and the deflection is

$$y = y_o \left(1 - 1 + \frac{T}{\tau}\right)$$

$$= y_o \frac{T}{\tau}$$

From this we see that the amplitude of any pulse on the chart is dependent on both the intensity of the I-pulse which determines y_o, and the duration T of the I pulse. It would thus appear that for a pulse duration of 1/100th of the time constant, the amplitude of the pulse recorded on the chart would be a factor of 100 too small. As the millisecond pulses frequently caused deflections greater than that due to intense normal pulses it seems as though the I-pulses must be very intense indeed. This was not the case as the time constant for charging was a factor of 10 less than the nominal time constant. The return to sky noise level was at a rate near that expected from the nominal time constant. This can be clearly seen from fig. 2-8 which is a section near the beginning of the record of the I-pulse storm of 1st January, 1968. The chart speed was 250 mm/min, but the time constants had not been changed to 0.1 seconds on all channels. Thus the time constants for the 16 MHz and the 18 MHz right hand channels were 0.1 seconds while all the other channels had a time constant of 0.5 secs. I-pulses are seen on the 16 MHz total power and the 18 and 22 MHz right hand circular channels. The difference in rise and decay time constants is clearly visible on the 22 MHz record. Typically the decrease in pulse amplitude due to the change in time constant from 0.5 to 0.1 secs. was not greater than a factor of 2.

The characteristics of the I-pulse activity differed considerably from storm to storm and from time

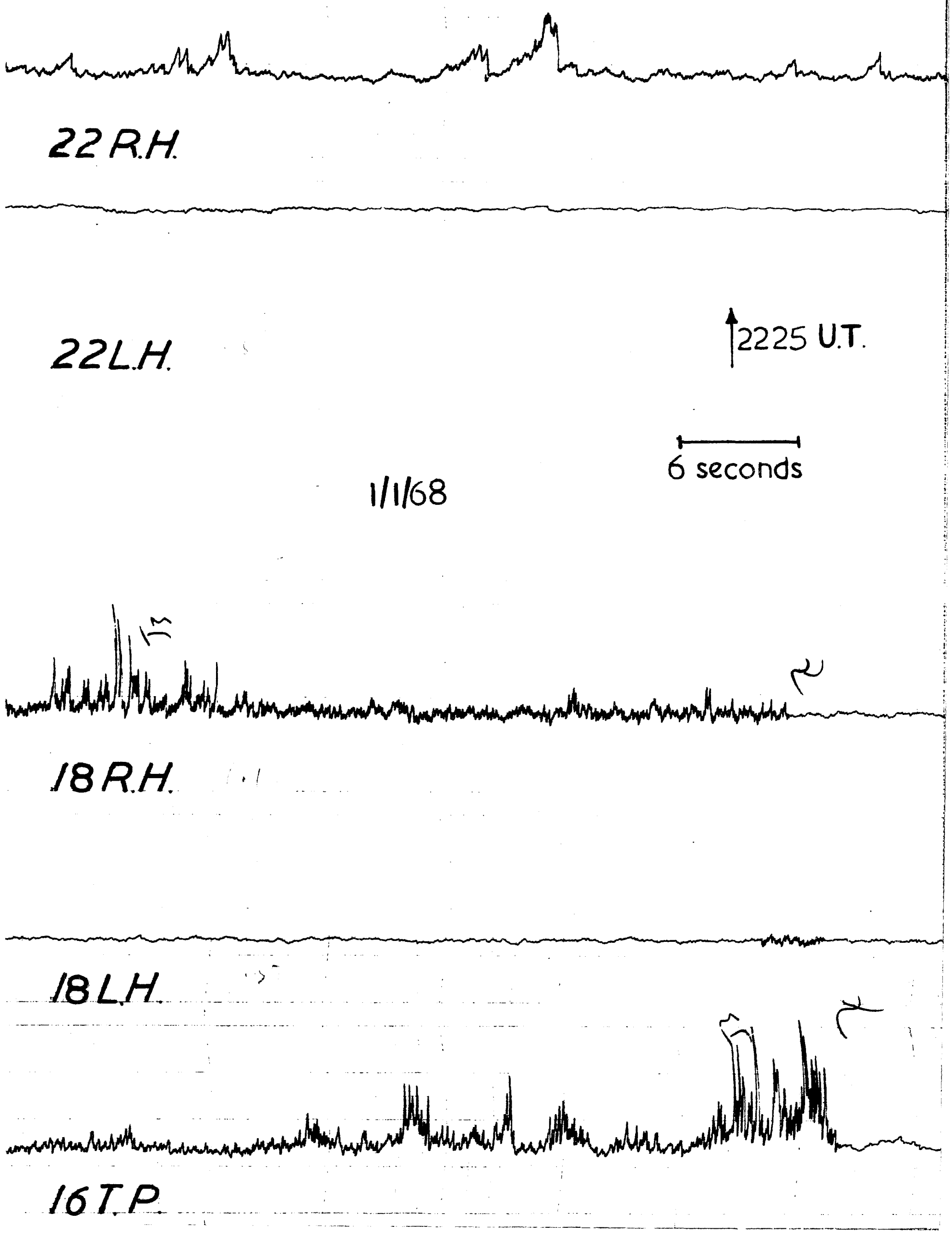


Fig. 2.8. The difference in charge and discharge time constants is clearly shown in this section of pen recorder chart.

to time during a single storm thereby making the concept of a "typical" storm meaningless. A description of the range of characteristics observed is nevertheless in order. I-pulse activity preceded normal pulse activity on several occasions and more rarely I-pulse activity followed a normal pulse event. There were instances where both I-pulses and normal bursts occurred together, either on different frequencies or at alternate times on one frequency. Some storms contained only I-pulse activity with no normal or long bursts although on these occasions there was evidence that some of the pulses were short but not I-pulses. During a period of I-pulse activity the pulses could appear individually at intervals of 10 seconds or more, or at such short intervals that the pen of the recorder could not return to the sky noise level between pulses. During spells of the latter kind of activity the spitting pulses appeared to be superimposed on normal or long pulses. Half an hour of record run with a time constant of 0.01 sec. in the course of the event of 16th March, 1968, showed that I-pulses superimposed on normal pulses were not impossible but that some bursts with this appearance must be due to the effect above.

Over half the I-pulse events observed exhibited a definite time structure of the order of seconds superimposed on the short pulse structure. This gave the storm the appearance of consisting of bursts of noise containing a large number of pulses. At times the amplitude of the pulses dropped to sky level between bursts but at other times pulses with low amplitude joined the bursts. Of the remaining storms another 20% showed a tendency towards grouping but because of the longer intervals between I-pulses the grouping is not obvious. The rest of the storms consisted of isolated pulses with occasional bursts of many pulses.

The characteristics of the pulse structure of a storm often changed during the course of the storm. Storms starting with isolated pulses usually showed a gradual increase in the frequency of I-pulses until burst groups formed. On several occasions the bursts of I-pulse activity changed to normal bursts but only once did the opposite happen. As a storm progressed the I-pulses tended to increase in amplitude. This could be due to either an increase in intensity or an increase in pulse length.

The next 3 figures illustrate the various kinds of I-pulse storms which were observed. In all these figures time runs from right to left along the chart. Isolated I-pulses together with some interference are shown in fig. 2-9 on both 16 MHz channels and the 18 MHz total power channel. The pulses towards the end of the 22 MHz left hand circular trace are probably I-pulses. Fig. 2-10

Fig. 2.9.

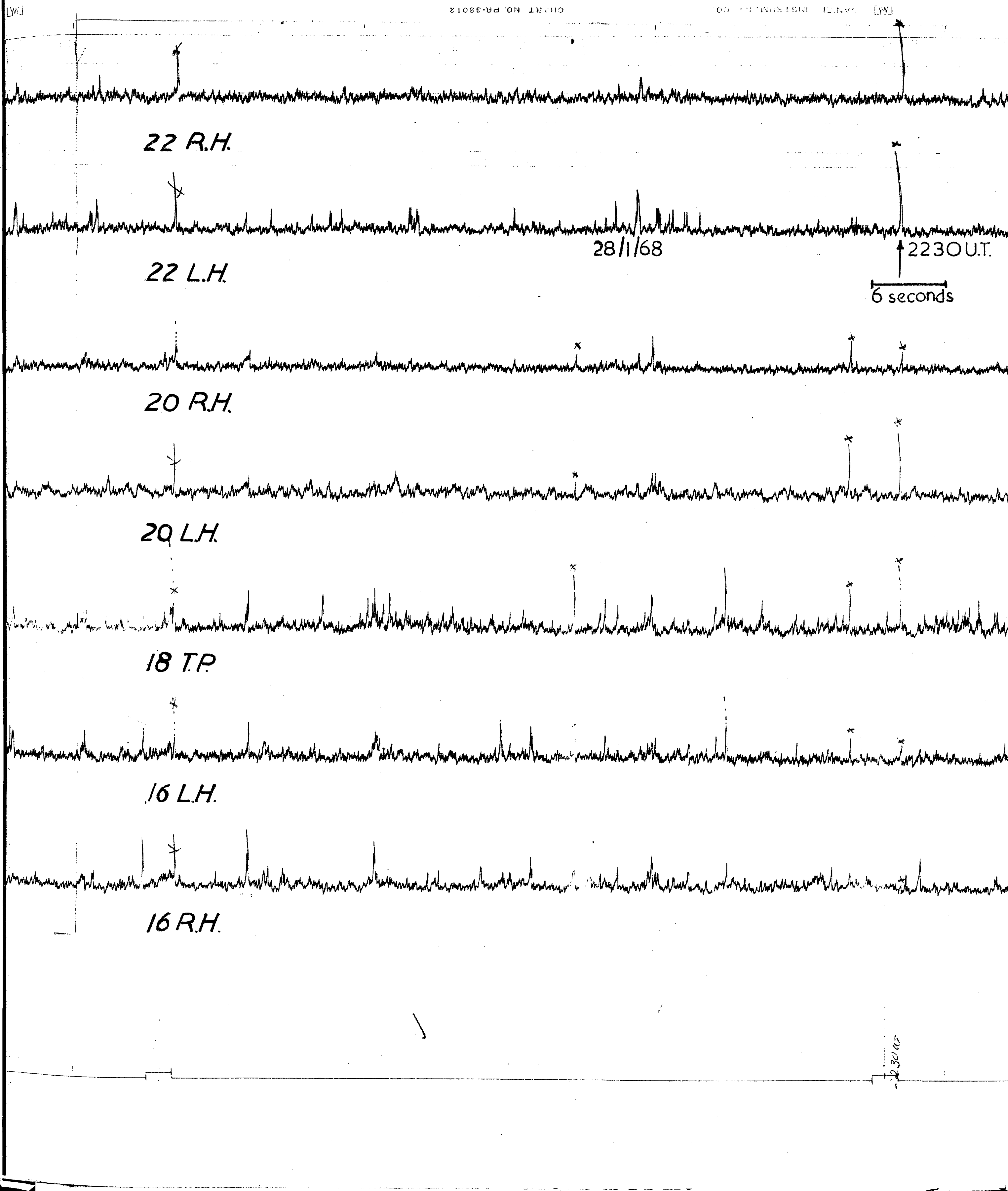
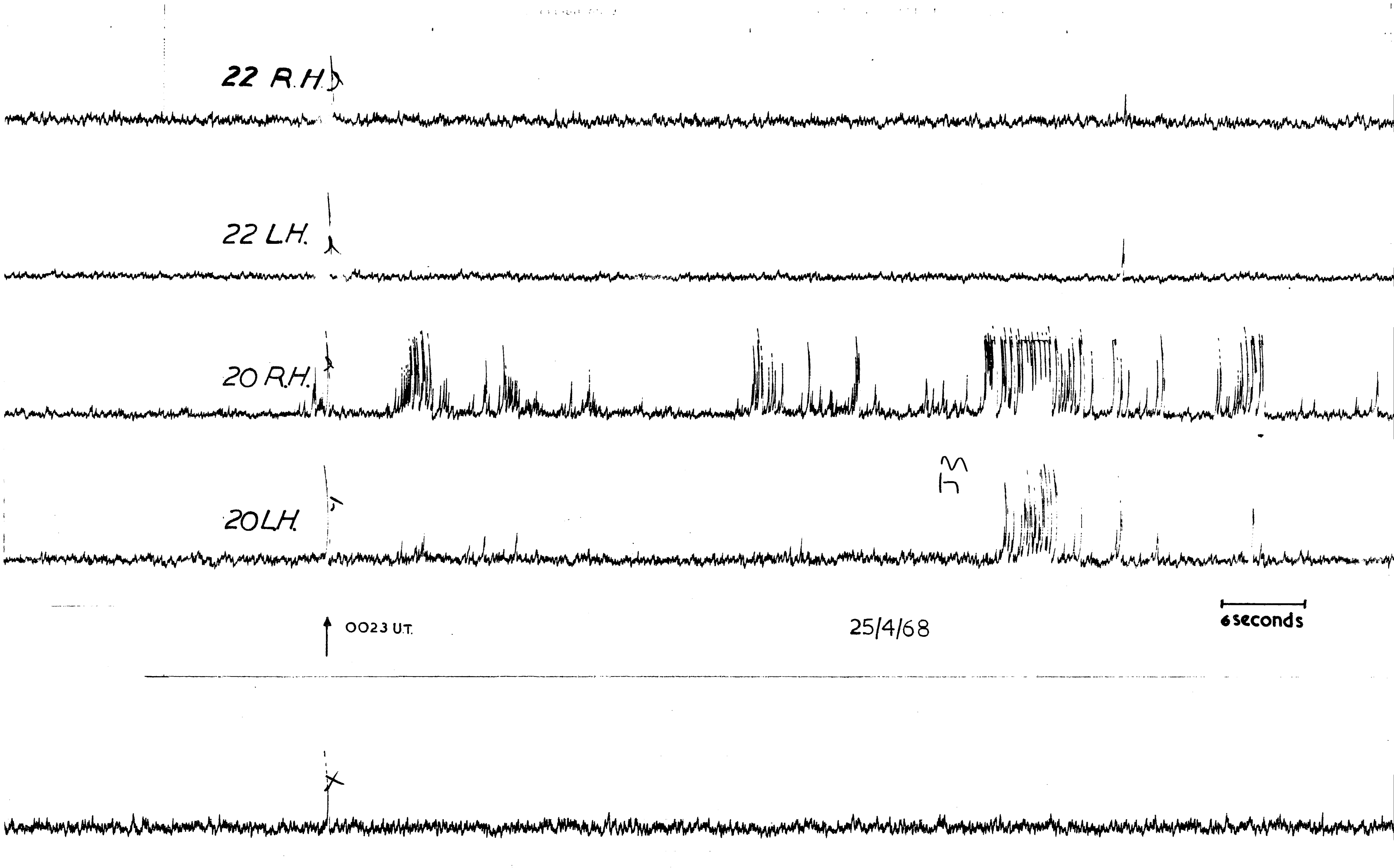


CHART NO. PR-38012
22 R.H.
22 L.H.
28/1/68
2230 U.T.
6 seconds
20 R.H.
20 L.H.
18 T.P.
16 L.H.
16 R.H.

Fig. 2.10.

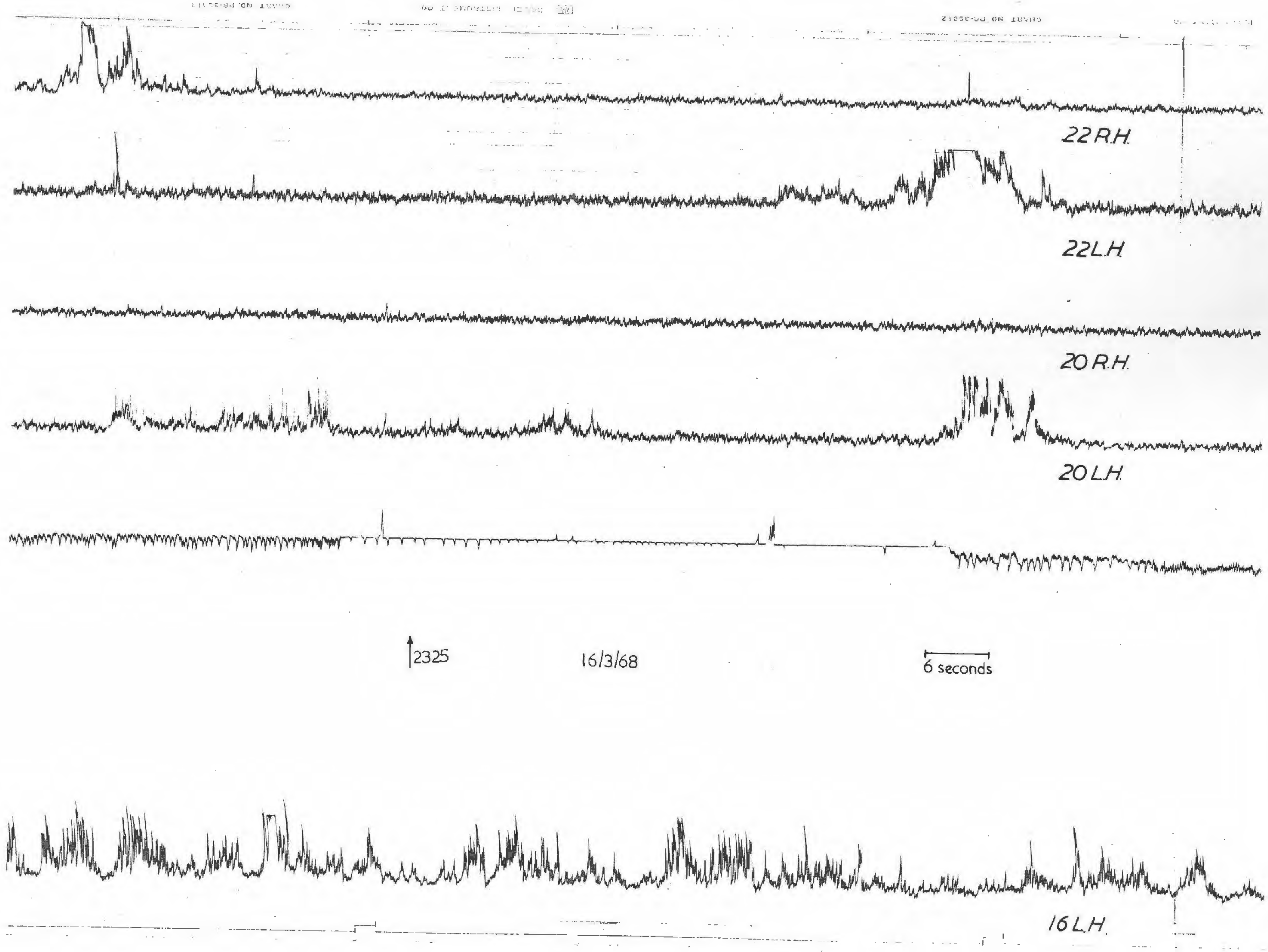

22 R.H.
22 L.H.
20 R.H.
20 L.H.
0023 U.T.
25/4/68
6 seconds

shows I-pulses forming bursts of activity with one burst of exceptionally high intensity where the pen was held at full scale deflection for several seconds. Most of the activity is on the R.H. channel with occasional bursts of activity on the left hand channel. Towards the end of the section shown the timing relays produced a wide band interference pulse on all channels. Wide band pulses such as this are usually obvious at a glance. Finally fig. 2-11 shows normal activity at 22 and 20 MHz while there is I-pulse activity at 16 MHz. The normal burst on the left hand 20 MHz channel was followed a minute later by I-pulse activity. The I-pulse activity on 16 MHz is superimposed on normal bursts, perhaps showing a midway point in the transition from the I-pulse event preceding this section and the normal and short pulse event which followed.

The pen recordings of I-pulses have only been able to provide information about I-pulses collectively and have given no information about individual pulses. Neither their length nor their polarization (as will be seen later) can be determined. The pulse measurement experiment provided some of this information.

The first I-pulse storms observed during the apparition showed that instead of pulses having a minimum

Fig. 2.11.


22 R.H.
22 L.H.
20 R.H.
20 L.H.
2325
16/3/68
6 seconds
16 L.H.

length of the order of 1 millisecond, as expected (Gallet 1961, Kraus 1958, Douglas and Smith 1967, Lee 1966) most pulses had lengths considerable shorter than this. The apparatus was modified to reduce the minimum pulse length measurable as much as possible. The modification did not help much as the bandwidth of the receiver-amplifier system was determined largely by the receiver which had a bandwidth of 5 kHz. The pulses recorded using the data recorder were more severely limited by the 4 kHz bandwidth of the recorder at the tape speed used (7½"/min.).

An I-pulse which appeared on the pen record as a single pulse often consisted of a number of these sub-millisecond pulses over an interval of the order of milliseconds. Other I-pulses consisted of single submillisecond pulses. Both these types of I-pulse are shown in fig. 2-12 which was filmed from a few seconds of the tape recording made during the storm on 25th April. The pulses displayed are the squared I-pulses used for pulse length measurement. The distortion due to the data recorder is clearly visible. The sweeps are separated by at least 50 msecs. and an approximately 1 millisecond scale is shown. Some of the groups of submillisecond pulses shown last for 3 or more milliseconds and these presumably are the I-pulses measured by previous workers.

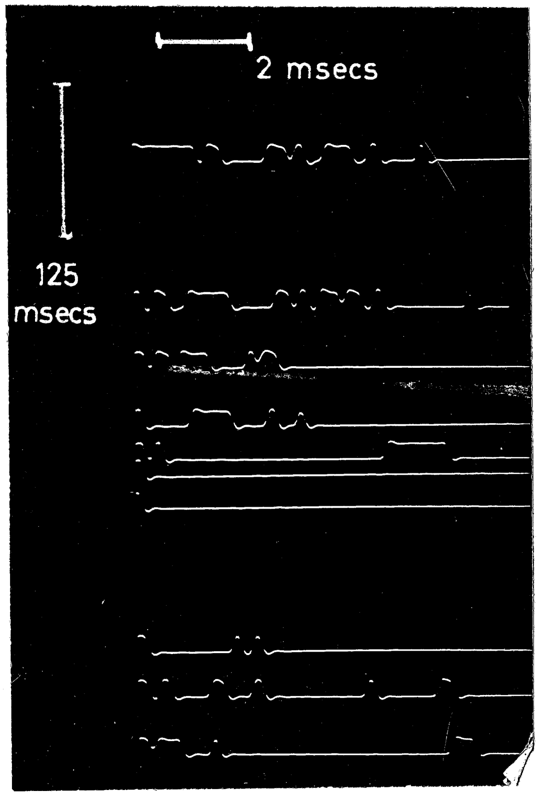


Fig. 2.12. Squared I-pulses photographed from an oscilloscope. Time scales are shown both along and across the film.

It is possible that the submillisecond component reported here is not a real effect but one which arises during the amplification or squaring process. This could be tested by using two receivers tuned to within 50 kHz or less of each other and comparing the squared outputs. A single record with good correlation on a submillisecond scale would be sufficient to exclude the equipment as a possible source of the structure. With this in mind the tapes with squared I-pulses recorded on them were scanned for signs of this correlation. There were no records available where pulses from signals with the same polarization and with frequencies within 50 kHz of each other had been used. There were however records at frequencies which were within the 0.4 MHz of each other and with opposite circular polarizations. Likely sections were photographed using a double beam oscilloscope but no correlation was found which lasted for more than one millisecond or more than one or two successive pulses. These odd correlations could have been static or other interference and cannot be given much value.

Riihimaa (Riihimaa 1968) has pointed out that the I-pulses he observed using his high resolution swept frequency receiver have bandwidths less than 50 kHz at times. The results of Gordon and Warwick (Gordon and Warwick 1967) using a swept frequency polarimeter suggest that signals of opposite circular polarizations are more likely to anticorrelate than correlate. The lack of correlation found between signals which had opposite polarization and were possibly well separated in frequency, can not be conclusive proof either for a Jovian origin or for an instrumental origin.

Factors in favour of a Jovian origin are the recent reports of similar submillisecond structure by Slee and Gent (Slee and Gent 1967) and by Flagg and Carr (Flagg and Carr 1968). The former found a good correlation (0.6 to 0.7) for the submillisecond structure of the Jovian storms observed over baselines of the order of 1 km. Flagg and Carr using a receiver with a 100 kHz bandwidth found closely spaced pulses averaging about 20 μsec in length forming pulses of activity continuing on the order of milliseconds.

Distributions of pulse lengths were prepared from the photographic pulse length records. The films were compared in steps of one minute with the corresponding pen record and only those minutes containing certain I-pulse activity were analysed further. In this way intervals containing a large amount of interference were eliminated. Those minute intervals containing I-pulse activity were enlarged using a microfilm reader and the number of pulses with lengths in each of a series of ranges counted. From these counts the histograms in fig. 2-13 were produced. The total number of pulses included in the 8th April histogram is 312 covering 26 minutes; in the 25th April histogram is 459 pulses covering 27 minutes and in the 26th May histogram is 907 pulses covering 51 minutes. These are the only storms which have been analysed in detail but other storms have been examined and the distribution will not be significantly different from these.

The feature of the histograms which is immediately obvious is that the majority of the pulses are near the minimum resolution of the apparatus. The broken line marked $^2/F_{max}$ represents the shortest pulse which could be measured with accuracy; the frequency F_{max} being the upper cut-off of the receiver amplifier systems. As can be seen, the majority of the pulses were shorter than this limit. The I-pulses have a component with lengths less than 0.5 milliseconds but this experiment does not resolve the minimum pulse length.

Although both circularly polarized components were recorded on the pen recorder chart and the film record of pulse lengths, little can be said about the polarization of individual pulses for a number of reasons. As mentioned earlier the amplitude of pulse shown on the pen record is not necessarily a measure of the intensity

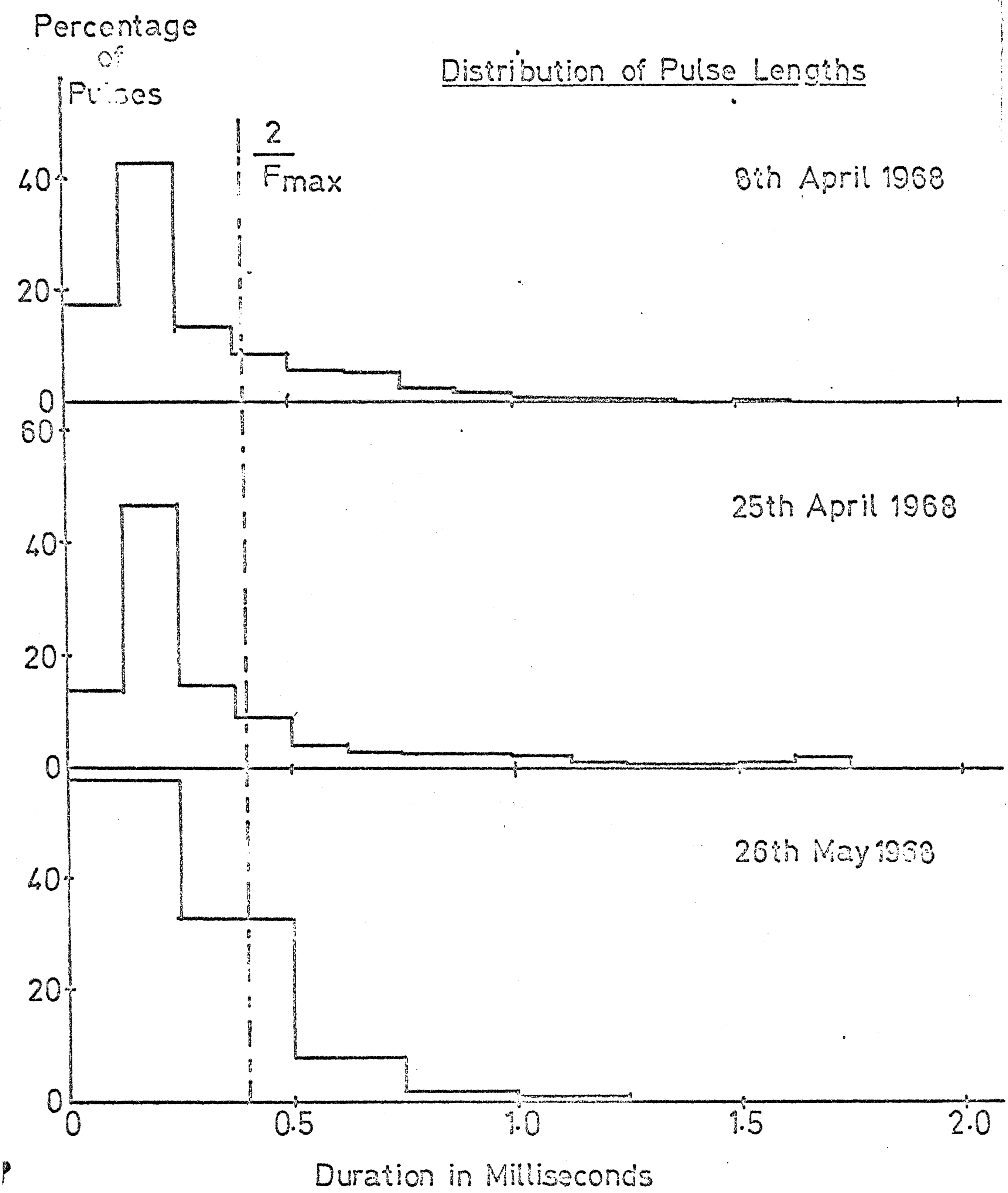


Fig. 2.13 Distribution of Pulse Lengths.

of the pulse. Although the nominal time constants were the same for both polarizations at the same frequency the response to a sharply rising pulse need not be the same. The noise level calibrations give no information on this response. Axial ratios cannot be determined for these reasons.

Another difficulty is identifying individual pulses on both channels. It has been seen that there were no correlations on a submillisecond scale and the recorder did not respond to this structure so polarization and measurements on that scale are impossible. There was however correlation on a millisecond scale but in this case any axial ratio would not represent the polarization ellipse but would be a measure of the average intensity on left and right hand channels.

The hybrid rings used to obtain the two polarization components were found AFTER THE END OF THE OBSERVING SEASON to be inaccurate as a result of the transmission line used not having the specified velocity factor and impedance. The phase difference introduced by each nominally quarter wave length of the line differed form a quarter cycle by about 10% but was the same for each length. Thus the contributions from each set of linear elements of the antenna which are combined at each of the outputs of the ring will not differ in phase by a quarter cycle but will differ by some fraction of a cycle say x. At one terminal the contribution from the horizontal element will be x cycles ahead of the contribution from the vertical element while at the other terminal the vertical element's contribution will lead that from the horizontal element by the same fraction x. It can be seen from this that the components from the hybrid ring will be elliptical with same major and minor axes and the same orientation relative to the elements of the antenna but will be left and right hand elliptical polarizations. Although the components will not readily yield axial ratios it is possible to obtain a qualitative estimate of whether the activity was predominantly right hand or left hand polarized.

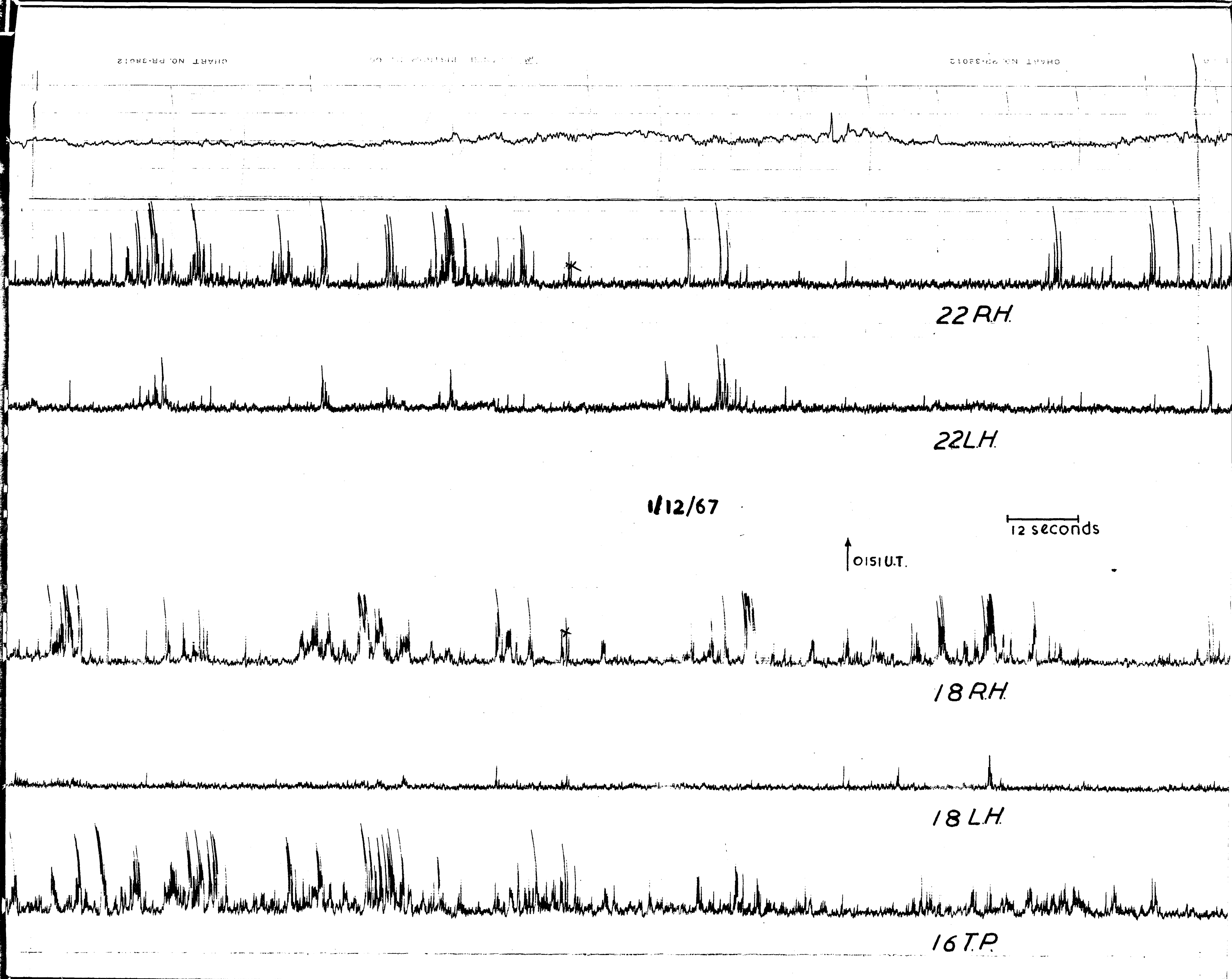
Fig 2-10 shows predominantly right hand I-pulse activity with considerable variations in the left hand component. The left hand elliptical component is always less intense than the right hand component.

Fig. 2-11 shows activity which was largely left hand polarized on 22 and 20 MHz. Unfortunately the 16 MHz right hand channel was not in operation during this storm. At the end of the record an intense right hand burst occurred at 22 MHz indicating a change in polarization sense over the period of about a minute.

Fig. 2-14 shows short bursts of I-pulse activity where occasional left hand bursts appear amongst the dominant right hand bursts.

Changes in the sense of polarization such as shown in the figures mentioned above occurred during several storms. On most occasions one sense of polarization was received throughout the storm with irregular bursts of opposite sense interspersed. There did not appear to be any difference between the pulse lengths observed on opposite polarizations.

Fig. 2.14.


22 R.H.
22 L.H.
1/12/67
12 seconds
0151 U.T.
18 R.H.
18 L.H.
16 T.P.

3. SOURCES OF I-PULSE STRUCTURE IN JOVIAN RADIATION.

In this chapter the possible sources of the I-pulse structure will be discussed. The first section presents a review of the theories suggested by previous workers. These theories are discussed in the second section in the light of the results presented in chapter 2 and in the final section suggestions for future work on I-pulses are made.

3-1. Review of possible origins of I-pulse structure.

Any satisfactory theory for I-pulse radiation must explain the association of I-pulse activity with B and C sources rather than A source and the greater sensitivity of I-pulse activity than normal activity to Io position. (Olsson and Smith 1966; Baart, Barrow & Lee 1966). It must be able to account for pulses with the shortest duration measured. If I-pulses are due to a pattern drifting across the earth, the drift rate required must be greater than 10^4 km/sec. (Slee & Higgins 1965, Slee & Gent 1967). The pulses appear to drift in frequency at above 35 MHz/sec (Riihimaa 1968a, Gordon & Warwick 1967) and are probably not correlated (although possibly anti-correlated) in the two oppositely circularly polarized components at the same frequency (Gordon & Warwick 1967; Barrow 1968). In addition the theory must not require that the sources have any properties which would make emission of normal and long bursts impossible.

Each of the suggested origins of I-pulses will be discussed in turn.

(a) Coherent source region.

It has been suggested that the millisecond structure of the bursts could be due to a coherent source region (Dulk, Rayhrer & Lawrence 1967). Consider a source region which can be divided into a number of elementary sources radiating continuously. At some instant of time there will be a definite set of phase relations between these sources which will define, for this instant, a beam pattern for the source consisting of a number of narrow lobes. The narrowest lobe will have an angular width

$$\theta = \frac{1}{D} \qquad 3.1$$

where D is the diameter of the source region in wavelengths (Gordon & Warwick 1967). The time taken for the rotation of Jupiter to sweep this lobe across earth is

$$t' = \theta/\rho \qquad 3.2$$

where ρ is the rotation rate of Jupiter. Substituting from equation 3.1 into 3.2 this time becomes

$$t' = \frac{1}{\rho D} \qquad 3.3$$

This beam pattern will apply for any source at a single instant of time.

At a later time the phase relation between the elementary sources will have changed and the beams will be directed in different directions in space. Apart from this Jupiter will have rotated and the beams will have been swept over the Earth. There are thus two variations with time taking place, either of which could cause the I-pulse structure. The signal received on Earth will depend on a coherence of the signal and the size of the source region.

The coherence of the source depends on the averaging time of the receiver which is effectively the time constant T of the receiver, and the "coherence time" of the source. The coherence time will be taken as some measure of the average time which the phase relation between the elementary emitters stays constant and will be represented by τ. The source itself can radiate continuously for a period of minutes or hours or could be sporadic. Intermittent radiation with a time scale of the order of milliseconds or less could account for the I-pulse structure irrespective of the coherence of the source. If the source is continuous millisecond pulses could only be present when the source is coherent or partially coherent.

If the averaging time T is very much greater than the coherence time τ, the beam pattern will change many times during a single unit of averaging time and the resulting beam pattern will be the average over all these patterns which will be the pattern of each of the elementary sources. This is the incoherent radiation case. As τ increases relative to T the coherence will increase and fine structure will become apparent. For $\tau \gg T$ the beam pattern will persist for very much longer than one unit of averaging time and the radiation will be coherent. The pulse lengths observed will depend on the relative magnitudes of τ and t, lobe transit time at Earth. If $\tau \gg t$ several lobes of the pattern will be able to sweep past the observer before the phase relation, and hence the pattern changes. The shortest pulses observed will be determined by t , and so by D, the source width. On the other hand if $t \gg \tau$ the pattern will change before a single lobe sweeps past the observer and the shortest pulses will be determined by the value of τ.

The cases discussed above are the limiting cases but there is no reason for excluding intermediate cases. As Dulk, Rayhrer and Lawrence suggest, it would be necessary to measure the correlation between signals received over a baseline of 300 km or larger in order to distinguish between different possibilities.

(b) Another suggested source for the I-pulses is scintillations in interplanetary space (Lee 1966). It has already been shown that the N pulses originate in the interplanetary plasma (Douglas and Smith 1967) and are modulated by ionospheric scintillations (Smith et al 1960). Possibly continuous radiation from the Jovian source is diffracted first by irregularities in interplanetary space giving it a bursty character and then suffers a second diffraction in the ionosphere gaining the well-known groups of bursts.

The scintillations observed on earth are due to the diffraction pattern produced by the phase changing irregularities in interplanetary space drifting past the observer. This drift is due to motion of the irregularities perpendicular to the Earth-Jupiter line. Space probes to Venus have shown that the radial speed of the solar wind between Earth and Venus is 400-700 km/sec and there is no reason to suppose that this speed will change significantly beyond Earth. (Neugebauer & Snyder 1962). In any event it is extremely unlikely to increase beyond Earth. One of the most convincing arguments in favour of an interplanetary origin from N pulses was the reversal in direction of this drift across earth at Jupiter's opposition as would be expected from the change in direction at opposition of the component of the solar wind at right angles to the Jupiter-Earth line. The derived drift rates for N pulses agree well with the measured solar wind speed. (Douglas & Smith, 1967).

If the I-pulse structure is to be explained in terms of scintillations in interplanetary space the drift rate of the pattern across Earth should show similar behaviour The structure on a millisecond scale has been found to be simultaneous over long baselines and the minimum rate of drift determined from this is of the order of 10^4 km/sec (Slee & Higgins 1965, Slee & Gent 1967, Douglas & Smith 1967). This is very much greater than the solar wind speed.

From fig. 3-1 it can be seen that the drift speed V of the pattern in the plane containing the observer will be

$$V = v \frac{D_1 + D_2}{D_1} \qquad 3.4$$

where v is the component of the solar wind perpendicular to the Earth-Jupiter line; $D_1 + D_2$ is the Earth-Jupiter distance and D_1 is the distance from the diffracting screen to Jupiter. Using a value of 500 km/sec for the solar wind component v (which is rather larger than would be expected) and substituting for V and D_1+D_2 the above equation gives

$$D_1 = 3.5 \times 10^7 \text{ km.}$$

and the diffracting screen would thus be near Jupiter. This value of D_1 van be regarded as a maximum. This is about 400 Jupiter radii from the planet; Earth's magnetosphere extends to less than 20 Earth radii on

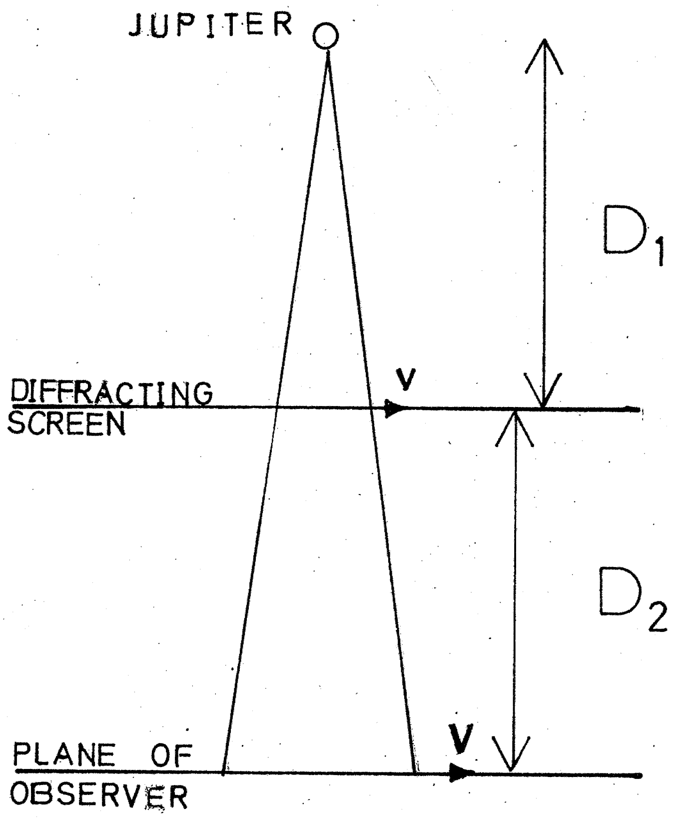


Fig 3.1 Diffraction Geometry for Stationary Source

the daytime side of the planet and it is thus unlikely that Jupiter's magnetosphere could extend this far.

A detailed treatment of the diffraction theory for propagation of radio waves through a medium containing phase changing irregularities would be out of place here. Reviews on this topic such as Ratcliffe (1956) provide most of the necessary information.

Most treatments are for the case of an infinitely distant source and an observer at a variable distance from the screen which does not apply here where the screen is closer to the source than the observer. The treatment by Pisareva (Pisareva 1957) deals with a spherical wave incident on a plane diffracting screen.

The nature of the diffraction pattern produced by a phase changing screen depends on three parameters. (Cohen, Gundermann, Hardebeck, Sharp 1967). These are the root square phase deviation introduced by the screen, the dimensions of the source and the ratio $\bar{D}/\bar{D}_o$ where

$$\bar{D} = \frac{D_1 D_2}{D_1 + D_2}$$

and $\bar{D}_o$ is the value of $\bar{D}$ for which the mean irregularity size covers a single Fresnel zone as seen from either the source or the observer. The I-pulses have intensity variations greater than the average intensity. In general the intensity scintillations increase with distance from the screen in the Fresnel region ($\overline{D}_o > \overline{D}$) and then change little in the Fraunhofer region ($\overline{D} > \overline{D}_o$).

Hewish, Dennison and Pilkington (Hewish et al 1966) have shown that, for 3.7 meter waves, at a distance of 0.5 A.U from the sun the scale of the irregularities, ℓ, is about 100 kms in contrast to an earlier estimate of rather less than 5000km (Hewish, Scott, Wills 1964). This estimate has been confirmed by Cohen et al (1967) at about 0.75 meters. The scale of the irregularities at Jupiter will be taken as having a minimum value of 100 kms. The previous workers have shown that beyond 0.5 AU from the sun the phase deviations are much less than one radian i.e.

$$\phi_0 << 1$$

(see also Little & Hewish 1966). This is commonly called the weak scattering case.

For the case of weak scattering Pisareva has shown that the mean square intensity variation is given by

$$F = 2\phi_0^2 \left\{ 1 - \frac{1}{1 + (2D/\pi D_o)^2} \right\} \qquad 3.5$$

and the scale of the diffraction pattern in the plane containing the observer is

$$\xi = \ell \, {}^{D_2}/_{D} \qquad 3.6$$

From 3.5 it can be seen that the intensity variation is a maximum when

$$\bar{D} \gg \bar{D}_0$$

that is when both source and observer are well into the Fraunhofer region. For a 100 km irregularity scale at 10 meters wavelength the limit of the Fresnal region is

$$\bar{D}_0 \simeq \ell^2/\lambda \qquad = 10^6 \text{km.}$$

Both source and observer are thus well into the Fraunhofer zone and large intensity variations are possible.

Substituting for $\bar{D}$ in 3.6 gives

$$\xi = \ell \frac{D_1 + D_2}{D_2} \qquad 3.7$$

Comparison of 3.7 and 3.3 shows that both the velocity and scale of the diffracting screen are scaled up by the same factor to obtain the velocity and scale of the diffraction pattern in the plane containing the observer. This implies that in order to obtain a pulse of millisecond duration at Earth it is necessary that the irregularities in the diffracting screen move with such a speed that a distance ℓ passes a point in a millisecond. With a solar wind velocity of 500 km/sec this would require an irregularity scale of 500 meters. This is far smaller than previous estimates making interplanetary scintillations an unlikely source of I-pulses.

Till now it has been tacitly assumed that the source was stationary. Riihimaa (Riihimaa 1968b) points out that this need not necessarily be the case. Figure 3-2 shows that for a source moving with a speed, u, at right angles to the Earth-Jupiter line and a stationary diffracting screen, the speed of the pattern in the plane containing the observer is

$$V = - u\frac{D_2}{D_1} \qquad 3.8$$

which when combined with the fixed source, drifting screen case gives

$$V = \frac{D_1 + D_2}{D_1}v - u\frac{D_2}{D_1} \qquad 3.9$$

A velocity component of 10^4 km/sec perpendicular to the Earth-Jupiter line would be necessary for the source to produce a pattern drifting over the Earth at this speed if the diffracting screen is not near Jupiter. Riihimaa shows that a group of electrons travelling along a field line in the magnetosphere, as required by the Ellis and McCulloch model of decametric emission, could easily have a velocity component of this magnitude.

The scale of the pattern presents no difficulties in this case. The drift rate of the pattern in the plane of the observer will be determined largely by the value of u since $u \gg v$ and so will be given by the equation 3.8. The scale of pattern in the plane of the observer will

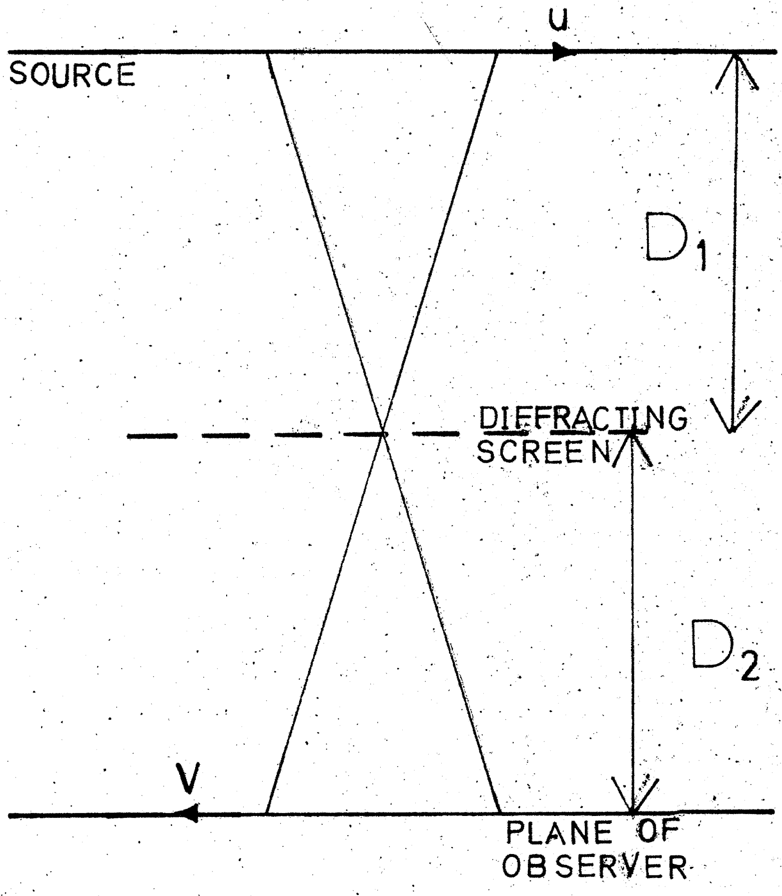


Fig 3.2 Diffraction Geometry for Stationary Screen

still be given by equation 3.6.

$$\xi = \ell \frac{D_1 + D_2}{D_1}$$

Taking a value of 500 km for the scale of the pattern at earth a millisecond pulse would require a drift rate for the pattern of 5 x 10^5 km/sec. This requires the diffracting screen be nearer Jupiter than Earth by a factor of 10.

(c) Only two swept frequency receivers have been operated with a sweep repitition rate sufficient to observe millisecond time structure. Both show pulses drifting negatively in frequency at rates of above 35 MHz/sec (Riihimaa 1968a, Gordon & Warwick 1967). The I-pulses could be the effect of observing continuous narrowbanded radiation which drifted through a fixed receiver bandwidth.

At a fixed frequency the duration, t, of the pulse drifting at a rate, D, would be given by

$$t = \frac{1}{D} \quad (B_R + B_I) \qquad 3.10$$

where B_R is the receiver bandwidth and B_I is the I-pulse bandwidth. The pulse length measured at a fixed frequency would then vary with the bandwidth of the receiver provided that the pulse was not limited by bandwidth considerations.

(d) Warwick and Gordon (1967) report that storms which contained structure in time on a scale of 20 milliseconds or less also showed fine structure in frequency and polarization. Using a swept frequency polarimeter with a sweep repetition rate of 25/sec. they found that activity on left and right hand circularly polarized channels tended to show distinct lanes of about 1 MHz width with no noise. In addition it was seen that activity on the left hand channel tended to anti-correlate with right hand activity. Figure 3.3 is an illustration from Gordon's thesis (Gordon 1966) showing the lanes in both circular components and the anti-correlation between polarizations. Riihimaa (1968a) reports similar lanes of low noise with frequency which he attributes to scintillation effects in interplanetary space of the type discussed in section (b) above.

They explain these effects as a Faraday rotation phenomenom at Jupiter. It is assumed that under certain circumstances two modes generated at the source can escape and that these modes propagate through a nearly uniform magneto-ionic medium as two elliptically polarized waves with mutually perpendicular major axes. The refractive indices for these two modes will differ, so that the modes will emerge from the medium having undergone different phase shifts. The resultant of the two modes will be an elliptically polarized wave where the major and minor axes and the orientation of the polarization ellipse will be determined by the shift in phase between the

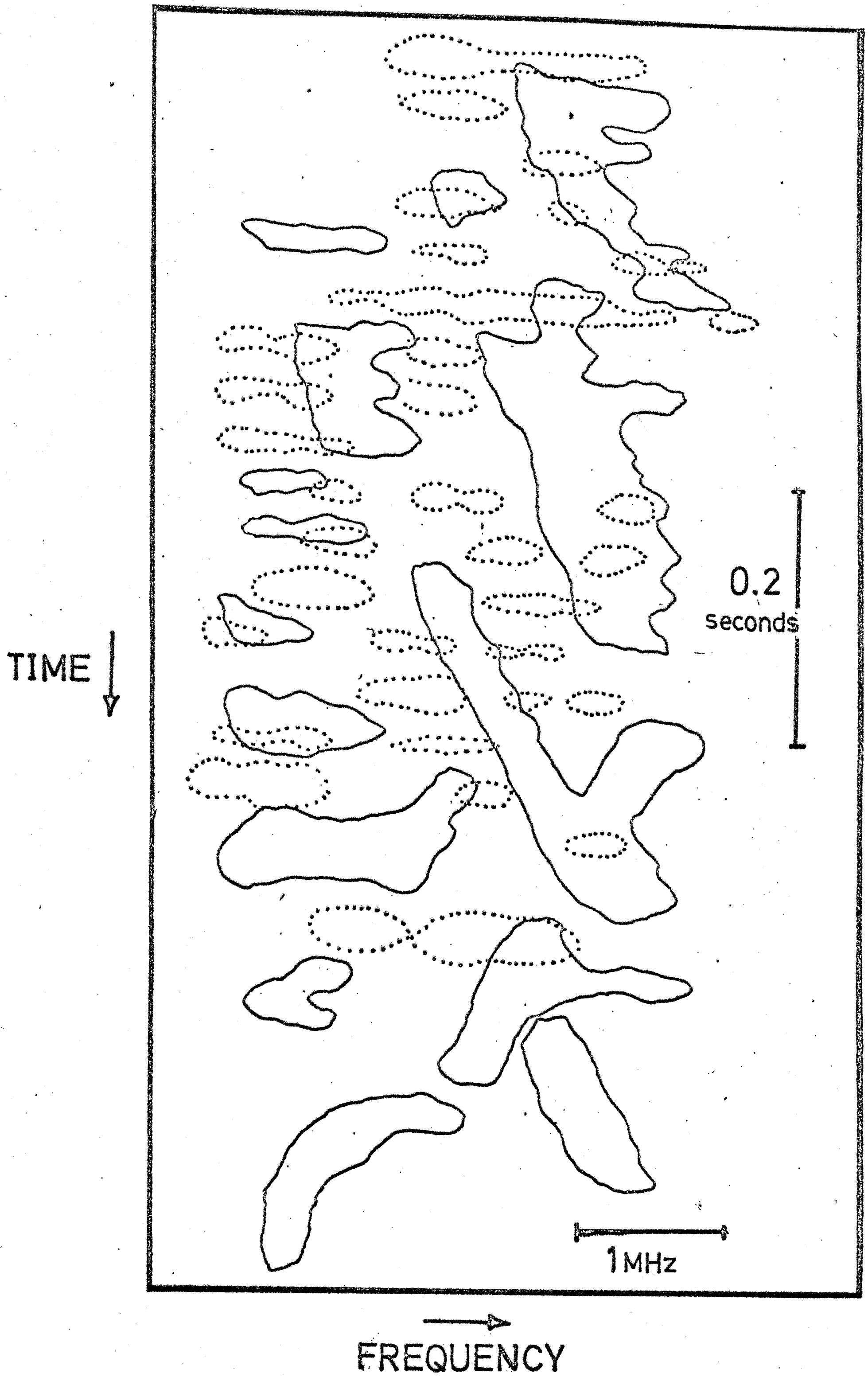


Fig. 3.3 The right-circularly polarized component (lines) superimposed upon the left-circular component (dots).

two modes. This phase shift will be dependent on the frequency of the radiation.

The characteristic modes for propagation through the ionosphere are nearly circularly polarized with the result that even though the two components might suffer different phase shifts, no terrestrial Faraday effect will be observed on the circularly polarized channels. Any one circular component received at the antenna, say for example the right hand circular component, will be the vector sum of the right hand circularly polarized components of each of the elliptical modes. Depending on the phase difference between the elliptical modes these components would be in phase or in antiphase with a corresponding maximum or minimum intensity. The dependence of phase difference on frequency would cause the observed lanes in the spectrograms. The assumption that the elliptical modes are mutually perpendicular ensures that the left and right hand intensity maxima anti-correlate.

Warwick and Gordon suggest that the fine structure in time originates from beaming by a coherent source of large dimensions as discussed under (a) above. The simultaneous appearance of this fine structure in both frequency and time they attribute to a uniform structure of the magneto-ionic medium, in their case Jupiter's ionosphere, over the whole source area. The phase path through the ionosphere is assumed to differ by less than 1% over the whole source area thus preserving the spatial coherence over the source and so making narrow beaming possible and also ensuring that the phase difference between the two elliptical modes is constant over the source thereby making the Jupiter Faraday effect possible. For a 1 msec pulse the source size would be 5 x 10^4 km which represents a large area over which the ionosphere must be uniform.

This origin for the Jovian I-pulses rests on the source being large and spatially coherent. If the source were however small the properties of the magneto-ionic medium required to make the Faraday effect possible would be more easily satisfied. It is possible that the Faraday effect itself is the origin of the I-pulses. If the phase difference between the elliptical modes changed on a millisecond time scale, the radiation received at Earth would alternate rapidly between left and right hand polarized. A linear antenna would give a peak in intensity when the major axis of the polarization ellipse lay along its length.

In this case the source could be small and in fact would have to be small enough to enable the phase path length for the two elliptical modes to change over the area of the source on a scale of milliseconds or less without differences of more than 1% arising over the source area. This rapid change in phase difference could be due to a change in the density of the magneto-ionic medium, a change in the ray path through the medium, or a change in the thickness of the medium. A source consisting of a shock front or a bunch of charged particles moving through the medium could possibly cause the thickness of medium through which the rays pass to change in the desired fashion.

The short record shown in fig. 3.3 has changes in polarization at a fixed frequency at intervals of the order of hundreds of milliseconds. Figures 2.11 and 2.14 show changes in polarization on a scale of minutes. Either of these could be the changes in polarization sense at a fixed frequency due to the Jupiter Faraday effect. Changes of polarization sense on a millisecond or submillisecond scale as suggested above have been reported. Dowden (Dowden 1963) and Barrow and Morrow (Barrow & Morrow 1968) suggest that events where bursts have a low axial ratio could be due to the simultaneous observations of pulses with opposite circular polarizations. Neither of these polarization studies could resolve activity on a millisecond scale. However Torgerson (Torgerson 1967) have used a polarimeter with a resolution of 0.2 msecs. and has found that some pulses are made up of independent left and right hand circularly polarized pulses in succession.

3-2. Discussion.

The most important of the results obtained in Chapter 2 is the existence of a submillisecond component. This component places restrictions on the possible origins of I-pulse activity in Jovian radiation which have been discussed in the previous section.

(a) Coherent source region.

If the submillisecond structure is due to the beam pattern of a large coherent source being swept across the Earth by the rotation of Jupiter then equation 3.3 can be used to determine the source size. From 2-12 it can be seen that the separation of pulses was at times of the same order of magnitude as the pulse lengths and thus minimum pulse separations of 0.5 msecs. would be a reasonable assumption. If this value is substituted into 3.3 along with the rotation rate of Jupiter ($0{\cdot}01^{\circ}$/sec), the source diameter for 10 m waves is found to be approximately 10^5 km which is larger than Jupiter's radius of 7×10^4 km. Warwick's theory requires that the decametric radiation be generated in the ionosphere of the planet. Thus an I-pulse origin due to the beam pattern of a large coherent source is impossible. McCulloch and Ellis' theory suggests a source area very much smaller than the area of the planetary disc. If Io's shock wave in the magnetosphere is responsible for the decametric radiation as suggested by Gledhill, the source size would probably not be more than a factor of ten greater than Io's diameter which again is less than 10^5 km.

From the above it seems unlikely that the source could be large enough to produce lobes which would sweep across the earth in less than a millisecond.

This does not rule out a source which has a coherence time of the order of fractions of milliseconds or a source which is stimulated on this time scale. These two cases can not be distinguished by pulse length measurements or by long baseline correlation methods. In the latter case the maximum source size for 0.5 millisecond pulses would be

$$c \times 0.5 \times 10^{-3}$$

$$= 150 \text{ km},$$

and in a dense magneto-ionic medium this estimate could be considerably too large. This is considerably smaller than Io's diameter thereby eliminating this method of production of I-pulses if the generation mechanism requires a source spread over Io's shock front as it passes through the magnetosphere.

(b) Measurements of pulse lengths provide no additional information in the case of I-pulses being due to interplanetary scintillations. As shown in the previous section it is necessary to assume that the source is moving with a velocity of 10^4 km/sec at right angles to the Earth-Jupiter line and that the diffracting screen is nearer Jupiter than Earth. A spaced site experiment capable of resolving velocities of greater than 10^5 km/sec would be necessary in order to check whether the I-pulses were a scintillation effect.

(c) It was found that the apparatus used could not resolve the shortest pulse lengths. If it is assumed that the pulses were due to frequency drifting radiation passing through the receiver pass band with a drift rate of 36 MHz/sec as suggested by Riihimaa (1968a) and Gordon and Warwick (1967), then the maximum bandwidth for the radiation which could produce a 0.5 msec pulse can be determined from 3.10. For a 5 kHz pass band the maximum bandwidth is 13 kHz. This is in agreement with Riihimaa (1966) who measured pulse lengths down to the limit of resolution of his instrument which was 50 kHz. Thus on the results of this experiment it is possible that the I-pulses could be due to frequency drifting radiation.

The pulse lengths measured with a narrow bandwidth receiver will have a minimum value determined by this bandwidth. As the bandwidth is increased this minimum value will decrease until at some point the time taken for the pulse to drift through the pass band of the receiver is of the same order of magnitude as this minimum pulse length. As the bandwidth is increased beyond this value the pulse lengths measured will start to increase and the minimum length will be determined by the bandwidth of the pulse and not that of the receiver.

Pulses which were found to have lengths greater than the limit of resolution of the apparatus thus would have had bandwidths greater than 13 kHz or would have had a drift rate less than 36 MHz/sec. If the results of Flagg and Carr (1968) who report measuring pulse lengths down to 0.02 msecs. with a receiver having a bandwidth of 100 kHz are correct, then the radiation must have bandwidths down to 600 Hz. In this case I-pulses must have bandwidths from 600 Hz to 50 kHz.

(d) If the Faraday effect at Jupiter is responsible for the I-pulses, rapid changes in polarization sense on a sub-millisecond scale should be observable. For the reasons given in the last part of chapter 2, the data obtained during the course of this experiment are not suitable for determining whether such changes occur. The minimum pulse length of 0.5 msecs obtained requires that the phase difference between the two characteristic modes change by 360° in less than one millisecond. It is difficult to imagine how such changes would be possible with the medium remaining uniform to within 1%, as required for the Faraday rotation to be observable, unless the source region is moving rapidly through the medium which is uniform. The source would have to be moving towards Earth to ensure uniformity.

3-3. Suggestions for future work.

This study has shown that I-pulses cannot be due to the lobes of the beam pattern of a large coherent source being swept across Earth or to scintillation effects unless the source region moves with a high component of velocity at right angles to the Earth-Jupiter line. Frequency drifting radiation has been seen to be unlikely unless the generation mechanism is capable of producing radiation with a wide range of bandwidths down to 600 Hz. The possible origins have been discussed separately but there is no reason for excluding combinations of the mechanisms. Riihimaa (1968b) suggests frequency drifting radiation with scintillation effects superimposed as a possible origin.

Among the possibilities not excluded are stimulation of the source on a millisecond scale either in the form of intensity modulation at the source or as the result of a coherence time of this order. In both these cases the circularly polarized components at a given frequency would always correlate in time although the intensity would not necessarily be the same. Activity at frequencies separated by more than 50 kHz would show no correlation. Frequency drifting radiation would again show a high correlation between both circular polarization at a single frequency but here there would be some correlation at separated frequencies with a delay between the same pulse at each frequency. The drift rate could be determined from this delay. If the I-pulses are due to a Faraday effect at Jupiter then left and right hand circularly polarized activity at a given frequency would tend to anticorrelate while there would be some relation between activity at closely spaced frequencies.

With these distinctions between different origins for the I-pulses in mind it is suggested that the following would provide a suitable test of the theories. Observations must be made simultaneously over a range of frequencies covering about 100 kHz in order to ensure that the same pulse is not observed over the whole frequency range. Either a swept frequency receiver or a number of receivers spaced in frequency by 10 to 20 kHz could be used. In order to resolve pulses with a duration of 0.2 milliseconds the sweep repitition rate for a swept frequency type receiver would have to be greater than 10^4/sec and even in this case there would be some doubt about the exact nature of what was recorded. For this reason a multichannel spectograph would be better. Both circular components must be recorded at least at one frequency in the range and preferably at all. Using the distinctions listed above, this should provide some information on the nature of the I-pulses. A simple form of this experiment has been run on several occasions during the early part of the 1968-69 apparition. Both circular components were observed at frequencies separated by 100 kHz and the outputs recorded on tape. No spitting storms were however recorded.

Other work worth doing would be observations with wide band receivers (100 kHz or more) in order to decrease the minimum measurable pulse length. Spaced site observations capable of resolving velocities greater than 10^5km/sec would provide useful information should the pulses be due to scintillation effects.

4. VARIATIONS IN PROBABILITY OF OCCURRENCE OF DECAMETRIC STORMS.

In this chapter the results of calculations performed on the longer term variations in the probability of Jovian decametric activity will be presented. The first section deals with variations over a period of several years while the second section discusses the variation of probability during a single apparition. It is found that the occurrence probability changes smoothly from year to year. In 1958-1959 it was a minimum while in 1964 it reached a maximum which suggests a cyclic variation with a period of about 11 or 12 years and it has been suggested that the solar activity cycle or the rotation of Jupiter round the sun could be the cause of this variation. This is the first effect which will be discussed. The second is the observed decrease in probability after opposition. This could be due to the influence of the maximum usable frequency of the Earth's ionosphere on Jupiter reception or to radiation from Jupiter's magnetospheric tail, if it has one, being obscured after opposition.

The data obtained by the Rhodes University observatory would be unsuitable for the types of analyses reported here owing to its discontinuous nature. To be able to compare probabilities for different years it is necessary that the equipment used be essentially unchanged as changes in sensitivity could have a marked effect on probability of occurrence. Observations of Jupiter have been in progress here since 1962 but during this period the site of the observatory has twice been changed and different receivers have been used. The most suitable data for this sort of analysis is that of the High Altitude Observatory in Colorado. The spectographic records obtained there have been analysed and the resulting data published. (Warwick & Kriess 1964, Warwick & Dulk 1965, 1966). The published data for each date includes the following:

(a) the period during which Jupiter was observed,

(b) the period during which Jupiter was active,

(c) the intensity of the storm on a scale of one to three,

(d) the burstiness on a scale of one to three,

(e) the maximum and minimum frequencies at which activity was observed,

(f) the system III longitude range for activity periods.

In addition to the published data Rhodes University required microfilm records of the spectograms for the central part of each apparition and these are currently being analysed in greater detail than the published data.

4-1. The effect of changes in the declination of earth with respect to Jupiter.

The change in probability of occurrence on a scale of years has been associated with the sunspot cycle by many observers (see for example Carr et al 1961). In 1966 however Gulkis and Carr (1966) showed that the variation of the declination of earth as seen from Jupiter offered a better correlation with the observed probability variation. The minimum probability coincided well with the time when earth was at its furthest south relative to Jupiter's equatorial plane. They suggested that the radiation was confined to a beam or sheet fixed relative to Jupiter. The probability of occurrence in this case represents that fraction of time in which Earth was within this beam. Using this model they could explain the observed changes in source width in terms of the amount of time Earth spent within the beam and the apparent change in rotation rate could be interpreted as a cyclic motion of the sources relative to a system of longitude defined as having a period of 9 hrs. 55 min. 29.67 seconds and coinciding with System III (1957.0) at 0000 hrs. on 1st January, 1965. This longitude system they called System III (1965.0). To test the model they used the fixed frequency observation data of the University of Florida. This section is an attempt to extend their analysis to a wider frequency range.

Both Warwick's and Ellis's theories of the origin of decametric bursts predict that the radiation will be beamed along the field line direction at the source. Although subsequent refraction and reflection of the radiation in the magnetosphere and the ionosphere will alter the direction of beaming, the direction in which the beam emerges from the magnetosphere will be determined, at least in part, by the direction of the field lines at the source. In addition both theories require that the radiation be generated near the gyrofrequency at the source. Higher frequencies will thus be generated closer to the planet and will thus be beamed along a different direction. The beam or sheet of radiation at a particular frequency will be fixed relative to the magnetic dipole axis. Whether Earth is in one of the beams will thus be determined by the position of Earth relative to magnetic field. This is conveniently expressed in terms of the magnetic declination of Earth which is defined as the angle between the Jupiter - Earth line and the magnetic equatorial plane of Jupiter, with positive angles measured northwards.

If the magnetic dipole axis is assumed to be inclined at 10° to the rotational axis as suggested by decimetric observations (Morris & Berge 1962) then the magnetic declination changes by 20° for each rotation of Jupiter. For any particular frequency radiation will be received when the beaming direction coincides with the magnetic declination of Earth. This implies as Gulkis and Carr point out, that the longitude at which radiation at a particular frequency is received will change as the range of magnetic declination swept out is moved by the change in ordinary declination of Earth. To a magnetic dipole axis lying in the plane containing the 200° system III meridian this will mean that radiation is received for that central meridian longitude λ for which

$$\lambda = 200 + \arccos \left(\frac{\phi_o - D_E}{10} \right) \tag{4.1}$$

where D_E is the declination of Earth and ϕ_o is the magnetic latitude of the beam. One consequence of this is that the central meridian longitude for the centre of each source will change with frequency and with the declination of Earth.

It is more difficult to make predictions based on the Gledhill model of the magnetosphere as it is assumed that beaming is due to refraction effects in the disc. It is suggested that the radiation could be confined to cones above and below the disc. This suggests that reception of radiation will be related to the declination of Earth relative to the plane of maximum plasma density in the disc. For a disc tilted at 7° to the rotational equator the central meridian longitude of the sources would be given by

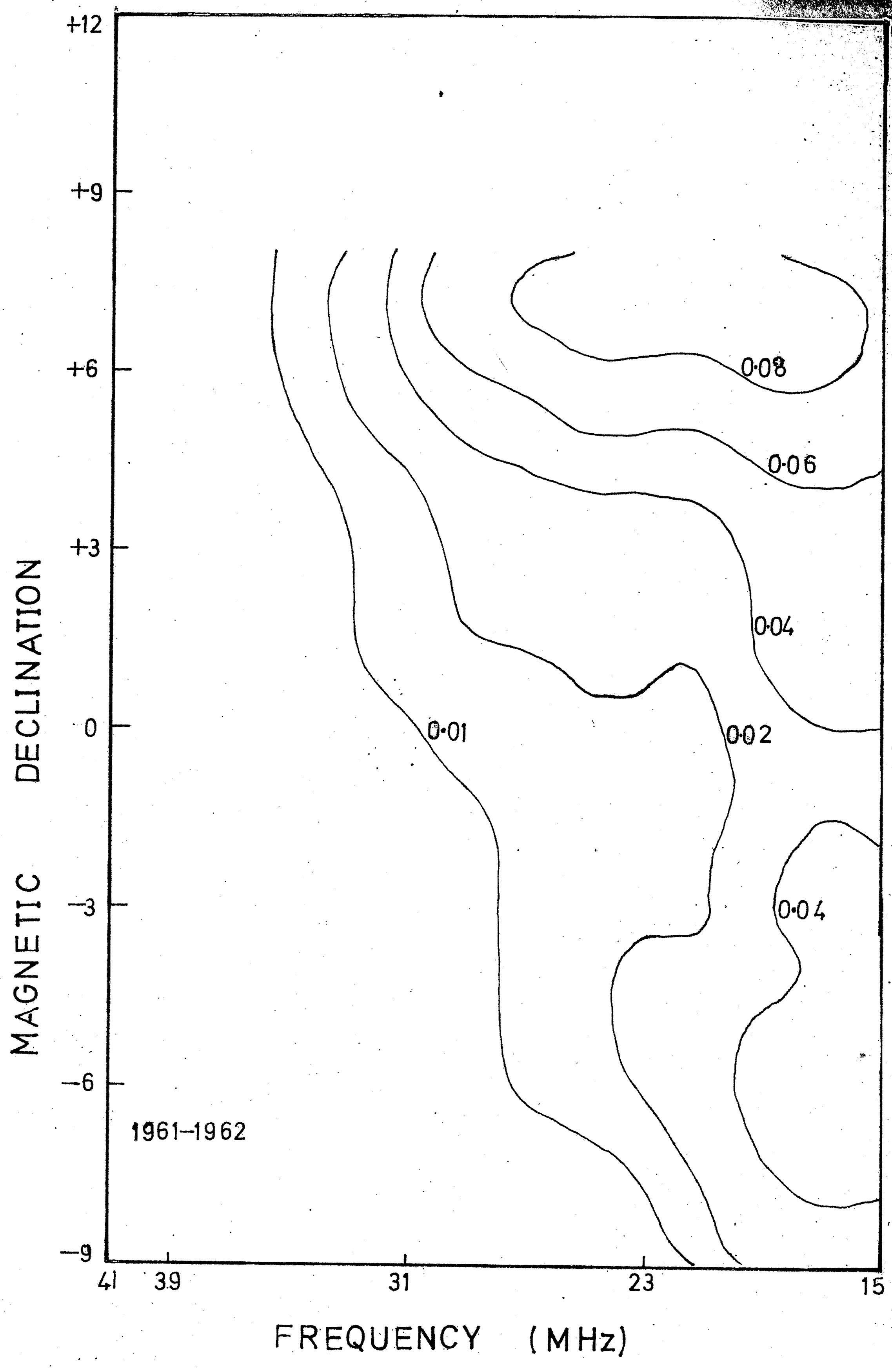
$$\lambda = 200 + \arccos \left\{ \frac{\phi_D - D_E}{7} \right\} \qquad 4.2$$

where ϕ_D is the latitude of the cone of emission relative to the disc.

If the radiation is confined to beam fixed relative to the magnetic field, then it should be possible to use the motion of the Earth through these beams to map them out. Consider a plot of probability of occurrence against frequency and magnetic declination. If the change in probability of occurrence is due only to changes in the amount of time spent in the beams then at a given magnetic declination and frequency the probability ought to remain constant over a number of years. In years of high probability the Earth is at its maximum northward declination. We would thus expect the probability at a given frequency to increase with magnetic declination. in general the maximum probability should occur at different declinations for different frequencies with a continuous variation in the magnetic declination of maximum probability with frequency being likely.

Figures 4.1 to 4.5 show plots of the kind described above for each of the apparitions 1961 to 1966. The data

These plots were obtained by the following method. The number of minutes during which Jupiter was active was found for each 1° by 2MHz area of the magnetic declination - frequency plane, and divided by the number of minutes that Jupiter was observed at that declination. This gave the probability for each area. This probability was associated with the point at the centre of the area. The contours plotted in the figures were obtained by interpolation between these points.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−3
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MAGNETIC DECLINATION
0·08
0·06
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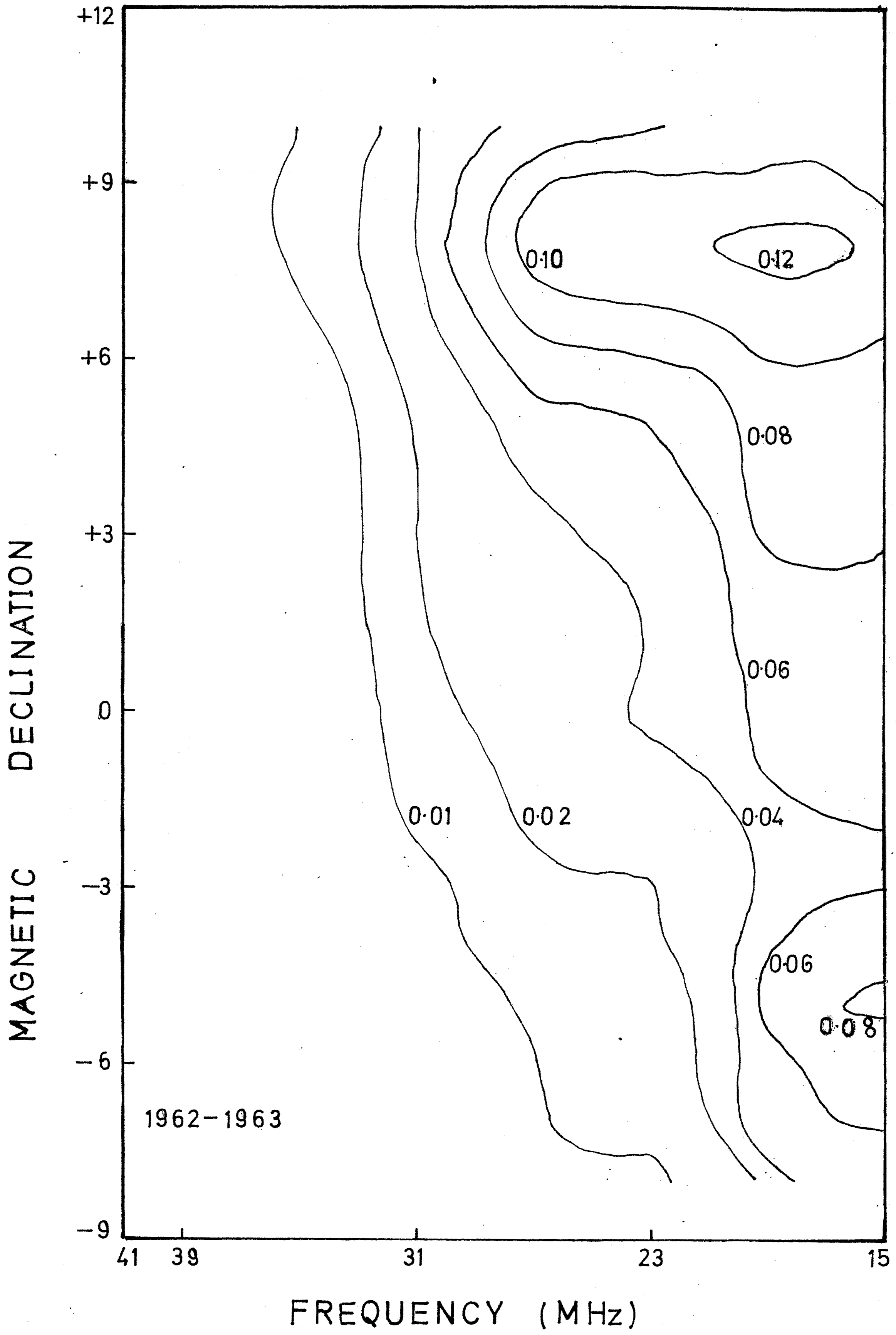
0·04
1961–1962
41
39
31
23
15
FREQUENCY (MHz)

Fig 4.1



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MAGNETIC DECLINATION
0·12
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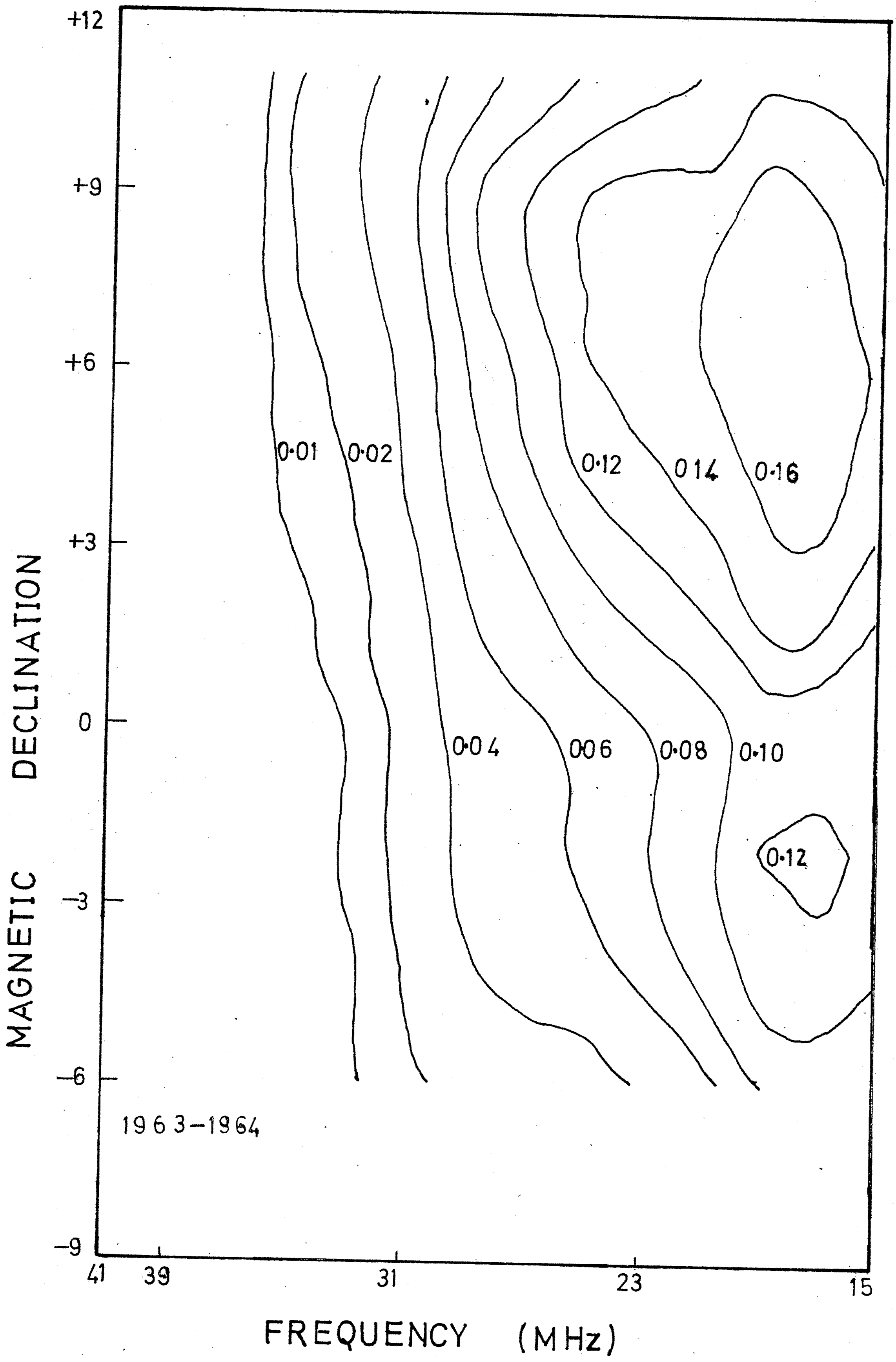
0·08
1962-1963
41
39
31
23
15
FREQUENCY (MHz)

Fig. 4.2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MAGNETIC DECLINATION
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0·10
0·12
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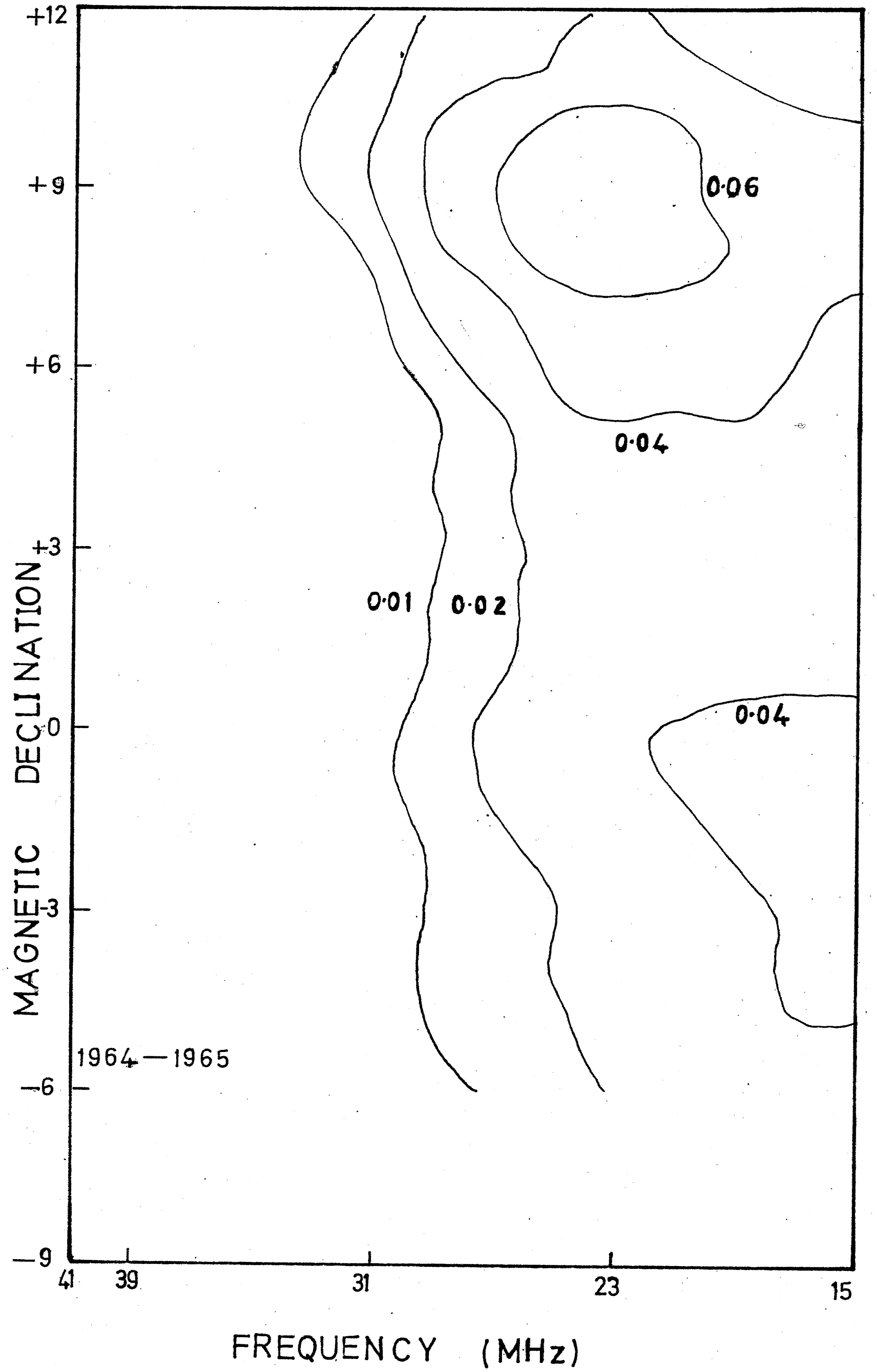
0·12
1963–1964
41
39
31
23
15
FREQUENCY (MHz)

Fig. 2.3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MAGNETIC DECLINATION
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0·04
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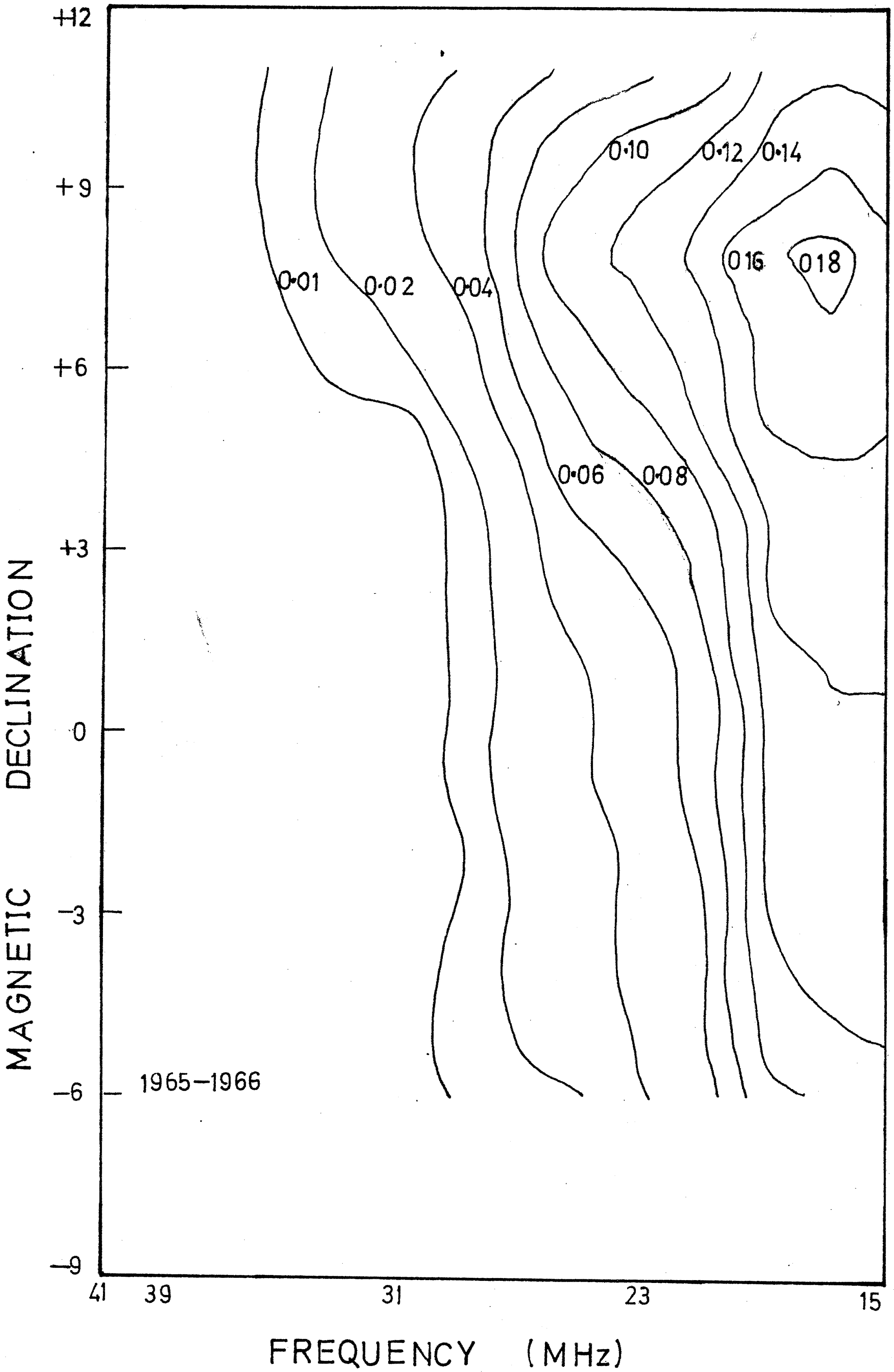
0·02
0·04
1964—1965
41
39
31
23
15
FREQUENCY (MHz)

Fig 4.4



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+9
+6
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0
-3
-6
-9
MAGNETIC DECLINATION
0·01
0·02
0·04
0·06
0·08
0·10
0·12
0·14
016
018
1965–1966
41
39
31
23
15
FREQUENCY (MHz)

Fig. 4.5

used to obtain these plots was the published data of Warwick. Each storm is represented by a rectangular area in the magnetic declination-frequency plane bound by the maximum and minimum frequencies and by the magnetic declinations at the start and end of the storm. This is far from being the true distribution of activity with frequency and magnetic declination and so care must be taken in interpreting the plots. Only activity which occurred when the central meridian longitude fell between 200^{o} and 20^{o} has been included in this analysis. There are fewer storms from the other hemisphere resulting in poorer statistics. The diagrams for that region have not been included. They tended to have more isolated peaks.

Only those parts of the curve have been included which fell between the maximum and minimum declinations reached on at least two thirds of the observed rotations. Beyond these limits the results are statistically unreliable.

One feature about which there can be no doubt is the considerable variation of probability at a fixed point in the frequency-magnetic declination plane from apparition to apparition. Comparison of figures 4.3 and 4.4 shows that the probability at most points in the plane dropped by a factor of at least a half over a period of one year. This implies that the probability is not determined solely by the declination of the Earth.

It has been assumed tacitly till now that over the course of a single apparition the observing profile over the Io position - central meridian plane will be reasonably uniform. The following check shows that this is not a major cause of the probability variation. All the activity during the 1963-64 and 1964-65 apparitions was divided into Io-related and non Io-related events according to the limits given in Appendix "A". Io related events showed a decrease of about 8% in total duration from 1963-64 to 1964-65 while non Io-related events showed a 70% decrease. In 1963-64 about 1/5 of all activity was Io-related whereas during the following apparition half the activity was Io-related. It is obvious from this that it is the events not related to Io which determine the change in probability. The comparison presented here is between the two extreme cases but the conclusions are valid for all years. The duration of Io-related activity changed little from apparition to apparition but large changes in non Io-related activity were common.

As the observing period was at times larger than the rotation period of Jupiter the probability variations cannot be due to an unfavourable central meridian observing profile. There must be some other factor which determines the probability of occurrence and which probably has a larger effect on Io independent activity.

The diagrams for each of the apparitions show an increasing probability with increasing declination at any particular frequency as expected. At most frequencies and particularly the higher frequencies the probability continues to increase till the maximum reliable declination is reached. The only evidence of a peak common to all distributions is the peak at 18 MHz and 7^{o} or 8^{o} declination. There is another peak at 18 MHz on most diagrams which however appears to drift in magnetic declination of Earth relative to the rotational equator. The range of drift is from -6^{o} to -2^{o} in four years. All graphs show a gradual decrease in probability with increasing frequency as would be expected.

Most storms drift in frequency with time and so an analysis of the kind done here where each storm is represented by a rectangle can show little of the fine structure. For this reason the analysis was repeated with the original spectographic data reanalysed in the following way. Instead of assigning a maximum and minimum frequency and a starting and ending time to each storm, the spectra were analysed in 1MHz frequency steps. A starting and ending time was assigned to each 1 MHz interval, with periods of activity separated by quiet periods of half an hour or longer being assigned separate starting and ending times even though activity might be continuous at other frequencies. This re-analysis is unfortunately not complete at the time of writing but data for the 1961-62 apparition and for parts of the following two apparitions are available.

Figure 4.6 shows a magnetic declination-frequency-probability plot for these data for the longitude range 200° through 360° to 20°. Figure 4.7 shows the same plot but with the System III (1965.0) longitude system of Gulkis and Carr used in place of the (1957.0) system. The contours are similar to those for the other figures but show a few important differences. It is likely that the decrease in probability at +9° declination is not real but a result of the poor statistics.

Both distributions show at peak in the 17 MHz probability at about +7° declination. The System III (1965.0) distribution has the peak displaced towards lower declinations by about 1°. The width of the peak in both cases indicates that the majority of the radiation is confined to a beam with a width of about 3 degrees measured to half of the maximum height above the average

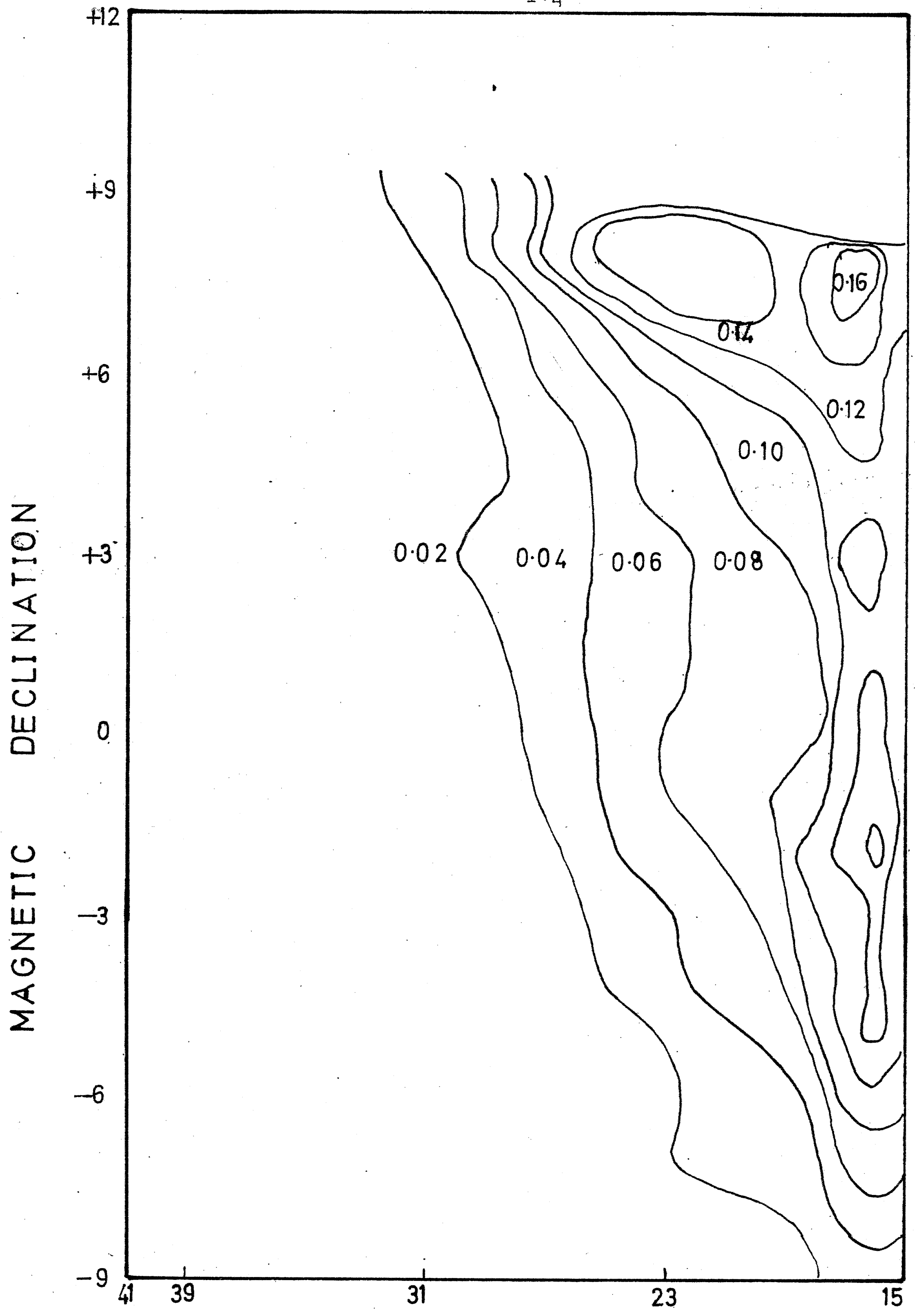

Fig 4. Probability Distribution using System III (1957.0)

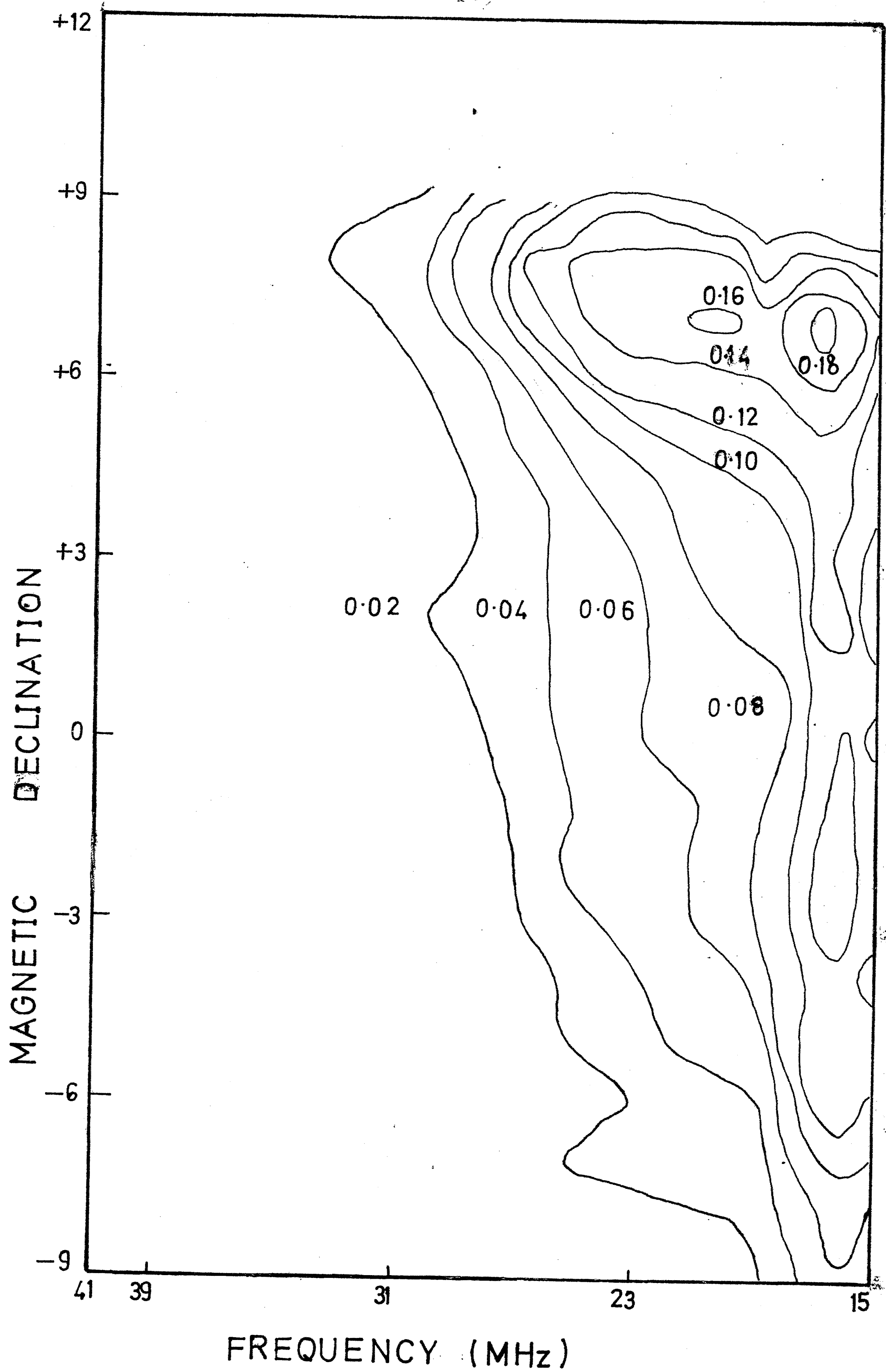

Fig 4.7 Probability Distribution using System III (1965.0)

probability at 17 MHz.

It is possible that the peak shows a slight shift to higher frequencies with increasing declination. Figure 4.8 shows the probability distributions with frequency for each of the higher declinations for which only a few observations were made. These show that the peak has shifted to 23 MHz. At frequencies above this the probability shows the same continuous increase WITH MAGNETIC DECLINATION mentioned earlier.

The data used to obtain figures 4.6 and 4.7 did not cover a sufficiently long period of time for it to be certain that the beaming is a real effect. Should the peaks change position by less than the change in ordinary declination over several years then the beaming would be a real effect. Analysis of the data for years during which Earth was at a high declination should show whether the peak at 17 MHz was real. If the beaming should prove to be real it would be an important consideration in future theories for the origin of the radiation.

Although distributions have not been shown for the Gledhill model of the magnetosphere the distributions would not be very different from the above. The declinations measured from the plane of the disk only change by 14^{o} per revolution of the planet. Thus for a period during which the declination relative to the rotational axis changed little, the distribution would be similar to those given but with the range of declination compressed.

4.2. Possible radiation from Jupiter's magnetospheric tail.

Gruber (1966) has shown that the probability of emission falls sharply after opposition and has suggested that there is a component of Jovian radiation which is generated in Jupiter's magnetospheric tail. The tail would be obscured after opposition thereby causing the observed decrease in probability. This section describes a simple test which was applied to this theory.

Theories of Jovian radiation assume that the Io-related activity is generated either in the vicinity of Io or at longitudes below the satellite. Both positions of Io for which the probability of emission is enhanced are well clear of the position of the tail, if it exists. It is therefore likely that the Io-related radiation does not originate in the tail. Figure 4.9 shows the variation of probability with time before and after opposition, arranged over the years 1961 to 1965. It is obvious that the decrease in non Io-related activity is far greater than the decrease in Io-related activity.

It has been suggested that the decrease in probability after opposition is due to less favourable observing conditions since observations of Jupiter after opposition must be during the evening when the maximum usable frequency of the ionosphere is still high. The low frequency radiation tends to be more

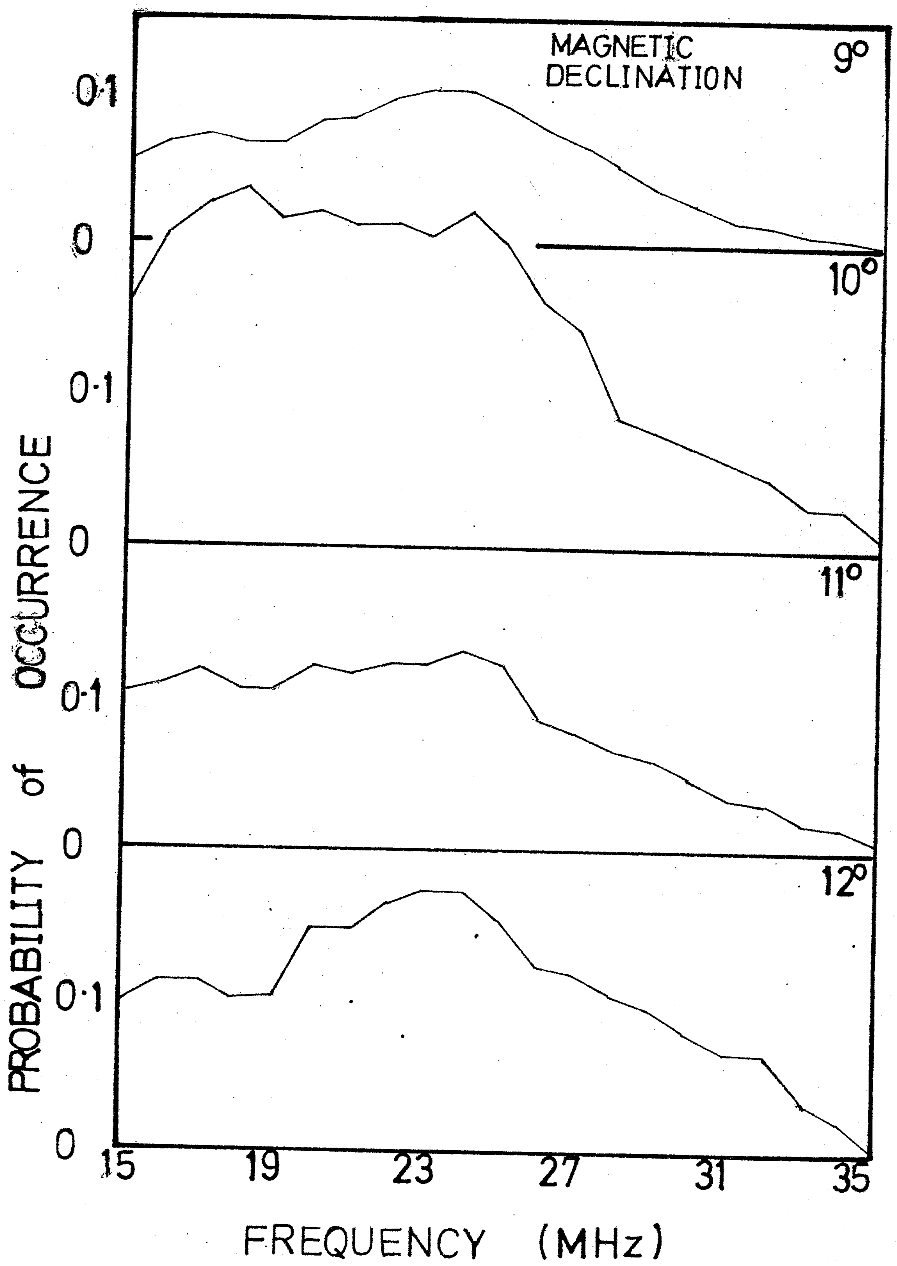

Fig 4.8 Probability Distributions for Higher Declinations not shown in Fig 4.7

independent of Io position. For this reason only those storms with a maximum frequency greater than 25 MHz were included in the analysis of data to produce figure 4.9.

From this it would appear that there is some source on Jupiter which is not related to the position of Io but which is more active before opposition than after. Gruber's theory of emission from the magnetospheric tail could provide such a mechanism.

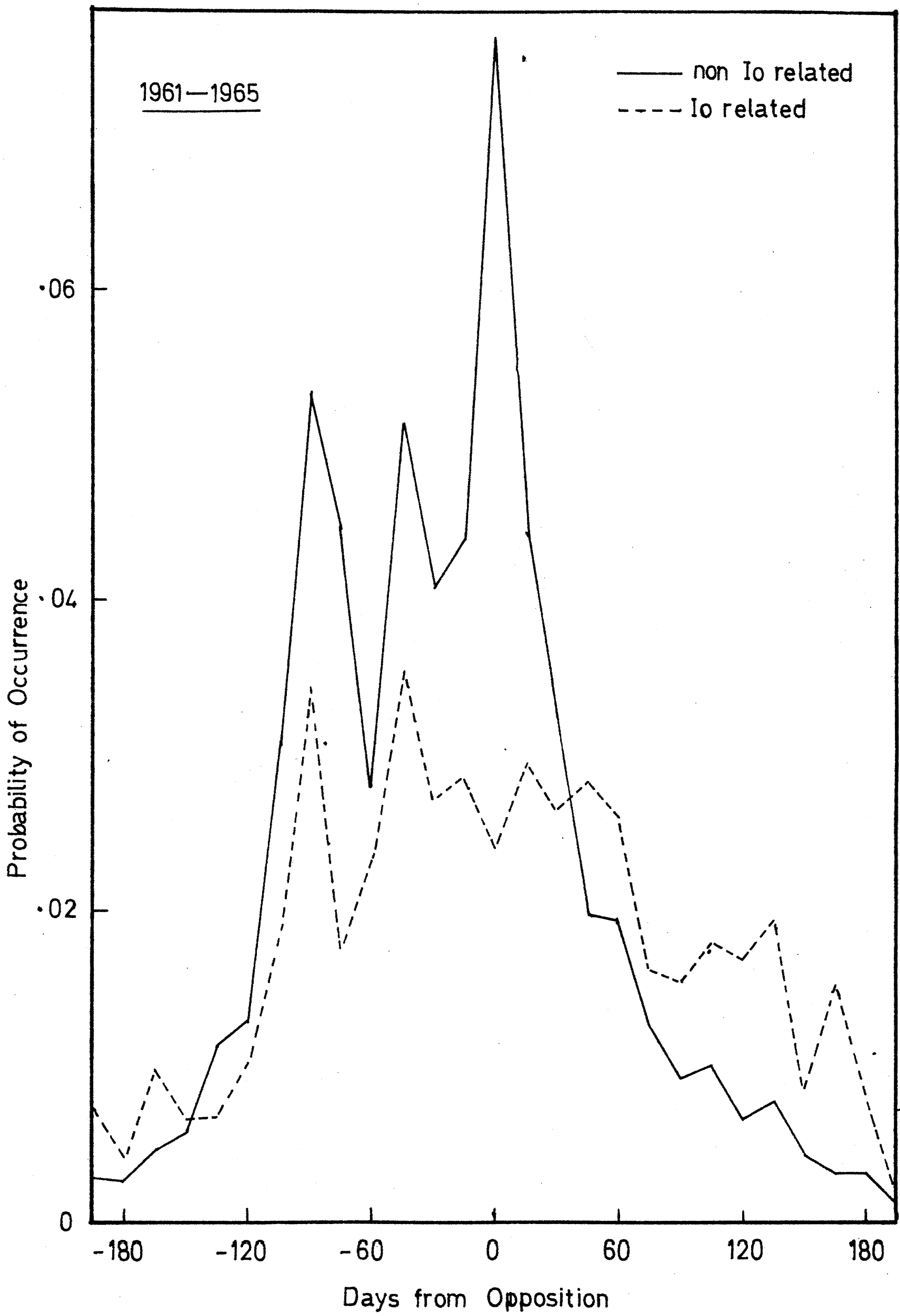

Fig 4.9 PROBABILITY DEPENDENCE on DATE from OPPOSITION

APPENDIX "A".

It is known that the probability of a Jovian decametric storm being received at earth is very dependent on the longitude of the central meridian at Jupiter and on the position of Io in its orbit. On the basis of these relations it is possible to make fairly reliable predictions of the times when Jupiter activity is most likely. Figure A.1 shows a plot of probability of emission against system III longitude of the central meridian and departure of Io from superior geocentric conjunction. (from Dulk 1965). It can be seen that two rectangular blocks enclose nearly all points in the central meridian longitude - Io phase from superior geocentric conjunction plane where the probability is greater than 0.3. The prediction charts used consisted of tables showing all times when Jupiter and Io had coordinates in these rectangles.

Till June 1968 Florida State University provided the prediction charts used. After this date a programme for Rhodes University's I.C.T. 1301 computer was written by the author and Mr. N.J. Attridge to produce similar prediction charts. A specimen print out is shown in table A.1 and a key to this chart is given in table A.2. The chart also shows the transit time of Jupiter at a longitude of 30° east of Greenwich. Transit time at Grahamstown is 14 minutes later.

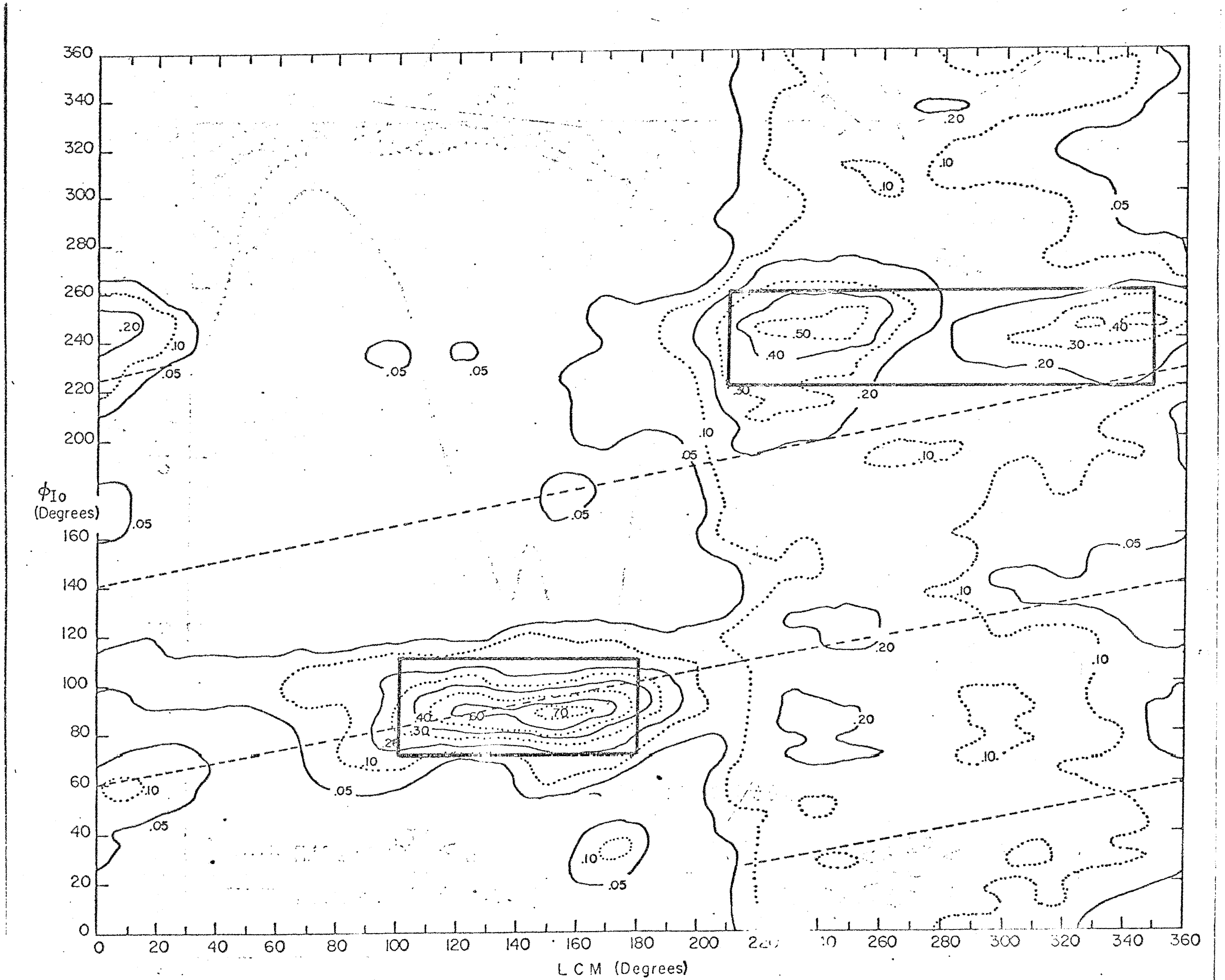
ϕ_{Io}
(Degrees)
L C M (Degrees)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
.05
.10
.20
.30
.40
.50
.60
.70

Fig A·1

```
YEAR 1969  MONTH  1                                              ※ TRANSIT
                  SAT 200    400    600    800    1000   1200   1400   1600   1800   2000   2200   2400   200
JUL DATE| DATE  | UT 0       200    400    600    800    1000   1200   1400   1600   1800   2000   2200   2400
-------------------------------------------------------------------------------------------------------------
 10222  |  1    |   000000000   1JJJJJJJJJJJJJJAAAAA   00000000   111111111111111   000000000
 10223  |  2    |   111111111111111   ||||||||||||||0|0|0|0|0|0|0|0|0|0||||   11111111111111111   00000000   111111111111JJJA
 10224  |  3    |   AAAAAAAAAAAAAAA   000000000   11111111111111   000000000   111111111111111   000010
 10225  |  4    |   |0|0|0|0|||||||||||||||||||||   111111111111111   000000000   11111111111111   000000000   AAAAAAAAAAAAAAAAJJ1111111
 10226  |  5    |   111111   000000000   111111111111111   00000000   |||||||||||||||||||||||||||||   11111111111111
 10227  |  6    |   000000000   111111111111111   000000000   AAAAAJJJJJJJJJJJJJJ111   00000000   111
 10228  |  7    |   111111111111   000000000   111111111111111   |||||||||||||||||||||||||0|0|0|0|0000   111111111111111
 10229  |  8    |   000000000   11111JJJJJJJJJAAAAAAAAA   000000000   111111111111111   000000000
 10230  |  9    |   111111111111111   ||||||0|0|0|0|0|0|0|0|0|0||||||||||   11111111111111   00000000   111111111111
 10231  | 10    |   11 AAAAAAAAAAAAAAAAAAA   000000000   111111111111111   000000000   111111111111111   00
 10232  | 11    |   000000||||||||||||||||||||||||||||||   111111111111111   000000000   111111111111111   000000000   AAAAAAAAAAAAJJJJJJ
 10233  | 12    |   111111111   000000000   111111111111111   000000000   ||||||||||||||||||||||   11111111111111
 10234  | 13    |   ||||| 000000000   111111111111111   000000000   AJJJJJJJJJJJJJJJAAA   00000000
 10235  | 14    |   11111111111111   000000000   111111111111111   ||||||||||||||||||0|0|0|0|0|0|0|0|0|0|0||   11111111111111
-------------------------------------------------------------------------------------------------------------
JUL DATE| DATE  | SAT 200    400    600    800    1000   1200   1400   1600   1800   2000   2200   2400   200
                | UT 0       200    400    600    800    1000   1200   1400   1600   1800   2000   2200   2400
```

SYMBOL	
O	Central Meridian longitude 100-180
11	Io position 70-110
10	B source prediction
1	Central meridian longitude 210-350
A	Io position 220-260
J	A and C source predictions.

TABLE A.2: Abbreviations used on prediction charts.

APPENDIX "B".

Cyclotron radiation generates a wave at the gyrofrequency. If the electrons are streaming along the field line in addition to rotating about it, the radiation undergoes a Doppler shift with the forward going wave being increased in frequency and the backward going wave being decreased in frequency.

The Appleton-Hartree formula for a collisionless plasma shows that the refractive index for propagation along the field line at frequencies greater than the cyclotron frequency is given by

$$n^2 = 1 - \frac{X}{1+Y}$$

where X and Y are the usual Appleton parameters (Budden 1961). From this it can be seen that the refractive index is imaginary unless

$$X < 1 + Y$$

or, substituting for X and Y and solving for the wave frequency f, unless

$$f > f_H + \sqrt{\tfrac{1}{4} f_H^2 + f_N^2} = f_x \qquad B.1$$

where f_H = cyclotron frequency

f_N = plasma frequency.

From B.1 it can be seen that $f_x > f_H$. It can be shown that B.1 holds for all directions of propagation.

Any wave radiating from near the planet to free space will pass through a region of decreasing gyrofrequency as it moves outwards through the magnetic field.

If the wave frequency was originally at or below the cyclotron frequency it cannot escape unless the plasma density is negligible at the Y=1 point. The forward radiated Doppler shifted component will be shifted to a frequency greater than the cyclotron frequency and also greater than f_x if the electron stream velocity is great enough and so will be able to escape.

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