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A THREE FREQUENCY OBSERVATION OF THE 1967 CRAB NEBULA OCCULTATION BY THE SOLAR CORONA

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A THREE FREQUENCY OBSERVATION OF THE 1967 CRAB NEBULA OCCULTATION BY THE SOLAR CORONA

by
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of the University of Maryland in partial fulfillment
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ABSTRACT

Title of Thesis: A Three Frequency Observation of the 1967 Crab Nebula
Occultation by the Solar Corona

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Thesis directed by: Dr. G. Westerhout

The results of an observation of the occultation of the Crab Nebula by the solar corona for June 1967 are reported. The occultation was observed at 139 MHz, 403 MHz, and 1705 MHz using the 85-foot antenna of the NASA Satellite Tracking Network at Rosman, North Carolina.

An enhancement and reduction of flux was observed at 403 and 1705 MHz. The maximum enhancement was 16% ± 12% at 6.5 solar radii and 7% ± 11% at 5.2 solar radii for 403 MHz and 1705 MHz, respectively. The minimum flux occurred at 4.8 solar radii with a 30% ± 12% decrease at 403 MHz and 14% ± 11% at 1705 MHz. Measurements at 139 MHz proved too contaminated by solar radiation to yield useful results.

The observations support previous reports of discrepancies in the multiple scattering mechanism and extend the wavelength range of the disagreement to 18 cm.

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I. INTRODUCTION

In June of each year the line-of-sight between the Crab Nebula radio source and the earth is such that the radiation from the source must pass through the solar corona. This particular situation, commonly referred to as the occultation of the Crab Nebula, permits in principle an investigation of the solar corona through its transmissional properties.

At first, the most direct determination of the electron density attempted was the observation of the K or electron component of the zodiacal light. The reliability of this method is affected seriously by the F or dust component of the zodiacal light. The difficulty lies in trying to separate the contribution of one component from the other. At a distance less than approximately 4 solar radii the F component is very weak and the K component accounts for approximately all the observed zodiacal light. Visual observations of the scattering of solar radiation by free electrons during a solar eclipse will give estimates of the electron density of the corona (Blackwell and Ingham 1961). Since this method proves impracticable beyond 4 solar radii another independent method is needed.

Machin and Smith (1951) have shown that the observations of a radio source at a small angular distance from the sun might be an acceptable alternative. The radiation emitted by the radio source would be deviated in passing through the corona, and when the angular distance from the sun becomes small the deviation may be great enough for the radiation not to reach the earth. This critical angular distance at which the radiation is blocked becomes the effective occultation radius of the corona. Since the radius depends upon the wavelength (or frequency), the measurement of the occultation radius for a series of different wavelengths should give, in principle, an estimate of the electron density at varying heights in the corona. Such observations have been carried out with this phenomenon in mind (Machin and Smith 1952, Hewish 1955, Vitkevitch 1960, Blum and Boischot 1957, Hewish 1958, Slee 1959, Hogbom 1960, Erickson 1964, Hewish and Wyndham 1963, Slee 1961).

The observations of the Crab Nebula occultation especially at meter wavelengths have shown systematic changes in the intensity and apparent position of the source. However, the main effect observed proved to be an apparent broadening of the source. Hewish (1955) suggested that the observations can be best explained on the basis of multiple, small-angle scattering caused by irregularities of or deviations from the normal electron density in the corona. Erickson (1964) compiled data from a number of observers at many wavelengths and verified that the apparent diameter varies as wavelength squared as suggested by Hewish, supporting a multiple scattering theory. The measurements have demonstrated further that the apparent broadening of the source is accompanied by a decrease in the intensity of the source as is acceptable under the multiple scattering theory. The effects become larger with decreasing angular distance of the source from the sun.

At wavelengths below 2 meters, observations appear not to be consistent with the multiple scattering mechanism. Blum and Boischot (1957, 1959) have reported that the flux of the Crab Nebula at 169 MHz showed increases of about 50% when the source and sun were separated by approximately 7 solar radii in both 1957 and 1958. In 1964, Kundu (1965) attempted to check this result at a frequency of 430 MHz. The observation did not show the increase obtained at 169 MHz but there was a 20% decrease in the flux at 5 solar radii and a slight increase in apparent diameter. The increase in diameter is consistent with multiple scattering but the observed large decrease is just as inconsistent as the large increase at 169 MHz.

Erickson (1966) continued this investigation during the 1965 occultation with a dual frequency observation. At 430 MHz, the flux appeared to remain constant contradicting Kundu's results. The observation at 234 MHz seems to support Boischot's results in that an increase of 30% was observed during the occultation. None of these latter observations supports the multiple scattering theory.

Basu and Castelli (1963) described a somewhat astonishing observation of the occultation of the Crab Nebula during 1962. The observing wavelengths were 25 cm and 10 cm. The results were a progressive increase in the angular diameter of the source with decreasing angular distance from the sun. Certainly this result is totally unexpected for the multiple scattering theory; for at these short wavelengths, it is impossible to obtain any effect since the closest approach of the Crab Nebula is only about 5 solar radii.

In view of the discrepancy, observations of the 1963 occultation were independently taken at 18 cm by Wyndham and Clark (1963) and at 6 cm by Hughes, Downes, and Murray (1964). At 18 cm no positive evidence of a change in source diameter was found with an upper limit of 1.2 minutes of arc. There was no evidence for a change in position greater than 0.7 minutes of arc. Similarly, at 6 cm there was no evidence for a systematic increase in the source diameter greater than 1.0 minutes of arc. Also, the apparent position of the source and its flux show no evidence of a detectable systematic change.

To further test these results, observations of the Crab Nebula were taken in June 1967 using the 85-foot parabolic reflector of the Rosman Data Acquisition Facility of the NASA-Stadan Satellite Tracking System. The resolution of this antenna does not compare favorably with others employed in this observation; however, some advantages were obtained from a capability of full sky coverage, of simultaneous operation at three frequencies, and of an opportunity to observe a large number of times during the day. Since it was felt that the ability to statistically average a number of individual measurements might outweigh the lower resolution, observations were taken at 139 MHz, 403 MHz, and 1705 MHz.

II. INSTRUMENTATION

The Rosman Data Acquisition Facility (DAF) was established primarily for the acquisition of data from satellites requiring high-gain multifrequency antennas at a ground station located in the eastern part of the United States. The site is approximately 35 miles southwest of Asheville, North Carolina, in the Pisgah National Forest. The site is lower than surrounding terrain to provide radio frequency shielding from interfering sources, and precautionary measures have been taken to provide a fairly noise-free environment for good reception.

The Rosman Antenna No. 1 is an 85-foot-diameter paraboloid of revolution with a focal length of 36 feet. The surface consists of double-curved aluminum-sheet panels separated from the reflector structure so that the antenna can be independently adjusted. The aluminum surface of the reflector is painted a flat white to scatter solar radiation. The antenna reflectors are mounted on an X-Y type mount designed specifically for tracking satellites. An X-Y type mount has two transverse-roll axes. The advantage of this type of mount for tracking satellites is that there are no gimbal-lock positions in the usable sky coverage. The antenna is capable of tracking at rates from 0 to 3 degrees per second, with accelerations up to 5 degrees per second per second as required. The pointing accuracy is approximately ± 40 seconds of arc. The antenna has five operational modes: (1) it will automatically track a signal; (2) it can be driven by a teletype drive-tape input; (3) it can be manually operated; (4) it can be slaved to an acquisition antenna; and (5) it can be operated in various search modes.

The Crab Nebula observations were carried out using teletype drive-tapes as input. These tapes are prepared by a computer coordinate conversion program. An IBM 7094 computer was used to compute the right ascension and declination of the Crab Nebula for the observing epoch. The 1950 position was taken from the Howard-Maran catalogue (1965), precessed to the observing epoch and corrected for static pointing errors. The right ascension and declination scan map was prepared and the coordinates converted to the X-Y coordinates needed by the antenna. The teletype tape was made with update positions given at one second intervals.

The antenna data system provides for the measurement, digital encoding and read-out of the antenna shaft angles for feeding into the servo system, visual read-out, and teletype punch. These position data and data-quality codes are punched on five-level paper tape in teletype code once every 10 seconds or once every second, whichever is selected.

The support for the antenna feed system on the reflector surface is a quadripod. The head of the quadripod is a hollow structural square housing designed to hold an integral feed and receiver box which is 4 feet square and 6 feet long. The feed system is designed to provide autotrack in any one of four polarizations: two orthogonal linear and two circular. For telemetry reception, two orthogonal polarizations are provided simultaneously, either linear or circular. For

139 MHz and 403 MHz, the operator at the control console can select the polarization he desires by setting a switch on the console. At 1705 MHz, polarization is manually selected by component substitution in the antenna feed network. Standard monopulse circuitry, with coaxial hybrids, are used to obtain the sum channel and tracking channel outputs from the array of four dipoles. The Crab Nebula observations were carried out using the sum channel of the monopulse array. At these frequencies, the source is less than two percent polarized so that polarization considerations were ignored and a right-handed circular polarization was used to minimize interference with spacecraft telemetry operations.

Figure 1 is a block diagram of the radio astronomy receiving system. The system is a typical Dicke-type switching radiometer employing I.F. gain modulation. A coaxial switch has been placed at the output of the polarization control for each feed. This switch provides for the switching of the received signals to the radio astronomy equipment or the telemetry equipment. For calibration of the radio astronomy system, a diode-tube noise generator is used for the 139 MHz equipment, and an argon-discharge-tube noise generator is used for the 403 MHz and 1705 MHz equipment. The level of the signal injected into each system is determined by a 3-position-calibration temperature control switch. This switch controls the signal level by changing the current flowing in the 139 MHz diode noise tube and by changing the attenuation between the 1705/403 MHz argon discharge tube and the respective directional couplers. The three positions on the switch represent the following approximate temperatures.

Frequency	A	B	C
139 MHz	10°K	100°K	500°K
403 MHz	1°K	10°K	100°K
-1703 MHz	1°K	10°K	100°K

The incoming signal from the antenna is continuously compared with a signal of known strength. This comparison is made at a 105 Hz rate by Dicke-type coaxial switches. The comparison loads are resistors located in a 328° ± 1°K oven.

Five-channel preamplifiers are provided for each frequency band. Five channels are to accommodate both the tracking and telemetry receiving functions. Low-noise transistor amplifiers are employed at 139 MHz and non-degenerate parametric amplifiers are employed at both 403 MHz and 1705 MHz. Such units possess inherently good phase stability and provide suitable system sensitivity.

The radiometers used in the observations operate on a center frequency of 30 MHz. To feed the 30 MHz radiometer, the 1705 and 403 MHz signals are first converted to 135 MHz and 133 MHz, respectively. These signals, along with the 139 MHz signal, are then fed to post-converters which produce a 30 MHz signal for each of three radiometers.

The radiometers contain a gain modulator for I. F. control of the comparison signal, an I. F. attenuator for protection from saturation, an I. F. filter with a bandwidth of 5 MHz, a detector, a tuned audio amplifier, a synchronous detector, an internal integration constant of 3 seconds, and a dc amplifier.

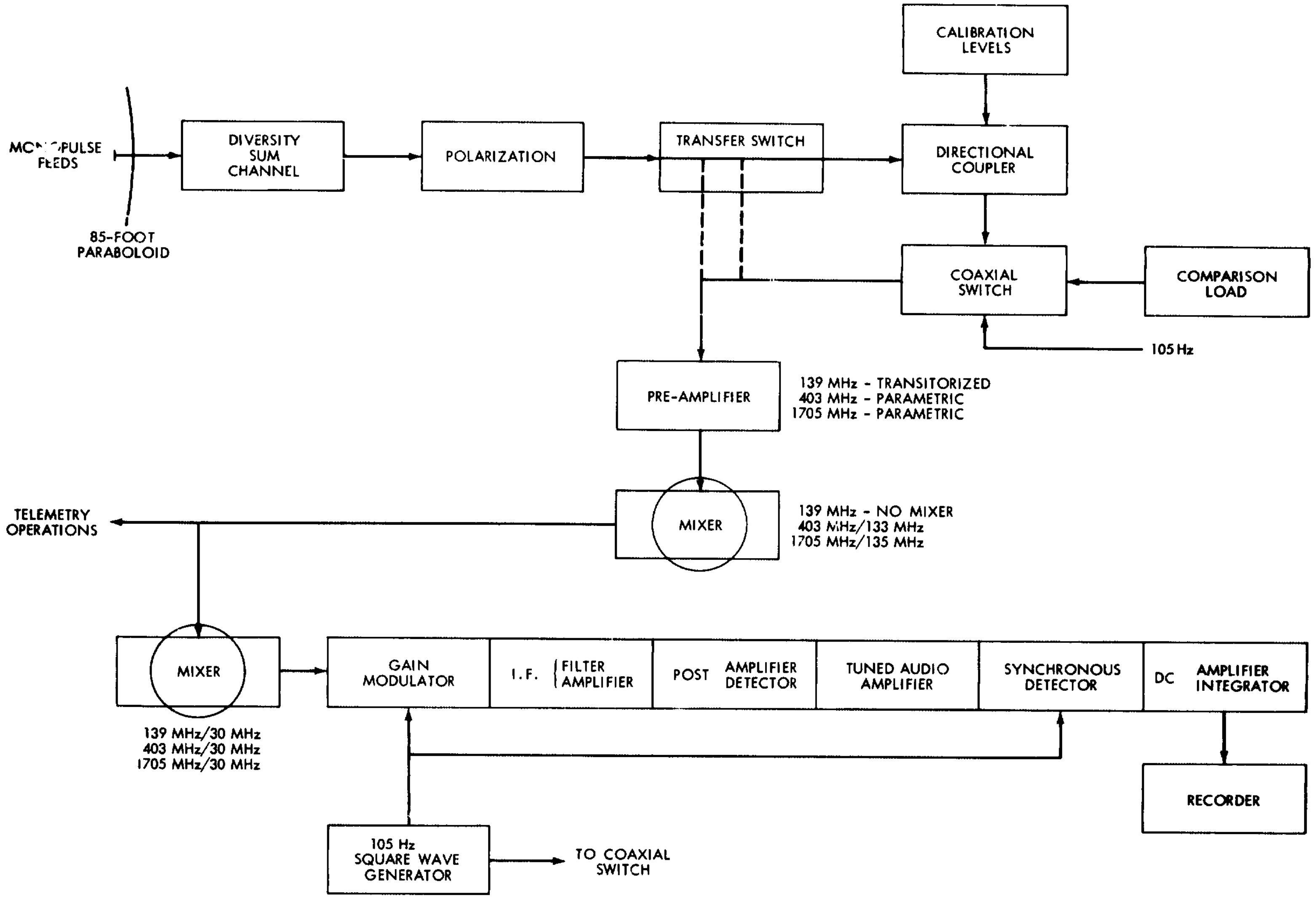

Figure 1. Receiving System, Block Diagram 1 of 3 Channels

The recording system consists of a 6-channel analog recorder. Each of the radiometers employs two channels to record its output. One channel is set at a high sensitivity to record as much detail of the observation as possible; the second channel is set at a lower sensitivity to observe problems which may cause deflections outside the range of the first channel. During the Crab Nebula observation, the second channel was quite important when solar emission increased.

III. OBSERVATIONS

In planning the observational technique to be used for the Crab Nebula one had to consider several constraints. The first constraint consisted of providing a program for the observing site which could be completed without interfering with normal satellite telemetry operations. This constraint was overcome by setting up observations at each half-hour of hour angle above the horizon of the site. In this way, several measurements were assured each day. The second constraint arises from the first in that all observations although at different hour angles must be intercomparable. In an effort to calibrate this effect, extra observational days were taken during the pre-occultational period. As Figure 2 shows, there is no detectable systematic effect on the amplitude measurements for different hour angles.

The third constraint deals with the amplitude intercomparisons which must be made throughout the long observational period of 26 days. This correction was made in two parts. First, the amplitude of the Crab Nebula was measured relative to the calibration noise sources. Then, the noise sources were calibrated against a number of discrete radio sources. A combination of different sources was used. Among these were Cas A, Vir A, Cyg A, IC443, 3C 273, Hydra A, Her A, and Cent A. In most cases, the change in the calibration noise sources during each observational day appeared random and unpredictable even when

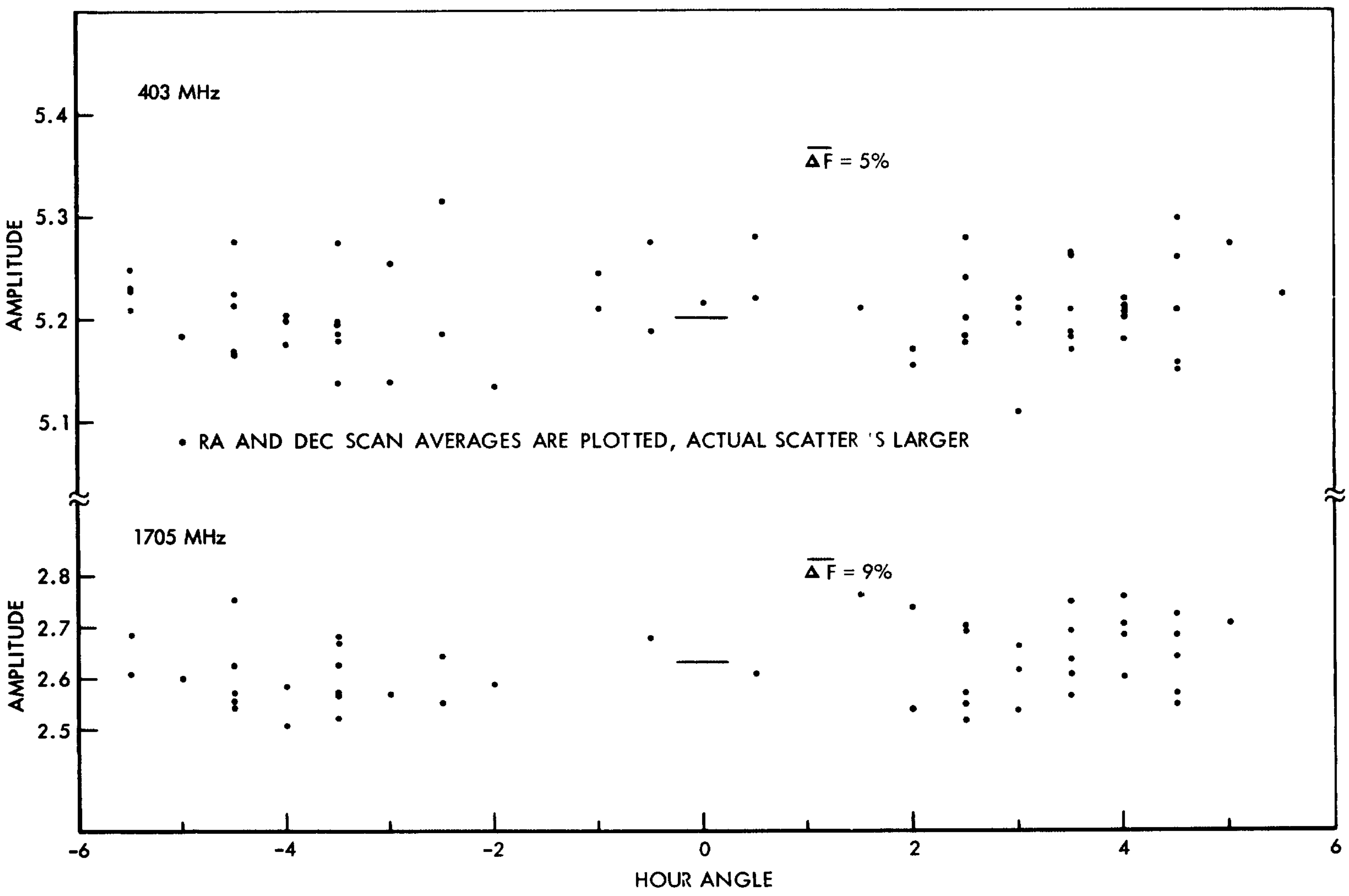

Figure 2. Crab Nebula Observed Flux as a Function of Hour Angle June 0–8 U.T.

compared after each observation. However, during the thirteen hour period when the Crab Nebula was unobservable the equipment was affected in a systematic manner. Figure 3 shows this systematic daily change. Due to the unsystematic change during the day and the systematic change from day to day only an average daily correction was applied to the data.

The fourth constraint requires that each measurement be that of the true amplitude of the Crab Nebula. Part of this uncertainty arises from the pointing error of the antenna system. This error can be divided into two parts; a static pointing error and a dynamic pointing error. The static pointing error is the result of bending in the prime focus area where the feeds are located and, to a lesser extent, of the structural stresses on the paraboloid. This error was calibrated by peaking on the source at each hour angle. The resulting calibration curve can be used then to set the antenna during the observational period eliminating the static error. For the Rosman 85-foot antenna, a maximum error of 12 minutes of arc was possible with a mean deviation of 3 to 4 minutes of arc (see Figure 4).

The dynamic pointing error appears to be a much larger problem. The Rosman antenna has a servo-controlled drive system constructed and set-up to track earth satellites at much higher velocities than usually employed in tracking radio sources. As a result the dynamic error is larger than the static error, and it is basically not a function of antenna pointing angles. The error appears to be about 12 minutes of arc with a mean deviation of 7 to 8 minutes of arc.

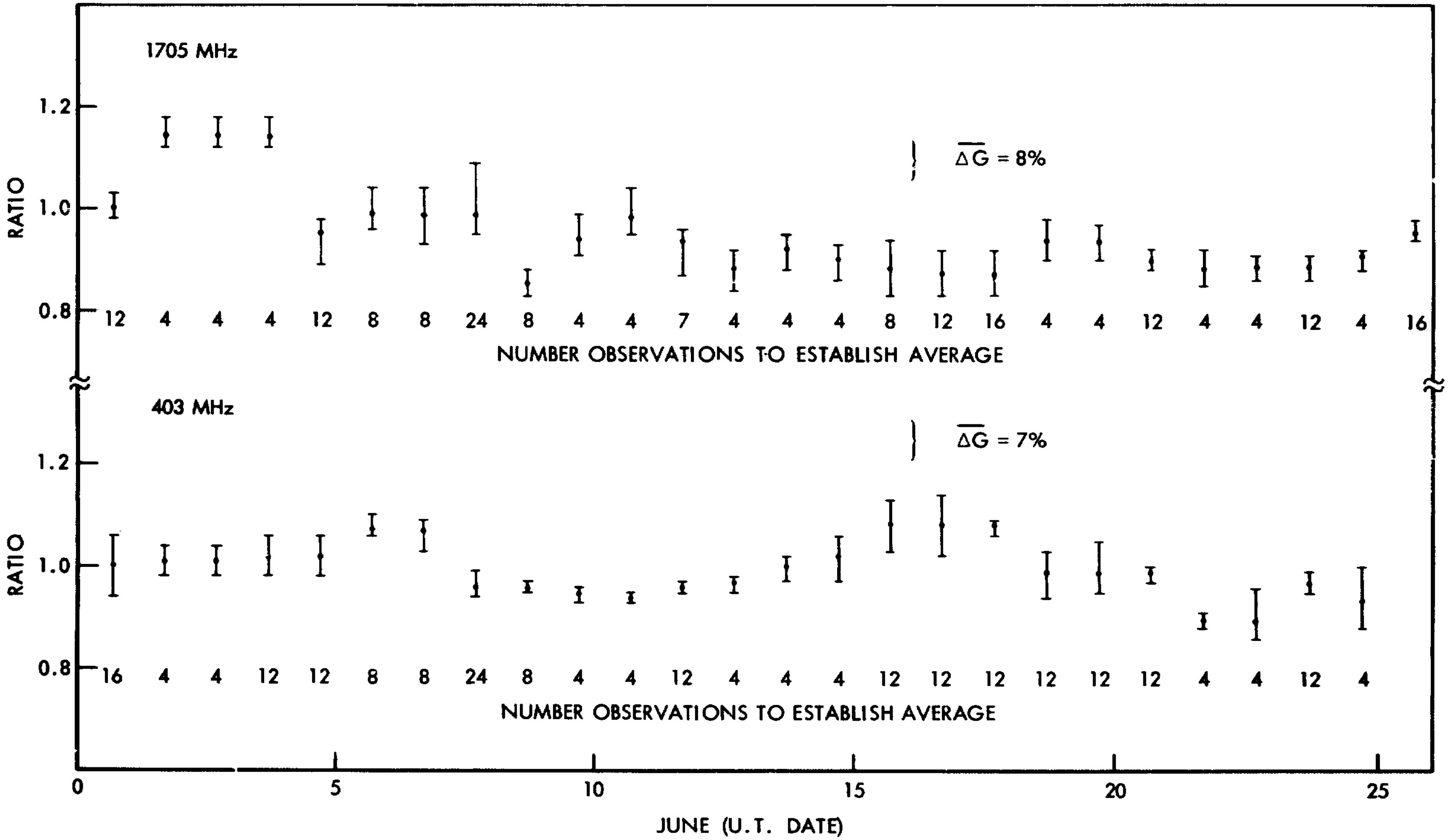

Figure 3. Change of Calibration Noise Source as Compared With Standard Sources (Factor by Which Observed Values of Crab Nebula are Multiplied)

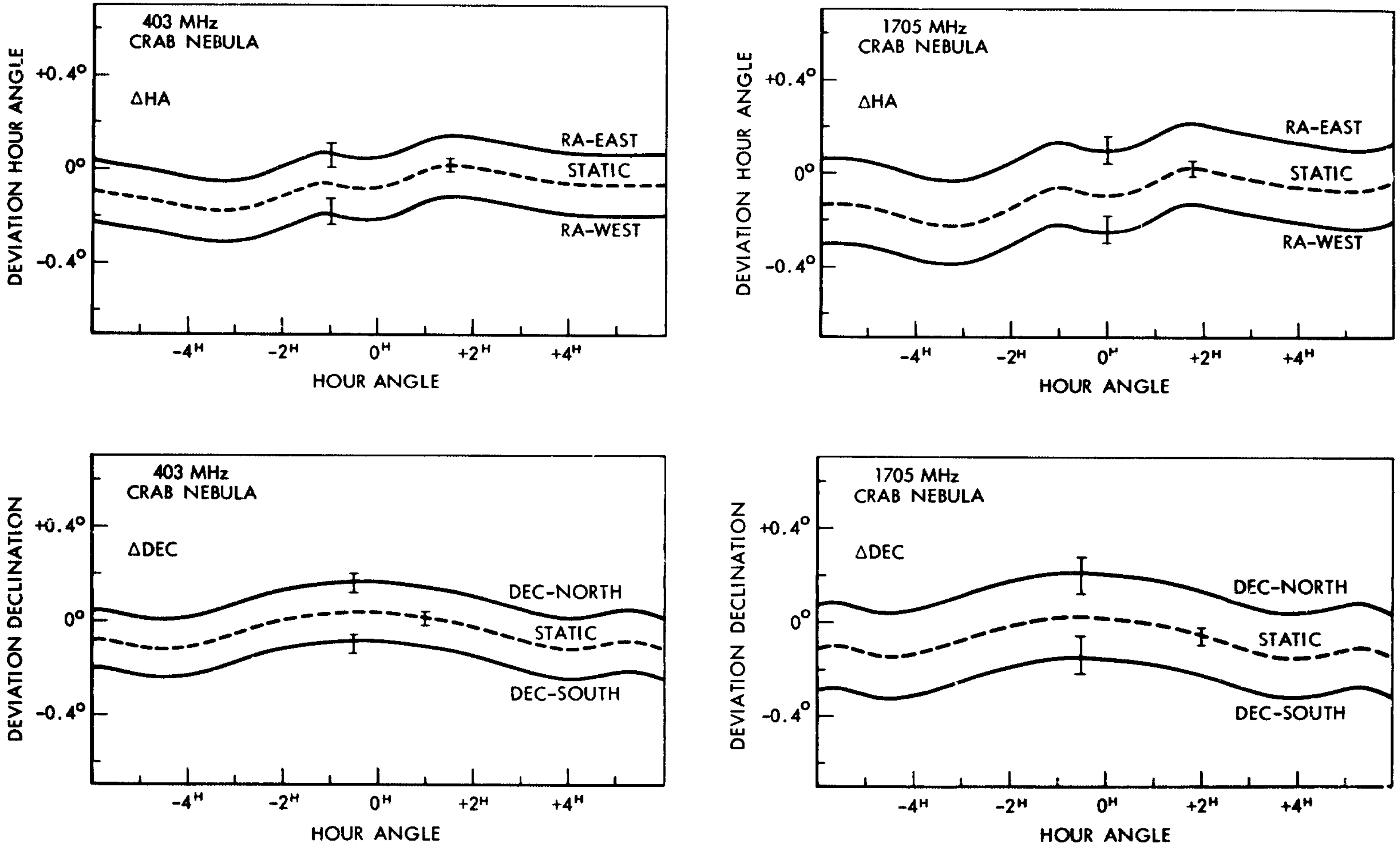

Figure 4. Dynamic and Static Pointing Errors — Declination of Crab Nebula

Naturally, this dynamic pointing error can be eliminated by taking drift scans of the source. However, there is the possibility that the source position will be deviated through some mechanism such as scattering or refraction. Since the magnitude of such a deviation is completely unknown, the data must at least be taken so that this error can be estimated. Since the sun passes north of the Crab Nebula, the maximum deviation is expected to be nearly all in declination.

For the antenna, a computer driven scan in right ascension and declination was found to be most usable. The dynamic error was found quite naturally to be completely in the direction of antenna travel and thus would not cause error in the amplitude measurements. However, the uncertainty in position will be largely due to the large mean deviation in the dynamic error. Through the right ascension and declination scans any movement of the source should be detected; however, in practice the broadness of the antenna beams and the pointing errors for the 85-foot antenna allow detection of large deviations only. Double right ascension and declination scans were employed finally in an attempt to improve the statistics, but high errors in position measurement were still encountered.

IV. DATA REDUCTION

The principal problem associated with the observation of the Crab Nebula is the contamination due to solar emission. The Crab Nebula was only 72 minutes of arc from the center of the sun on the day of closest approach, June 15. For comparison, the measured beamwidths of the antenna were 334 minutes of arc at 139 MHz, 126 minutes of arc at 403 MHz, and 34 minutes of arc at 1705 MHz (see Figure 5 for example). Since the solar flux is orders of magnitude greater than the flux of the Crab Nebula, a large solar contribution to the profiles must be subtracted.

Three steps were used to obtain this solar contribution. First, two months prior to the occultation the sun was observed in such a manner as to fully construct the antenna receiving pattern. Second, one week prior to and after the occultation solar scans were made with the antenna set to approximately the same relative position with respect to the sun that were used on the seven central days of the occultation. This established any modification the different hour angles might cause and confirmed the way each part of the beam pattern would contribute to the profiles. Third, the right ascension and declination scans used to obtain the occultation measurements were extended in angular limits to a point where the sun could be observed as its separation from the Crab Nebula diminished and then as it increased. In this manner the change in solar flux from scan to scan could be determined.

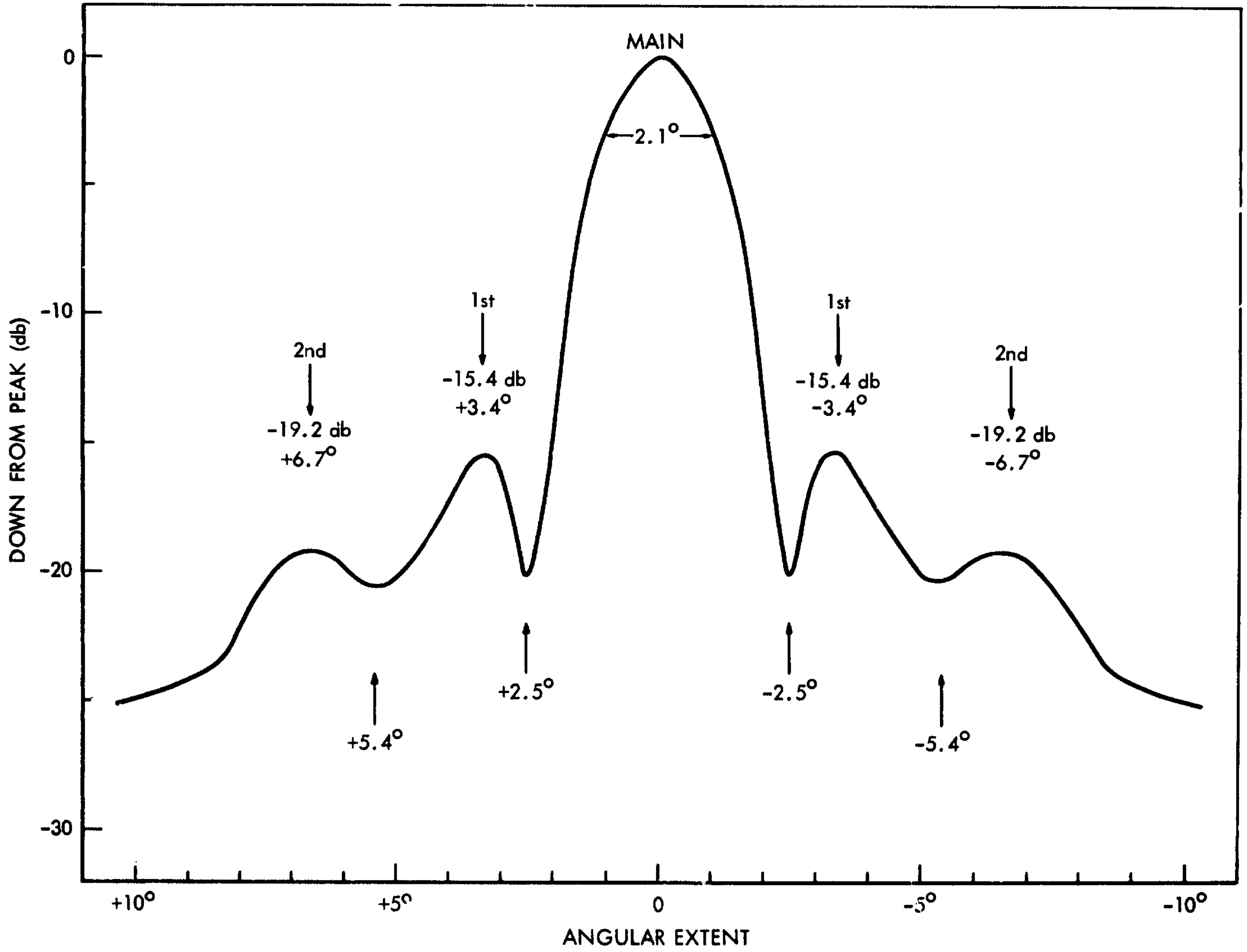

Figure 5. Beampattern 403 MHz

These three methods seem to form a complete picture of the solar contribution to the observed profiles. This picture remained fairly stable during the observation. They present a completely consistent picture of the antenna receiving pattern. During the observational period the solar flux at the observing frequencies was fairly constant with few bright regions of emission (see Figure 6). Those few instances of increased emission were apparently easily taken care of through the observational method employed.

Having obtained the solar contribution during each observation, the data was corrected then for this contribution. Each scan was long enough to include four sidelobes of the antenna pattern. The expected solar profile can be fitted then to those sidelobes (or main beam) not affected by power from the Crab Nebula. The excess radiation in the affected area of the pattern is attributed to the Crab Nebula.

The uncertainty in the subtraction is the main source of error in this measurement. The major contribution to the uncertainty in the heights of the restored Crab Nebula profiles is the placement of the baseline of the solar contribution. A secondary contribution arises from not being able to fit the observed sidelobes and main beam profiles due to short period variations in solar emission. Some additional uncertainty may arise from any asymetrical effects caused by the solar radio emission not being centered on the optical disk. Some attempt was made to allow for this effect but there was no improvement in the data, and the correction was eliminated as arbitrary.

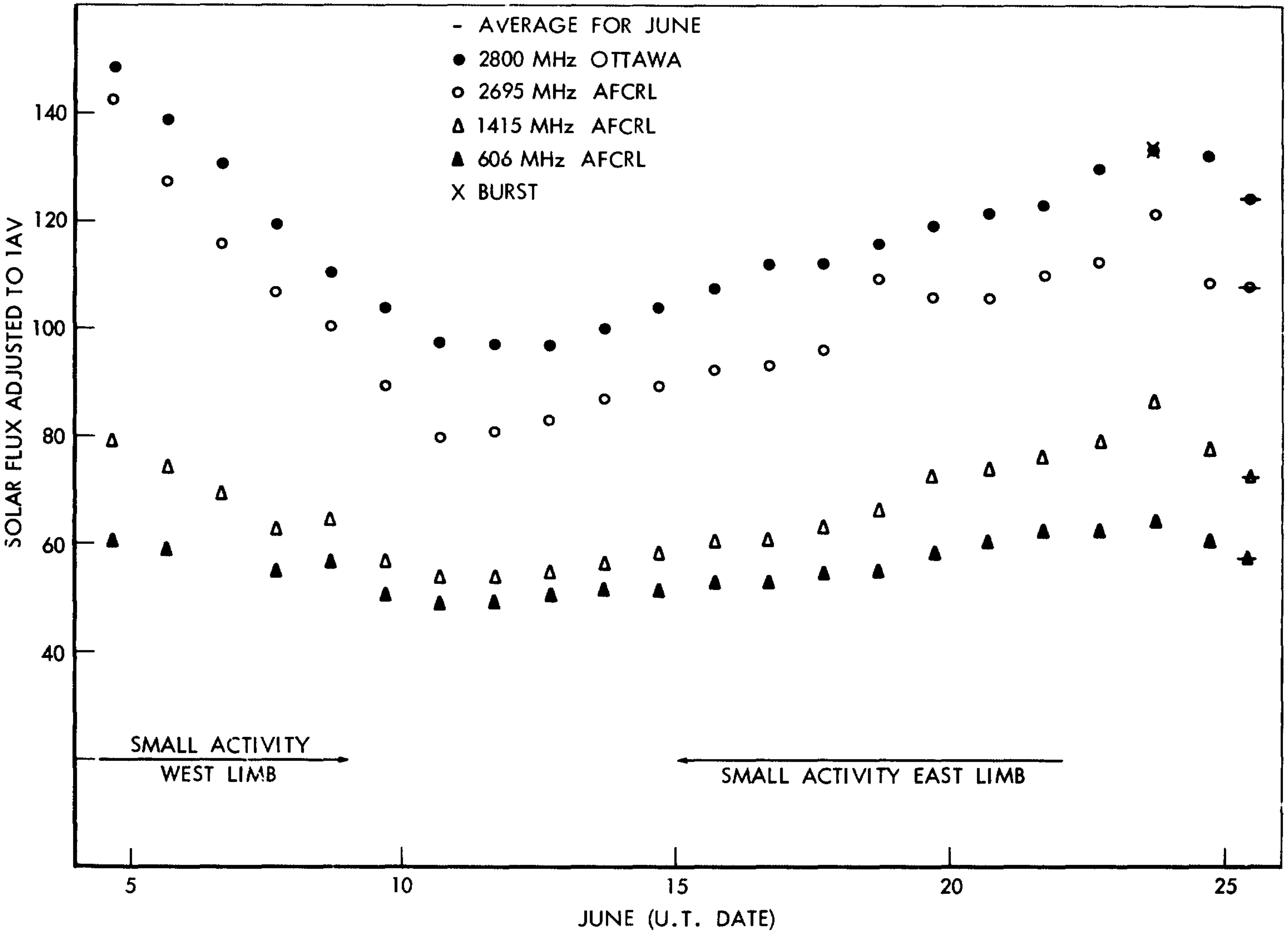

Figure 6. Solar Flux During Observation

The resulting Crab Nebula profiles have been corrected as indicated in Section III so that each profile is intercomparable with the others. The results for 403 MHz and 1705 MHz are shown in Figures 7 and 8. The 139 MHz data proved unreliable due to the solar contamination.

The bars shown on the graphs are not the error bars, but are the individual maximum and minimum values observed. Statistically, when not affected by solar contamination, the error bars are smaller. The solar contamination during the central days of the occultation, in most cases, removes this statistic advantage.

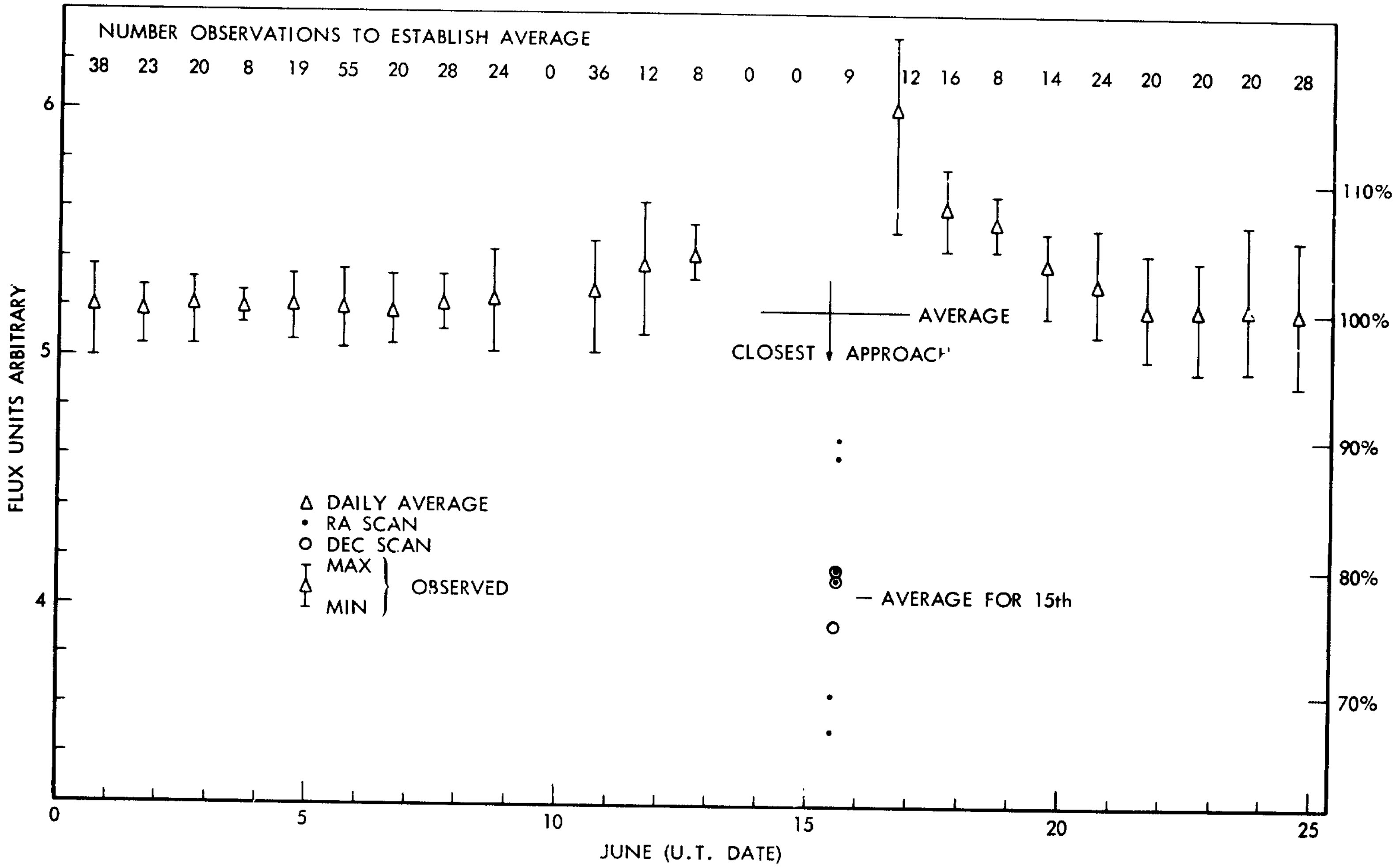

Figure 7. Change in Power from Crab Nebula at 403 MHz

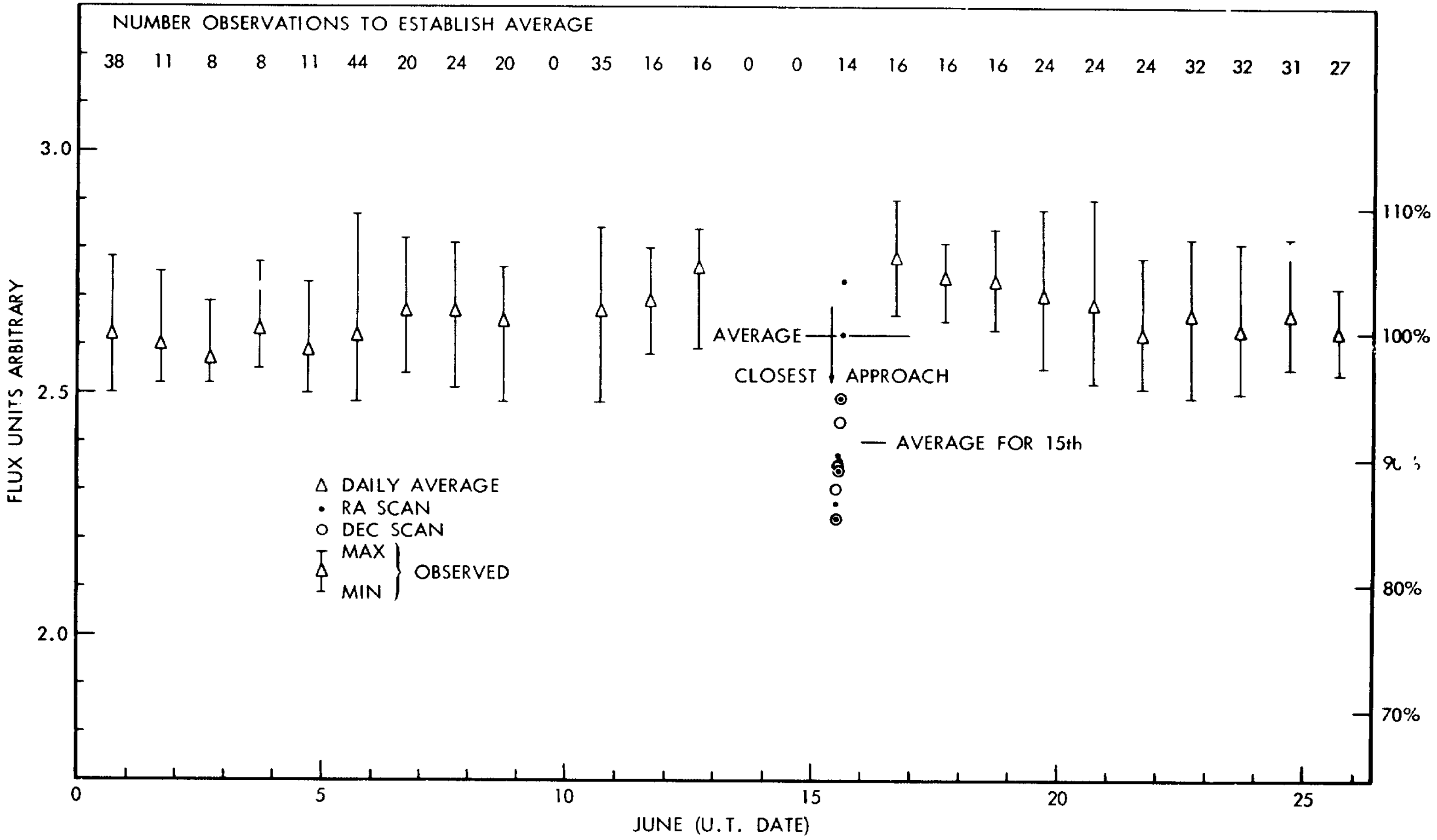

Figure 8. Change in Power from Crab Nebula at 1705 MHz

V. ERRORS

In analyzing the observational errors encountered in the observation, the constraints on the measurements must be reconsidered. First, the daily problems must be examined. Each individual measurement will contain errors. These errors are the result of a number of problems. Over a short period of time the system gain of the receiver will vary in both a random and systematic manner. Comparison with a standard noise source at the beginning and end of a measurement can eliminate any change which is linear in one direction; however, any other type of variation cannot be detected. The standard noise source power can also change and as a consequence adds to the error. These errors can compound during the process of moving the antenna over different areas of sky. Since the antenna points near the sun, heating in the feedbox area may introduce small errors also.

As mentioned previously in Section III, no systematic effect was detected during the day of each of the first eight pre-occultational days. The value of the probable error of these daily effects was determined by calculating the standard deviation of each individual right ascension or declination scan from the average value over the eight day period. The probable error was ± 2.5% and ± 4.5% for 403 MHz and 1705 MHz, respectively.

The second group of errors are the result of changes which occur on a day to day basis. Although there were no detected systematic changes during a day of observation, a systematic change in the calibration from day to day was noticed (see Section III). In order to obtain somewhat better data, this systematic change was eliminated by applying a single suitable correction to the observations taken each day. By measuring this correction a number of times each day, a probable error could be measured using the standard deviation of values from the daily average correction. The probable error was ± 3.5% and ± 4.0% for 403 MHz and 1705 MHz, respectively.

As previously discussed in Section III, the pointing errors of the antenna were investigated. The systematic errors in pointing were eliminated by a calibrated curve for the antenna. However, there still remained a random deviation in the pointing. The deviation in the static correction was 3 minutes of arc and 4 minutes of arc for the 403 MHz and 1705 MHz, respectively. This gives a total deviation of 7 and 8 minutes of arc, respectively. When compared to the antenna patterns, the probable pointing error is ± 1.5% of the response for the 403 MHz system and ± 6.5% for 1705 MHz.

Naturally, the main source of error in the observation is the solar contamination. The 403 MHz error is larger than that at 1705 MHz due to a larger beamwidth and a larger complement of sidelobes. At closest approach the sun was only slightly more than one-half beamwidth from the Crab Nebula. For 1705 MHz the distance was approximately two and one-half beamwidths.

In fitting the derived solar profiles to the composite profiles, not all of the structure could be exactly fitted due to unstable conditions in both the solar emission and the receiving equipment. In general, the correct fit was taken as that which most readily fitted the greatest portion of derived solar profiles. The probable error of this fit was then derived by rocking the profile about this average fit. The change in the subtracted value was then determined from these other reasonable fits. Naturally the maximum changes were on the day of closest approach, but since this varied little from the several days about closest approach this maximum was accepted as the most probable error. For 403 MHz this error was ± 4% while at 1705 MHz it was ± 5%.

By far the most serious problem with the fit of the derived solar profile is determining exactly where the solar contribution stops and that of the Crab Nebula begins. Naturally when the Crab Nebula contribution lies in a direction of rapidly changing response to solar emission, the slope assigned the baseline will greatly affect the emission assigned to the Crab Nebula. Similarly, if the Crab Nebula is near the maximum of a sidelobe response to the sun, one end (or even both) of the baseline could be blanketed to such an extent that it would be impossible to realistically assign a baseline much less a unique one. Again solar profiles were fitted in various ways to attempt assigning a probable error to this effect. The day of closest approach was accepted as most representative of this error. At 403 MHz a probable error of ± 10% was noted with ± 5% set for 1705 MHz.

In evaluating the various problem areas in this observation, strict measures were taken to assure the elimination of systematic errors. The nature of the solar contribution makes it quite susceptible to systematic errors; however, there is reasonable confidence that the errors are random in nature. Therefore, a probable error for the entire observation can be found in the standard statistical manner, being the square-root of the sum of the squares of each individual error. A probable error of ± 12% was found for 403 MHz and ± 11% for 1705 MHz.

VI. RESULTS

The resulting variation of the radiation from the Crab Nebula is very interesting. The results are unexpected when compared with proposed mechanisms acceptable at lower frequencies; however, the results are not unique and add weight to the previous disagreements of other observations.

The radiation from the Crab Nebula at 403 MHz was very stable until five days before and from five days after closest approach. At this time the apparent angular distance of the Crab Nebula from the center of the sun was 20 solar radii. During these five-day periods the radiation was enhanced reaching a maximum of 16% on June 16.3. The maximum preceding closest approach was not observed due to a faulty tracking servo on the antenna. The observed maximum occurred at 6.0 solar radii.

The time of closest approach, June 15.4 was not observable at the site due to horizon limitations; however, shortly thereafter a diminution of 30% in the flux was measured (June 15.5). The observed minimum occurred at 4.8 solar radii. Each succeeding observation showed less of a decrease. A decrease of less than 10% was measured before the source set. The following day found the flux enhanced.

The 1705 MHz results were very similar. The flux from the Crab Nebula remained fairly stable except for three days before and after closest approach.

This corresponds to an angular distance of about 12 solar radii. During this period the flux reached a maximum enhancement of 7%, June 16.0. This would correspond to an angular distance of 5.2 solar radii.

Similarly, a diminution of flux was observed shortly after source rise of 14%. The observed minimum occurred at a separation of 4.8 solar radii. Each succeeding measurement showed less of a decrease in the flux. The last measurements of the day, June 15.6 show that the flux had returned to the average value or was showing a trend toward the value of the maximum enhancement.

As stated before, even though the subtraction of the solar contribution could be subject to systematic errors, there is reasonable confidence that the errors are random. Thus from this point of view both the enhancement and diminution are real effects.

For 403 MHz the maximum enhancement was given as 16% ± 12% and the diminution as 30% ± 12%. Both of these values are sufficiently larger than their errors to be considered a consequence of some real physical effect. At 1705 MHz the diminution was 14% ± 11%, and was considered real as it was sufficiently larger than the error. The problem is not as clear for the maximum enhancement as the error exceeds the value found, 7% ± 11%. Based only on this evaluation of the experimental error, this enhancement cannot necessarily be considered real.

However, in the evaluation of the data any trends established or any variation in these trends may support the authenticity of the observation. Such is the case here. The pre-occultation data evaluated shows quite clearly that each individual data point bears no relation to the other data points. The scatter in the data appears quite random with no dependence on any parameters associated with obtaining the Crab Nebula flux. This complete randomness dissappears as measurements are made nearer the day of closest approach. In the case of the enhancements there is a systematic buildup in flux toward a maximum value with a decrease in angular separation of the sun and the Crab Nebula. This change to a systematic variation is vividly displayed in the diminution phase. As the source rises and measurements are taken at later hour angles, the flux increases steadily. This systematic change is even noticeable between the individual right ascension and declination scans in the steeper areas of the curve.

The instrumentation for this observation did not facilitate an investigation of either the variation of the diameter or apparent position of the source. Certainly any large changes could have been detected if they had occurred. A limit on the diameter of 30 minutes of arc at 403 MHz and 9 minutes of arc at 1705 MHz could have been detected. The detectable limit of the apparent position was 9 minutes of arc and 5 minutes of arc for 403 MHz and 1705 MHz, respectively.

It must be concluded from the above considerations that the observed behavior of the Crab Nebula flux as measured in this experiment is a reality. Whether or not this behavior is a correct representation of the radio emission of the Crab Nebula as modified by the solar corona is not uniquely determinable. However, one cannot but feel that it is a correct representation at the frequencies of 403 MHz and 1705 MHz and for the conditions in the solar corona at that time.

VII. CONCLUSIONS

Fortunately, the 1967 occultation was observed also by Ahern, Erickson, and Kundu (1968) at 234 MHz, 405 MHz, 750 MHz, and 1414 MHz. These observations tend to show results compatible to those in this paper at 139 MHz, 403 MHz and 1705 MHz.

At 234 MHz, the uncertainty in the solar subtraction rendered the data too poor for interpretation as was the case with the 139 MHz results reported here. The 405 MHz results were much more readily obtained as were our 403 MHz observations. Both observations show an enhancement and a diminution of the Crab Nebula flux. The 405 MHz enhancement was 13% compared to 16% ± 12% at 403 MHz. The maximum enhancement occurred at 5.3 solar radii as opposed to 6.0 solar radii reported in this paper. A similar situation is noted for the decrease as 25% is reported for 405 MHz against 30% ± 12% for 403 MHz.

The 750 MHz radiation was reported to be unchanged during the observation, but the 1414 MHz radiation may show a slight variation. This is consistent with the variation reported in this paper at 1705 MHz. Ahern et al. (1968) obtained their measurements through transit drift scans. The 1705 MHz results show that at the time such a drift scan would be made the flux level had returned to the pre-occultation level. It is felt that the 1705 MHz results of this paper are more clearly seen due to the statistical improvement of the larger sample of data.

A comparison with other observers in this frequency range shows a tentative similarity. Hughes et al. (1964) observed no effect at 6 cm which is consistent with an extrapolation from 18 cm (1705 MHz). The small variation found at 18 cm appears to be in disagreement with the non-variation found by Wyndham and Clark (1963), also at 18 cm, but such disagreement could be explained if contributed to differences in the 1967 and 1963 coronal properties. Such is not the case for the Basu and Castelli (1963) results. The inferred diameters of 20 minutes of arc at 10 cm and 25 minutes of arc at 25 cm would have been observable during the 1967 occultation. This effect was not observed and their results are not confirmed.

It remains to inquire into possible causes for the results which have been shown. The simplicity of the instrumentation must eliminate any effects of instrumental origin. The solar contamination is the most likely source of error and unfortunately is at its maximum during mid-occultation when the Crab Nebula shows its maximum variation. However, again it is emphasized that there is no reason to believe this correction was in error so that some physical cause must be sought.

At the time of this writing, no satisfactory physical cause has been found to explain the results. The most common failure of the theories proposed is the requirement of an electron density which is higher than that currently acceptable. The two most interesting theories are coronal scattering and uniform coronal refraction.

Coronal scattering results in a redistribution of the radiation into new angles and, depending on how it is redistributed, the result is either an increase or decrease in apparent flux (Erickson 1964). Radiation passing very near the solar surface will be strongly scattered; however, for the closest approach of the Crab Nebula the effect is much too small even for an enhanced electron density. At this time it does not seem that the occultation can be explained by coronal scattering.

Uniform coronal refraction will cause, in the absence of scattering, a bending of the radiation away from the solar surface (Bracewell and Preston 1956, Pawsey and Smerd 1953). This refraction will result in a shift in apparent position of the Crab Nebula and will cause an increase in apparent flux at the edge of an occulting disc through which radiation cannot transverse to the earth. This theory seems to predict the observed results very well with the exception of using a greatly enhanced electron density (James 1966). All reasonable coronal densities predict occultation radii which lie in the range of 1 to 3 solar radii for our high frequencies (Bracewell, Eshleman, and Hollweg 1969). In order for the occultation radii to be extended to the area of 5 solar radii the electron density must be increased much more than an order of magnitude. Therefore, coronal refraction effects fall short of explaining the results.

Despite the confused picture which is presented by the many observations of the occultation of the Crab Nebula, it is hoped that advancements have been made through the observations presented in this paper. Furthermore, it is hoped that this data can be used in future work on establishing a consistent observational basis for the theory.

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