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GEOPHYSICAL INSTITUTE
OF THE
UNIVERSITY OF ALASKA

ABERRATIONS OF RADIO SIGNALS TRAVERSING THE AURORAL IONOSPHERE

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INTRODUCTION

Program Objectives:

The primary objective of this research program is two-fold. The ultimate goal is to evaluate the effects of the auroral ionosphere on tracking and data acquisition capabilities of the NASA 85-foot antenna located in the vicinity of Fairbanks, Alaska. Since the most significant such effects are believed to arise from the irregular structure of the auroral ionosphere, an associated fundamental goal is to achieve a quantitative description of that structure and an insight int its nature and origin.

In regard to the first of the above objectives, the following three questions have been posed to the contractor by NASA:

1. How much attenuation can be expected in satellite signals traversing the auroral zones and received by the NASA 85-foot antenna on 136 Mc/s, 400 Mc/s, and 1700 Mc/s;

2. How frequently can said attenuation be expected and can it be predicted in advance;

3. What problems can be expected in autotracking procedures with the 85-foot antenna due to auroral ionospheric effects?

It seems advisable to comment on the physically meaningful interpretation of questions number 1 and 2. If the word "attenuation" is interpreted to mean an average decrease in signal strength during a given satellite pass due to ionospheric absorption, the immediate answer to question 1 is "practically none." Even under the most extreme conditions, absorption of a 136 Mc/s signal is likely to result in only a few tenths of a decibel decrease in signal strength. The effect at 400 and 1700 Mc/s is less in proportion to the square of the frequency.

Due to scattering by irregularities in the electron density of the ionosphere, however, comparatively very large fluctuations in the received signal strength, above and below the average for the pass, are to be expected. It is possible that large-scale ionospheric structure could produce an average decrease (or increase) in received signal strength, especially during a short satellite pass, due to ionospheric "defocusing" (or "focusing"). Based on experience with radio-star signals, however, the principal investigator believes that such occurrences would be very rare compared with fluctuations above and below an ionospherically unaffected average signal intensity. Consequently, in the work done on this contract, questions number 1 and 2 are being interpreted by replacing the word "attenuation" with the word "fluctuation."

Besides the prime objectives outlined above, there are certain additional objectives inherently implied by the primary ones. In particular there are the questions of how to predict the ionospheric effects under consideration and what to do with this and the other information obtained by the research program. The latter question is largely an engineering one, although the contractor will endeavor to provide the scientific foundation essential to its solution. The former question is fundamentally a scientific one and requires for its answer basic knowledge about the phenomena giving rise to the observed effects and in particular the relationship to other observable phenomena of the auroral ionosphere, including visible auroral displays.

The purpose of this report is to summarize the progress made toward achieving the above objectives during the first six months of this contract and to relate that progress to earlier work, including that done by the contractor under contract NAS5-1413. In preparation for such a summary, the methods being used will be reviewed briefly below.

Experimental Methods:

To attack the problem outlined above, the contractor has undertaken a two-pronged experimental program. The most extensive part of the program, experimentally, concerns the monitoring of radio-star signals beneath the auroral ionosphere with a compliment of radio interferometers. The measurements are intended to yield a description of the radio-star wavefront arriving at the ground after traversing the auroral ionosphere. This information, when obtained over a sufficient period of time (at least one year) and under sufficiently varied ionospheric conditions, can be applied directly toward answer of the questions described above. It also will be used to deduce a description of ionospheric structure. Associated with the radio-star measurements are other geophysical measurements, in particular of line-of-sight auroral luminosity and of local magnetic variation. These measurements are providing some insight into the production mechanism of auroral-zone ionospheric irregularities and hopefully will suggest means of predicting occurrences of significant radio scatter. In addition to the measurements being carried out directly by project personnel, the results of ionospheric measurements performed under other programs at the Geophysical Institute are being used.

The second aspect of the experimental program is direct inspection of satellite records currently being obtained at the NASA data acquisition facility near Fairbanks. Certain of these records are being compared directly with radio-star records to test the validity of conclusions about satellite tracking and data acquisition, which are or may be made from the radio-star measurements. These records also are beginning to yield information about ionospheric structure which is supplemental to that gleaned from the radio-star records, in particular the gross extent of irregularity patches.

SUMMARY OF PRELIMINARY RESULTS

Based on the first six-months work under this contract and on the results of earlier work done under contract NAS5-1413, the following tentative answers to the three major questions posed to the contractor by NASA and listed on page one of this report can be given:

1. No appreciable attenuation due to ionospheric absorption of satellite signals traversing the auroral zones and received by the NASA 85-foot antenna on 136 Mc/s, 400 Mc/s, and 1700 Mc/s is to be expected. However, possibly severe fluctuations in received signal strength above and below the mean level definitely are to be expected due to ionospheric scattering of the signal. The magnitude of these fluctuations at 136 Mc/s may be expected to extend from zero up to and possibly beyond 20 decibels, peak-to-peak, as measured on the DAF logarithmic AGC recording channels. Twenty-decibel fluctuations at 136 Mc/s might be expected to be accompanied by approximately ten-decibel fluctuations at 400 Mc/s and by fluctuations on the order of one decibel at 1700 Mc/s. (The frequency dependence of the fluctuations must be regarded as extremely tentative at this time.)

2. The occurrence frequency of scattering effects is a strong function of the solar activity cycle. It also exhibits diurnal and seasonal variations. The diurnal variation is rather constant throughout the solar cycle, with a strong predominance of nighttime over daytime scattering. The seasonal variation seems to evolve with the solar cycle, with equinoctial peaks predominating near solar minimum and with a broad winter-time peak predominating near solar maximum.

Inspection of 136 Mc/s AGC records from Numbus, obtained during the late summer and early autumn of 1964, revealed some evidence of ionospheric scattering as the satellite passed above the auroral-zone ionosphere on most nighttime passes. Typically these fluctuations measured less than 3 decibels, peak to peak, but on at least two occasions reached 20 decibels. A general increase in the frequency and severity of such events may be expected with the development of the new solar cycle now beginning, which will reach its maximum stage in 1968-69.

It is pointed out that the above statements refer to satellites whose signals traverse the auroral ionosphere. Currently, "the auroral ionosphere," in which most scattering takes place, appears to be situated most of the time somewhat north of Fairbanks. The scattering zone may be expected to expand as the solar cycle develops until, at solar maximum, it will include the part of the sky from the northern horizon to a few degrees south of the Fairbanks zenith. Farther south, the satellite results currently available are inconclusive. On the basis of visual auroral observations and radio-star measurements, however, one would expect decreased scattering to the south of Fairbanks except under conditions which are rare near solar minimum but less rare during solar maximum.

Concerning the possibility of predicting scatter conditions, of course, the only hope for complete reliability would be complete understanding of the scattering mechanism and of the nature and origin of the scattering irregularities. Baring this, a type of "prediction" might be based on observation of some geophysical phenomenon closely related to scattering. At present, available techniques hardly deserve the term "prediction" since they are likely to provide warning only minutes ahead of a satellite pass. The most promising such approach is to monitor auroral luminosity in the part of the sky across which the satellite is expected to pass. Recent radio-star observations have revealed a close relationship between visible aurora and radio scattering. The results appear to imply that the scattering is taking place directly from visible auroral forms, or from ion-density irregularities centered on the auroral forms and extending some distance away from them. This implication has been corroborated by Nimbus records obtained as the satellite line-of-sight passed through auroral displays recorded on the Geophysical Institute's all-sky camera.

The usefulness of auroral observations probably will deteriorate with development of the solar cycle. Work done by the contractor under contract NAS5-1413 showed that the degree of relationship between VHF-UHF scattering and visible aurora decreases toward maximum of the solar cycle. There appears to be a component of scattering irregularities directly associated with visible auroral displays which persists throughout the solar cycle, but a second component dominates the aurorally associated one near solar maximum. The second component may be due to the same originating mechanism as the first but lacking a clear-cut relationship to individual auroral events because of the general increase in auroral and geomagnetic activity near solar maximum. It may, on the other hand, be due to an independent originating mechanism. There is some evidence to support the latter view.

In either case, the only reliable means presently known for detecting the second component is radio-star or satellite scintillation observations. Use of radio-star observations for scattering prediction would depend upon further knowledge concerning the gross dimensions of irregularity patches. This question is under investigation in the present program. Other means of monitoring auroral-zone ionospheric structure could conceivably be put to use prior to the next solar maximum. To be useful for DAF purposes, such techniques would necessarily have to be sensitive to the existence of F-layer irregularities and preferably also to E-layer irregularities. A combination of ground-based and topside ionospheric soundings might provide the desired information. Currently, however, ionosonde recording and analysis techniques do not appear to be sensitive to the irregularities primarily responsible for auroral-zone VHF-UHF scattering. However, little work has been done on comparing radio-star scintillation records with topside soundings and such work could prove fruitful in this regard.

3. Not only does ionospheric scattering of radio signals produce fluctuations in the received signal strength but also in the apparent arrival direction of the signal. When a DAF system operates in program mode under such conditions, the fluctuation in arrival direction is detected as fluctuations in the servo error voltages. Only limited comparison of servo error recordings and radio-star records has been carried out to date, but deviations of a few degrees in angle appear to have been caused by ionospheric scattering on certain Nimbus passes. Under such conditions, attempts at autotracking would produce dish oscillations as the servo system tries to follow the fluctuating arrival direction. Under severe conditions of "angle" or phase scintillations, the tracking receiver also may lose phase lock. One suspected case of such an occurrence has been found on a 136 Mc/s Nimbus record obtained during conditions of extensive visible aurora.

Phase variations may be expected to follow the frequency-of-occurrence patterns described above for amplitude fluctuations, including an increase of occurrence and severity with development of the present solar cycle. Similarly, the discussion concerning possible prediction techniques holds for autotrack problems as well as for signal-strength variations. The extent of the effect under currently prevailing geophysical conditions has not yet been explored as far as has that of signal-strength effects.

Experimental progress has been made on describing the gound-level wavefront of scattered radio-star signals and the ionospheric structure responsible for the scattering. However, this aspect of the program has not yet progressed far enough to quote results. When results are available, they will be reported in the monthly progress reports. This work may be of direct use in evaluating the utility of ground-diversity techniques for enhancing DAF reliability in the auroral zone near solar maximum. It is definitely necessary as an empirical basis for understanding of the scattering process and of the nature of the scattering irregularities.

DETAILS OF FIRST SIX-MONTH'S PROGRESS

Theoretical Considerations:

The model used for describing the effects of ionospheric scatter on radio-star and satellite signals rests on the concept of an angular spectrum of plane waves whose phasor sum at any point in space yields the complex amplitude of the signal wavefront after scattering. This concept bears a close relationship to that of an antenna polar diagram. The mathematics involved is mainly that of Fourier transformation, with the Fourier partner of the angular spectrum being equivalent to the field distribution over the aperture of an antenna. The mathematical foundation for application of these concepts to the usual ionospheric case - that of a random aperture distribution - was given by Booker, Ratcliffe, and Shinn (1950). In this case, the spatial and angular dependence of the signal characteristics can conveniently be considered within the framework built by Rice (1944, 1945) for describing the temporal and frequency dependence of random noise signals.

In the more recent open literature, certain questions have been raised concerning the application of the above work to radio-star scintillation and, in particular, to radio-star visibility fades. (Visibility fades were defined and discussed in Sceintific Report No. 1 of contract NAS5-1413.) The importance of such fades to the ionospheric measurements being carried out under the present program prompted a reconsideration of these questions. A brief qualitative discussion of these considerations follows.

Description of the scattering of a signal from a small source above the ionosphere is conveniently commenced by considering the signal wavefront as it passes through an irregularly ionized layer. The irregularities in ion density produce differential phase shifts as the wavefront passes. Immediately below the layer, the distribution of complex amplitude across the wavefront is determined by the structure of the layer. The field distribution, according to the theorems of Booker, Ratcliffe, and Shinn, can be Fourier transformed into a spectrum of infinite plane waves, traveling in different directions. At any plane beneath the layer, the "beating" of these plane waves produces a distribution of complex amplitude which is, in general, different from that immediately below the scattering layer. At some distance from the layer, there are found to be irregularities in real amplitude as well as in phase even for a purely phase-changing screen. (The distribution of amplitude is often regarded as a "diffraction pattern" produced by the scattering layer.)

Given a large number of receivers and means for taking full account of the phase differences between all their received signals, one could measure the distribution of complex amplitude beneath such a scattering ionospheric layer at a given time. Alternatively, one could move a single receiver along the ground. If the layer retained its precise form for a sufficiently long time and if, again, one could maintain an accounting of phase, the spatial distribution of the complex field could be reconstituted from the temporal variation of the measured parameters. A Fourier transformation of the temporally varying signal would, of course, produce a frequency spectrum; this frequency spectrum could be related directly to the angular spectrum of the spatially varying field.

Neither of the above experiments is likely to be performed. If, however, the scattering layer itself drifts so that its complex amplitude distribution moves past a single receiving station, the second of the above experiments essentially can be performed. Such a sequence of events is thought to account for the scintillation of radio stars. A similar explanation can be invoked for the scintillation of satellite signals, where the necessary motion is produced primarily by that of the source rather than by that of the scattering layer. In either the radio-star or the satellite case, the observed modulation of the signal can be related to a spatial field distribution and the frequency spectrum of the former can be related to the angular spectrum of the latter. (To the extent that the scattering layer and its resulting field distribution change with time aside from simple drift motion, the degree of relationship between spatial and temporal characteristics and between the angular and frequency spectra is reduced.)

Complete reconstitution of the complicated field distributions produced by ionospheric scattering would be a formidable undertaking and one of questionable use for understanding the ionospheric processes involved or for evaluating propagation conditions. It is much easier and probably more useful to attempt a limited description of the statistical properties of such distributions. An important parameter for statistical description is the spatial autocorrelation function of the distribution, whose Fourier transform is the angular power spectrum. It can be shown that a phase-switch radio interferometer gives directly the value of the one-dimensional autocorrelation function for the antenna spacing employed. (See, for instance, Scientific Report No. 1, contract NAS5-1413.) This fact provides the basis for the experimental program being carried out under the present contract.

Let us consider briefly and qualitatively the information contained in the output of a phase-switch interferometer. It makes little difference whether the instrument is receiving a monochromatic satellite signal or a radio-star noise signal. In the latter case, the signal is rendered quasi-monochromatic by predetection bandwidth limiting, and the envelope fluctuations are averaged out by postdetection integration. In either case, the information contained in the output is the strength of the signals received at the two antennas and the phase difference between them. For a single plane wave, the phase difference is related simply to the arrival direction of the wave.

Suppose now that the phase difference reported by a phase-switch interferometer varies with time. The immediate interpretation is that the arrival direction of the signal is varying. We may study the phase variation and associated arrival direction as a function of time. Alternatively, as with any time-varying function, we may Fourier transform ourselves out of the time domain into the frequency domain. Now, as discussed above, if the phase variations are due to drift of an otherwise unchanging spatial distribution of phase, the resulting frequency spectrum is to be associated with an angular spectrum. Of course we must wait for some time before we can establish the frequency spectrum. But once it is established, we accept its existence at each instant of time even though only a single value of phase is measured at that instant. So also must we accept the existence of the angular spectrum at each instant even though only a single value of arrival direction is inferred at that instant.

There has been a tendency in the recent literature on scintillation studies to try to differentiate events in which a single plane wave of varying arrival direction is observed from events in which the simultaneous arrival of an angular spectrum is observed. The latter have variously been called "long duration fades" and "radio-star fadeouts." In Scientific Report No. 1 of contract NAS5-1413, they were called "visibility fades." (This last term is felt to be descriptive because such events may be explained in terms of a spreading of the angular spectrum as when the visibility of an optical source undergoing interferometric measurements is observed to decrease when the source is widened.) The intent of the foregoing qualitative arguments is to show that there is no fundamental difference between fades and more commonly observed scintillation. The difference is only one of degree.

The question has been raised, for instance, whether a visibility fade could be observed in the absence of ionospheric motion. The model here is that since the angular spectrum has spread, the observed visibility ought to be seen to decrease as in the case of radio-astronomy observations of radio-star angular widths. In the radio-astronomy case, the interferometer elements are separated more and more widely until the interferometer lobes are small compared with the angular width of the source, at which time the visibility is observed to decrease. In the ionospheric case, it might be argued, the ionosphere increases the angular width of the source by scattering, and the visibility ought to be observed to decrease. It must be remembered, however, that in the radio-astronomy case, the angular spectrum is produced by the source itself. Because of the short lifetimes of the individual radiation processes involved, the relative phases in the angular spectrum are reconstituted in times on the order of the coherence time of the received radiation. During any such time (on the order of the reciprocal of the receiver's IF bandwidth), a specific amplitude and discrete arrival direction of the signal would be reported by the interferometer. But always the signal is averaged over many coherence periods so that the true angular width of the source is measured.

In the ionospheric case, where short baselines are employed, the source before scattering is effectively a point. The ionosphere does indeed spread the point into an angular spectrum. But at any receiving site, the angular components add to give a specific amplitude and arrival direction until some ionospheric change has rearranged the relative phases in the angular spectrum. For a drifting but otherwise unchanging ionosphere, the observed angular spectrum phases are rearranged by the drift motion. Once again, if one had a large number of interferometers so that he could sample the field distribution over a large area of the ground under conditions of sufficient ionospheric scatter, an ensemble average of their outputs would show a visibility fade at any point in time. For a single interferometer, however, a fade can be observed only over a finite length of time during which the field distribution has drifted past the instrument. One then substitutes the time average observed with the single instrument for the ensemble average observed with the large number of instruments. How long one must wait to establish the visibility depends upon the rate of drift parallel to the interferometer baseline. Specifically, the average must be performed over a time long compared with any of the temporal phase variations - typically a few minutes for visibility fades observed in the past in Alaska. This time may be either long or short compared with the instrument postdetection time constant.

Since a phase-switch interferometer provides a measure of correlation between the two received signals, a visibility fade (i.e., a decrease in the average output) implies a decrease in that correlation. Thus a single interferometer or an ensemble of identical interferometers will record a visibility fade only when the autocorrelation distance of the received wavefront is comparable to or smaller than the antenna spacing. Now the collecting area of a single antenna acts like an ensemble of interferometers; thus if the wavefront structure becomes fine compared with the aperture of a single antenna, that antenna can suffer a visibility fade at an instant in time (or over a succession of such instants). Thus, while ionospheric motion (or other change) is required to produce a visibility fade on an interferometer of antenna spacing, d, a rough ionosphere could produce a fade, without motion, on a single antenna whose collecting diameter is d. This is not considered likely in reality but demonstrates a fundamental difference between interferometers and single antennas.

For an 85-foot antenna operating at 136 Mc/s and above, observable wavefront structure small compared with the aperture, whether stationary or moving, would appear to constitute an extreme condition of ionospheric scatter, indeed. Thus, visibility fades observed by the DAF system in Alaska probably need not be considered a significant problem. Recalling, however, that visibility fades are different from scintillation activity only in degree and that both phenomena may be described in terms of an angular spectrum, the observation of visibility fades by other means is important to the goals of this contract. Under conditions when visibility fades are observed on interferometers having spacings on the order of one hundred meters, significant amplitude and/or angle scintillation may be expected on the 85-foot DAF system. Under lesser conditions where scintillation is observed on an interferometer without significant visibility loss, scintillation is also to be expected on the DAF system; again the difference between scintillation and visibility fades is one of degree. The importance of visibility fades lies in their representation of severe scattering conditions and in the opportunity they afford for quantitative measurement of important scattering parameters.

The theoretical foundation for such measurements was laid by Bramley (1951, 1955), who explicitly combined the concept of an angular spectrum with the concepts of noise-signal analysis (Rice, 1944, 1945). It is to be noted that just as Rice's work concerns only noise signals, whose frequency components have a random distribution of phase, so Bramley's work concerns irregular wavefronts, the angular components of which have random distributions of phase. The assumption of random phases in the angular spectrum has far-reaching consequences on the interpretation of phase-switch interferometer recordings. In particular it is only for such an angular spectrum that the output of a single interferometer yields directly the spatial autocorrelation function (more accurately, one point on that function) during a finite observing time. By the same token, it is only for such a spectrum that a finite ensemble of instruments would yield the same information at a point in time.

There is no a priori reason for the ionosphere to produce a randomly phased angular spectrum although such spectra are commonly assumed. An experimental means of checking this underlying assumption is essential to the validity of the experimental results being sought in the present research program. A means of doing so is afforded by the phase-sweep interferometer, built by Boeing Scientific Research Laboratories, which is being used to supplement the phase-switch interferometers. The procedure consists of a detailed inspection of the statistical distributions of received amplitude and phase. At this point, let it suffice to say that such inspection is being carried out and so far has revealed that the signals received from radio stars after scattering in the auroral ionosphere usually do have randomly phased angular spectra. Exceptions to this usual case do exist and have significance in themselves, but they require further study before conclusions are drawn. For now, it is the usual case of random phases with which we shall be concerned.

Having demanded complete randomness of phases in the angular spectrum, we shall now, along with Bramley, allow ourselves one luxury of orderliness.

Specifically, let us permit one of the angular components to dominate over the others in amplitude. For now we shall say nothing about the distribution of amplitude or power in the remainder of the angular spectrum. This single component is equivalent, in Rice's analysis of random noise, to a sinusoidal signal in the presence of noise. In the spatial domain of the angular-spatial Fourier transform pair, it prevents the autocorrelation function from going to zero. Without inclusion of such a unique component in the angular spectrum our considerations would be restricted to autocorrelation functions which do reach zero. The ratio of the power in the unique component to that in the remainder of the angular spectrum represents the ratio of non-scattered to scattered flux in the received wavefront. In the case of backscatter rather than forward scatter, it would represent the ratio of specularly reflected to scattered flux; in the case of random noise theory, it would represent the power signal-to-noise ratio.

Having introduced the concept of a non-scattered or undeviated component in the angular spectrum let us return to the question raised earlier of a possible differentiation between events in which an angular spectrum and those in which a single plane wave of varying arrival direction is received. We concluded that the angular spectrum actually exists in both cases. As in any Fourier transformation, observation must be carried out over many variation periods (temporal or spatial) before a spectrum (frequency or angular) can be determined. Given a sufficient length of observation, then whether one thinks in terms of a single wave of varying arrival direction (and possibly of varying amplitude) or of an angular spectrum is a matter of choice. Under certain circumstances it may be convenient and informative to think in terms of both.

Consider, for instance, the case of ionospheric irregularities of some given average size superposed on a relatively much larger ionospheric structure. If one performs interferometer measurements over a sufficient period of time, he might determine the angular spectrum produced by the combination of large and small structure. Alternatively, it may be convenient to determine the spectrum arising from the small structure but to describe the effects of the larger structure in terms of time variations in the arrival direction of a "non-scattered" component, around which the scattered components are centered. If the large structure produces amplitude as well as phase deviations at the ground, both the non-scattered component and the scattered components would have to be allowed to change their amplitude with time. The latter effect could be ascribed to "focusing" and "defocusing" of all the angular components. If one is dealing with more than two distinct scales of ionospheric structure, of course, various combinations of the angular-spectrum and varying-ray concepts could be employed. It is to be noted that in no case can one discern the existence of structure small compared with the observing wavelength. Such structure gives rise to evansecent waves in the angular specturm, which attenuate rapidly during the propagation which follows the scattering process.

Radio-star observations being carried out under the present experimental program do show evidence, at times, of multiple-scaled ionospheric structure, especially on the lowest observing frequency, 68 Mc/s. A majority of the records, however, seem to show a preponderance of single-scale effects. The present quantitative measurements will be directed toward a description of such single-scaled structure under disturbed conditions. It is for such measurements that the work of Bramley provides a theoretical basis. The most pertinent of Bramley's results are contained in the following discussion.

Let $\overline{R}$ = the average amplitude of a phase-switch interferometer trace, which is also the value of the complex wavefront autocorrelation function for the antenna separation employed;

b = the ratio of the nonscattered to scattered flux received;

ρ = the value of the complex autocorrelation function of the irregular part of the received wavefront (produced by the scattered flux) for the antenna separation employed.

Then $\overline{R} = (b + \rho)/(b + 1)$.

An interferometer observing a radio star through a smooth ionosphere produces an interference pattern of constant amplitude, which can be taken as a reference for evaluating $\overline{R}$. That is, the quantity $\overline{R}$ is to be measured relative to the amplitude observed under nonscatter conditions, which is taken as unity. With interferometer baselines normally used (on the order of one or a few hundreds of meters) for VHF and UHF ionospheric studies, common ionospheric irregularities produce amplitude and phase scintillations without measurable decrease in $\overline{R}$. Under more severe scatter conditions, $\overline{R}$ becomes less than unity.

It will be noted that two conditions are required for the average amplitude of a phase-switch interferometer trace, $\overline{R}$, to go to zero. First, the autocorrelation function, ρ, of the irregular part of the received wavefront must be zero. That is, the antenna separation must be greater than the average "size" of a wavefront irregularity. Second, the ratio, b, of nonscattered to scattered flux must be zero. Thus the total correlation coefficient, $\overline{R}$, between signals received on two antennas - no matter how widely separated - will not go to zero if any fraction of the total flux is unscattered.

It can be shown that for randomly phased angular spectra, the distribution of real amplitude in the wavefront is normally distributed about its average value for sufficiently large values of b. (The normal distribution is a good approximation for values of b of about three or greater.) Under the same conditions, the distribution of phase in the wavefront is also normally distributed as is the distribution of phase difference between two points on the wavefront. In this case, Bramley has shown that the mean square deviation in phase difference is given by

$$\overline{\eta^2} = (1 - \rho)/b$$

By combining the expressions for $\overline{\eta^2}$ and $\overline{R}$, we can obtain the wavefront parameters b and ρ, as follows:

$$b = \left[\frac{\overline{\eta^2}}{1-\overline{R}} - 1 \right]^{-1}$$

$$\rho = 1 - b\overline{\eta^2}$$

If the ratio of nonscattered to scattered flux is close to zero, the distribution of amplitude in the wavefront approximates to a Raleigh distribution and the phase approaches an even distribution between zero and 2π. The distribution of phase difference in this case is rather complicated for arbitrary correlation, but Bramley has shown that the mean deviation in phase difference is given simply by

$$\overline{\eta} = \cos^{-1} \rho \approx \cos^{-1} \overline{R}$$

Experimental Considerations:

The foregoing discussion represents in a mostly qualitative way concepts required for statistical description, by experimental means, of a wavefront received at the ground after ionospheric scattering. A more detailed mathematical review of the development of these ideas and a generalization of them will be presented in a later report. For now, let us use the first special case described above to illustrate the measurements made possible by employing them.

First let us note that $\overline{R}$ is obtainable directly from the output of a phase-switch interferometer and $\overline{\eta^2}$ from a phase-sweep interferometer of the Boeing type. If these two instruments are operated at the same frequency and spacing, then the wavefront parameters b and ρ can be determined for that frequency and spacing. Now b represents the ratio of nonscattered to scattered flux and is not a function of antenna spacing. The autocorrelation, ρ, on the other hand, is a function of antenna spacing. The dependence of ρ on spacing, s, can be determined from the constant b and the spacing-variable $\overline{R}$ if additional phase-switch interferometers of different spacings are employed. Under the present experimental program, three spacings are employed at 68 Mc/s. Thus, three points on the autocorrelation function of the 68 Mc/s wavefront can be determined from the following relation:

$$\rho(s) = [\overline{R}(s)] [b + 1] - b$$

Experimental determination of b and of three points on the autocorrelation function provides a sound basis for estimating the correlation to be expected between signals received by antennas of arbitrary separation.

The measurements alluded to above also provide a means of checking certain models which have been proposed for the distribution of ionization in ionospheric scattering layers. Certain parameters of the ion distribution, such as the average size of an irregularity and the "optical depth for scattering" of the layer can be determined. In the proposed models, the optical depth for scattering is a simple function of observing frequency. Thus, determination of this parameter for several frequencies will allow a check on the supposed frequency dependence of the scattering process. This information is of considerable importance to DAF operations as well as to understanding of the ionospheric processes involved in scattering. For this reason, phase-switch interferometers also are being operated at 136.5 Mc/s and 223 Mc/s.

The phase-sweep interferometer being operated at 68 Mc/s with an east-west spacing of 220 meters yields continuous and independent amplitude and phase information, whereas the phase-switch interferometers yield a mixture of amplitude and phase information. From detailed analysis of the phase-sweep records, certain information can be gleaned which is obscured in the phase-switch records. First, the sta stical distributions of amplitude and phase allow a determination of whether the phase relationship in the angular spectrum is random or ordered. This information provides a check on the assumption underlying Bramley's work and is essential to validity of the measurements discussed above. Second, a comparison of the temporal autocorrelation function of the phase-sweep records with the spatial autocorrelation function determined by those measurements can yield information on the drift rate of scattering irregularities and on the changes they undergo as they drift. Third, comparison of the phase and amplitude records when combined with the results of fade measurements can yield the height of the bottom of the scattering layer.

During the first six months of this contract, observations necessary for the above measurements have been carried out with useful regularity. Record analysis, data reduction, and quantitative computation, however, have progressed slowly. It is intended to give emphasis to this aspect of the work during the next few months. Meanwhile, routine scaling of phase-switch interferometer results will be continued for comparison of present results with those obtained at other phases of the solar activity scale. Such relative results will be combined with the quantitative ones to provide a basis for estimation of ionospheric scattering effects on the DAF system near solar maximum.

The magnitude of solar-cycle variation in scintillation activity is suggested by Fig. 1, which was discussed in detail in monthly progress report number 1. Fig. 1 shows the monthly mean values of the mean fractional deviation in power received at College from the radio star Cassiopeia A at 223 Mc/s during the solar maximum period of 1957-58 and the year of waning solar activity, 1962. The general decrease in scintillation activity between solar maximum and 1962, especially during the winter months, is obvious. As was discussed in progress report number 1, the small amount of seasonal variation which appears in the 1962 histogram consists of equinoctial peaks and solstical minima. This is quite different from the winter-peaking pattern of the 1957-56 plot. If corroborated by the 1963 and 1964 records, whose scaling is now complete, this change in seasonal characteristic may imply the existence of two independent production mechanisms for scattering ionospheric irregularities.

Another change in auroral-zone scintillation with the solar cycle was reported earlier: an increase in degree of relationship with visible auroral displays with wane of solar activity. The rather direct relationship between radio-star scintillation and near-line-of-sight auroral intensity in March of 1964 is shown in Fig. 2. The four curves show the dependence of the mean fractional deviation in power received from a radio star and the intensity of auroral luminescence near the radio line of sight. The solid curves relate the hourly averages of mean fractional power deviation to hourly averages of auroral intensity; the broken curves relate the hourly peaks of the mean fractional power deviation (averaged over five minutes) to the hourly peaks of auroral intensity. The relationship depicted in Fig. 2 is expected to hold only near solar minimum. Based on radio-star records taken during the IGY, it is expected that scintillation activity will become less closely associated with visible aurora as the new solar cycle develops. This may be due to a second production mechansim for ionospheric irregularities, which is unrelated to the aurora and which has a strong solar-cycle dependence.

A characteristic of radio-star scintillation which is retained throughout the solar cycle (at middle latitudes as well as in the auroral zone) is its diurnal variation. Scintillation is predominantly a nighttime phenomenon, peaking statistically within a few hours after local midnight and minimizing (though not at zero) near midday. As a means of verifying the inospheric origin of suspected amplitude scintillation on satellite records obtained from the Gilmore Creek DAF, a similar diurnal variation was sought. This procedure was reported in progress report number 4, where it was concluded that fast fluctuations in AGC voltage observed at 136 Mc/s resulted from ionospheric scattering. Examples of these fluctuations, whose periods are on the order of one second or less, are shown in Figs. 3 and 4. Fig. 3 presents exar _es of daytime records and Fig. 4 of nighttime records. The expected preponderance of nighttime over daytime amplitude scintillation is illustrated expecially by comparison of the most disturbed records on the two figures.

As further evidence that the fast amplitude fluctuations observed at 136 Mc/s by the Gilmore DAF are of ionospheric origin, Figs. 5 and 6 are presented. These figures give examples of AGC records obtained, respectively, during an extended period of geomagnetic calm and during a period of moderate geomagnetic activity. There is a definite increase in fluctuation with increase in magnetic activity. While College K index was used as an indicator of magnetic activity in selecting the records of Figs. 5 and 6, it was used only in an average way over 30-hour periods. Thus the figures do not necessarily imply that K index itself is a reliable indicator of scatter conditions over shorter periods.

A much more detailed relationship appears to exist between line-of-sight visible aurora and satellite amplitude scintillation, which is consistent with radio-star results. An example of the relationship is presented in Fig. 7, which shows the beginning (northern) and ending (southern) segments of a 136 Mc/s AGC recording along with an all-sky photograph taken midway between them in time. The all-sky photograph shows considerable aurora in the northern half of the sky and none in the southern half. The upper AGC record, which corresponds in time to passage of the satellite line-of-sight through the northernmost auroral arc, shows marked fluctuations. The lower record, corresponding to a period of comparable ionospheric path-length through the auroral-free southern sky, shows no fluctuations.

A direct auroral influence on variations in apparent arrival direction of satellite signals was reported in progress report number 6. Because of the small number of such events which have been studied in any detail, examples will not be given here. All of the results reviewed in Figs. 1 through 7 of this report are supported by considerable collections of data.

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Bell System Tech. J., 24, 46 - 158, 1945.

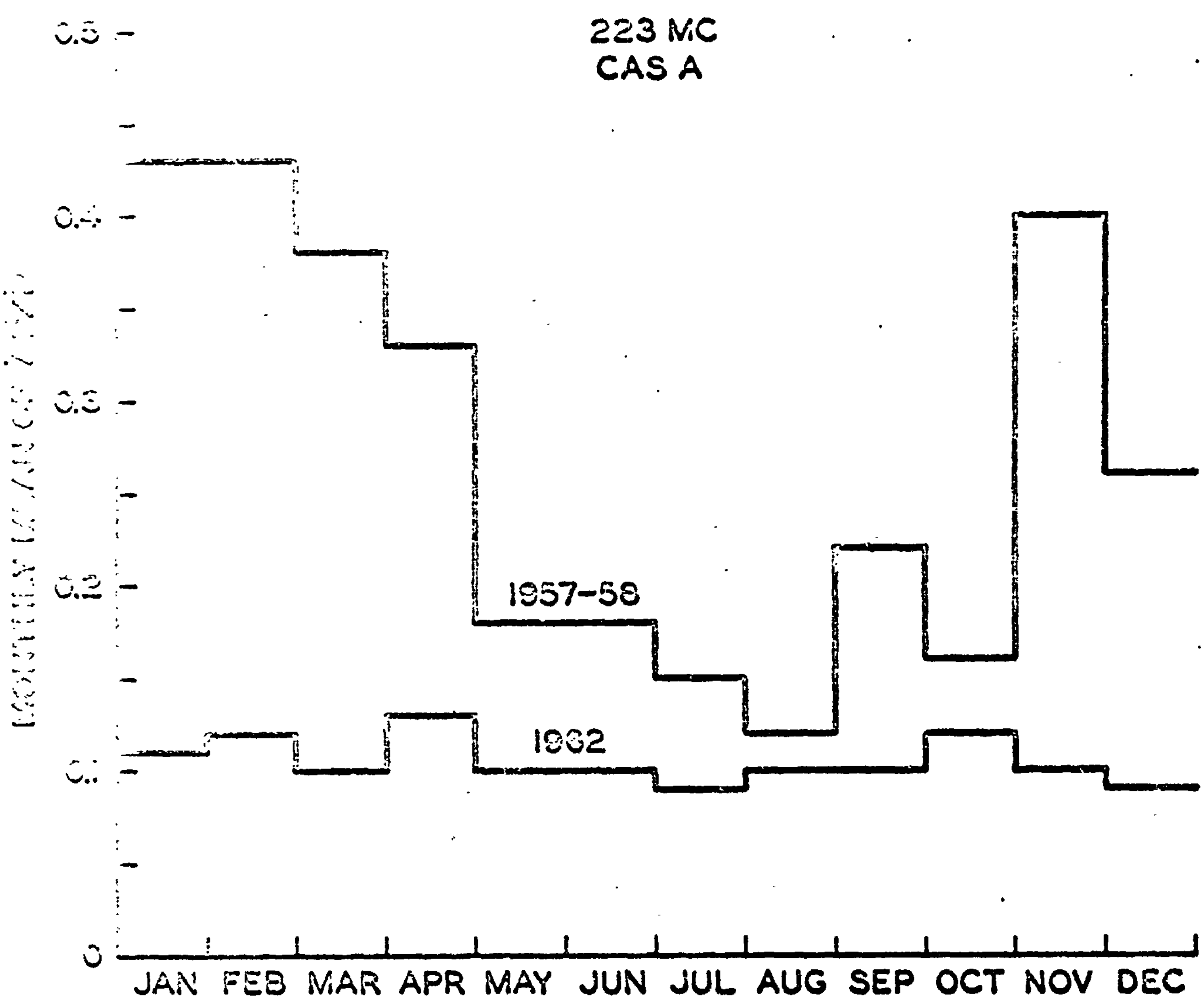
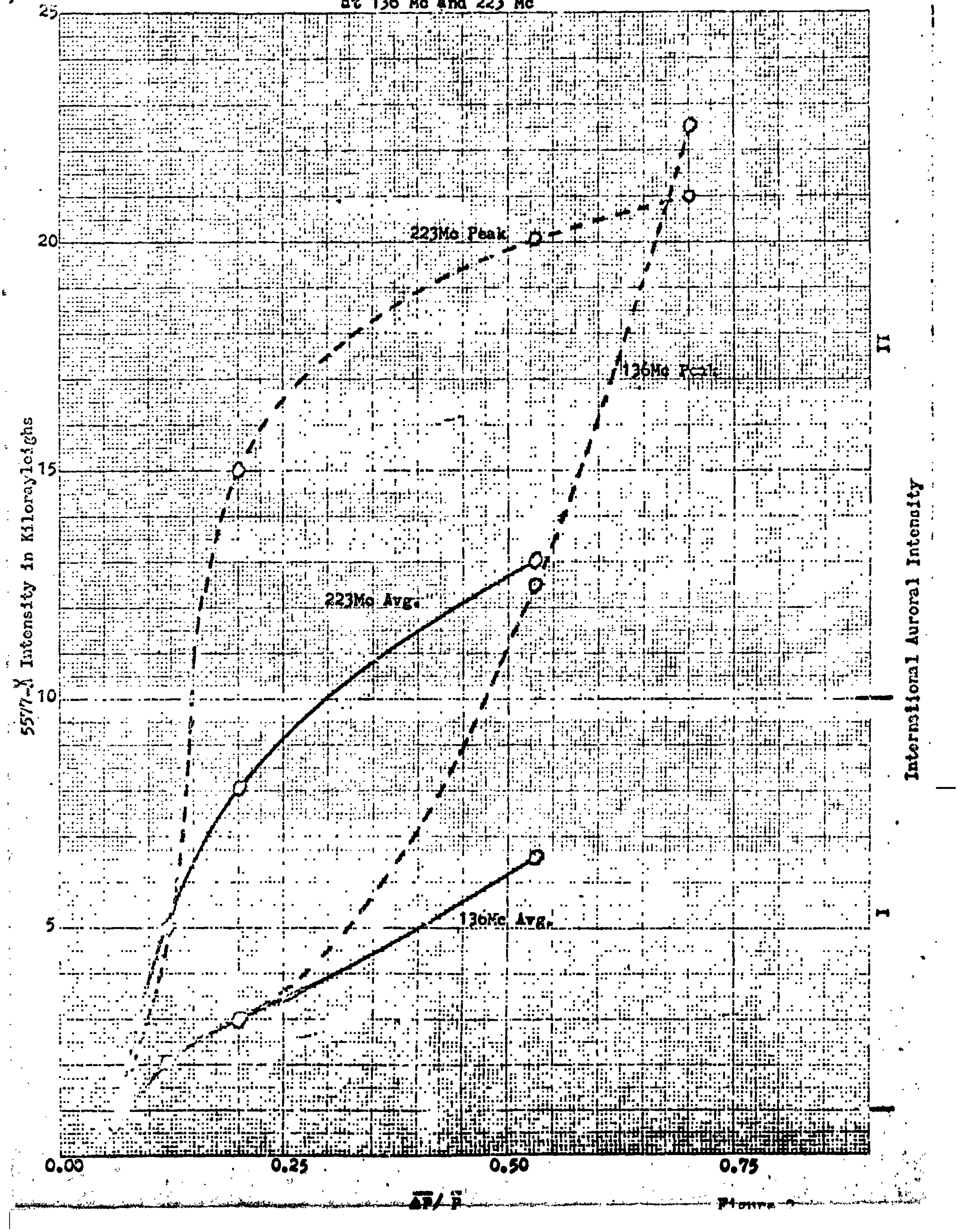

223 MC
CAS A
0.5
0.4
0.3
0.2
0.1
0
1957–58
1962
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

Figure 1

Intensity and Radio Star Scintillation
at 136 Mc and 223 Mc



AGC Records from Three Daytime Nimbus Passes

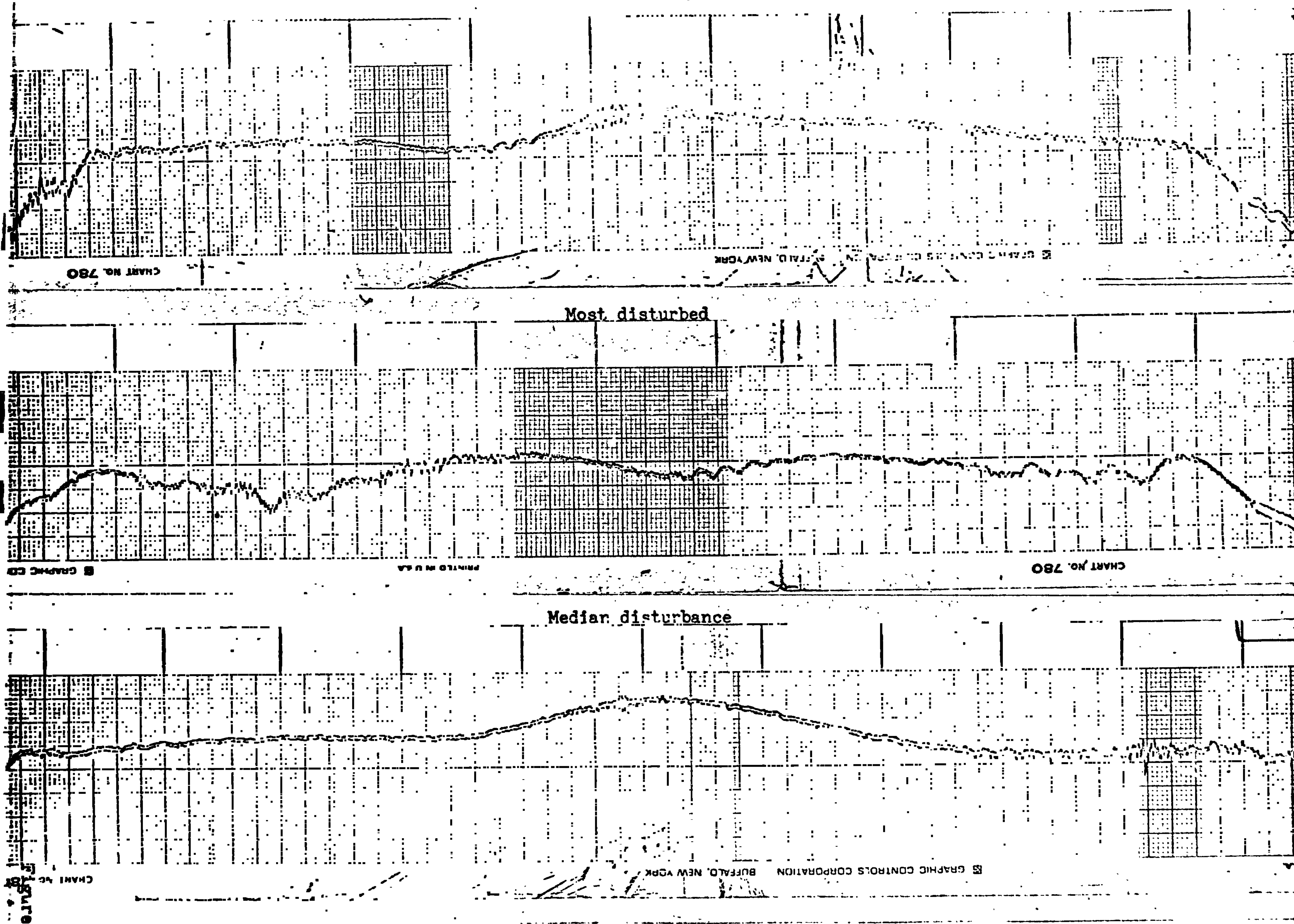
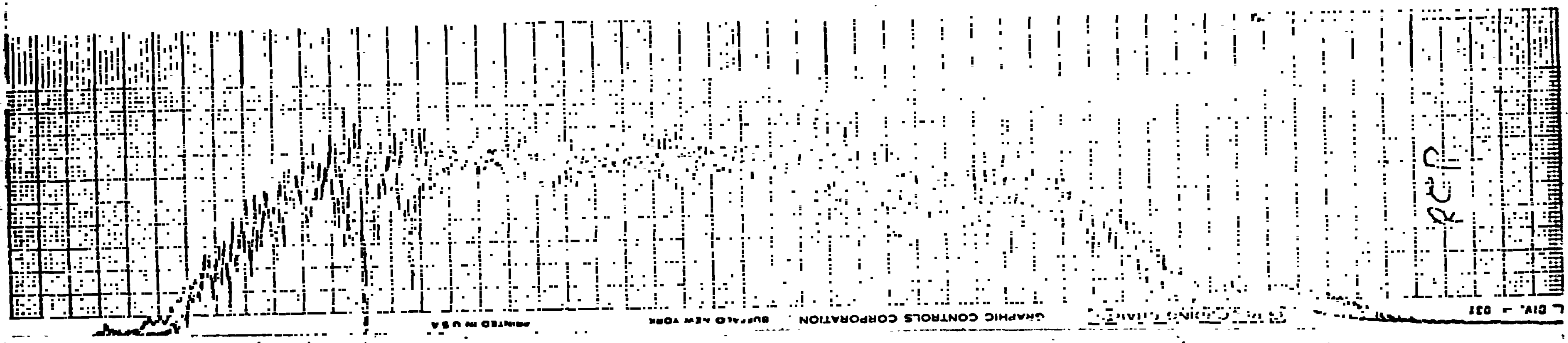
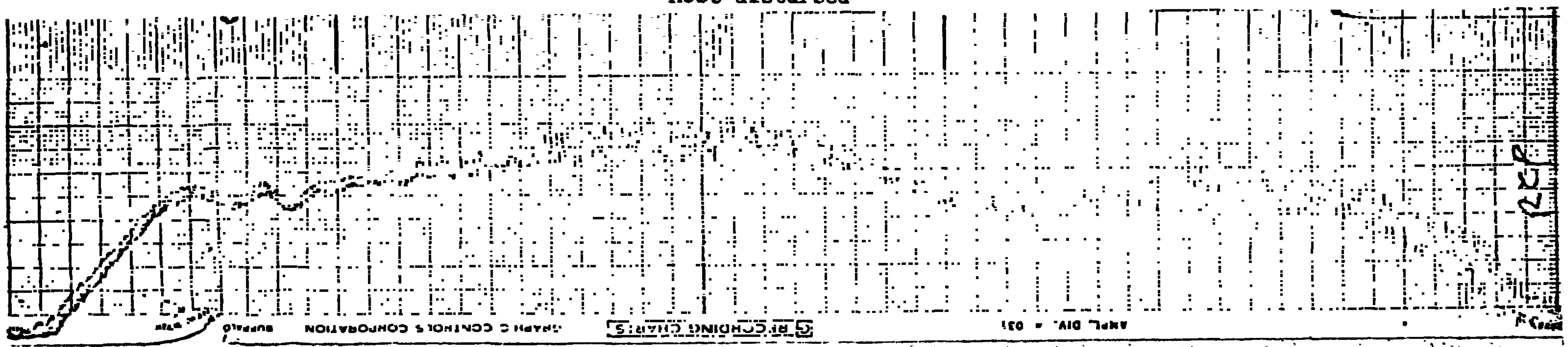


Figure 3

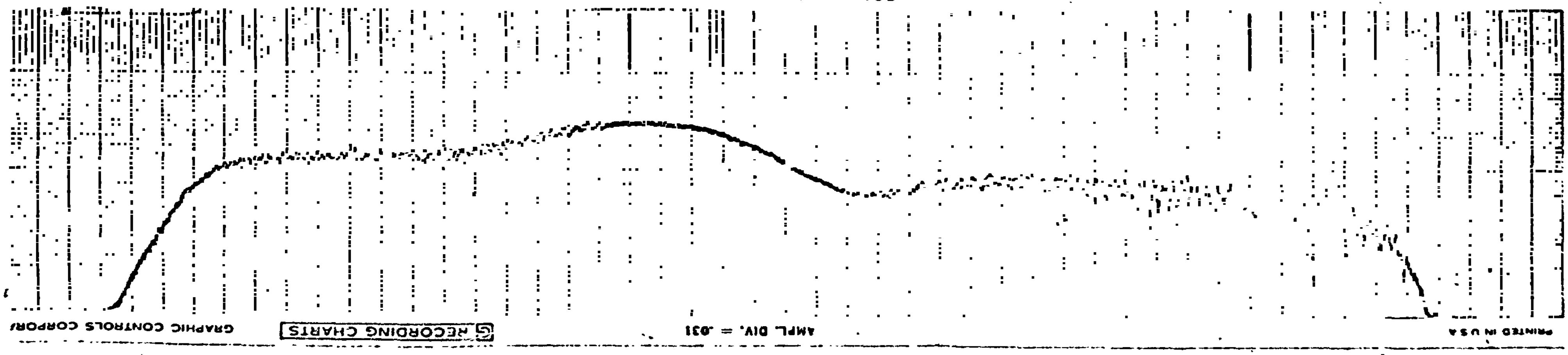
AGC Records from Three Nighttime Nimbus Passes



Most disturbed



Median disturbance



Least disturbed

Figure 4

Three 136 Mc/s AGC Records
from Nimbus
on a Geomagnetically Quiet Day

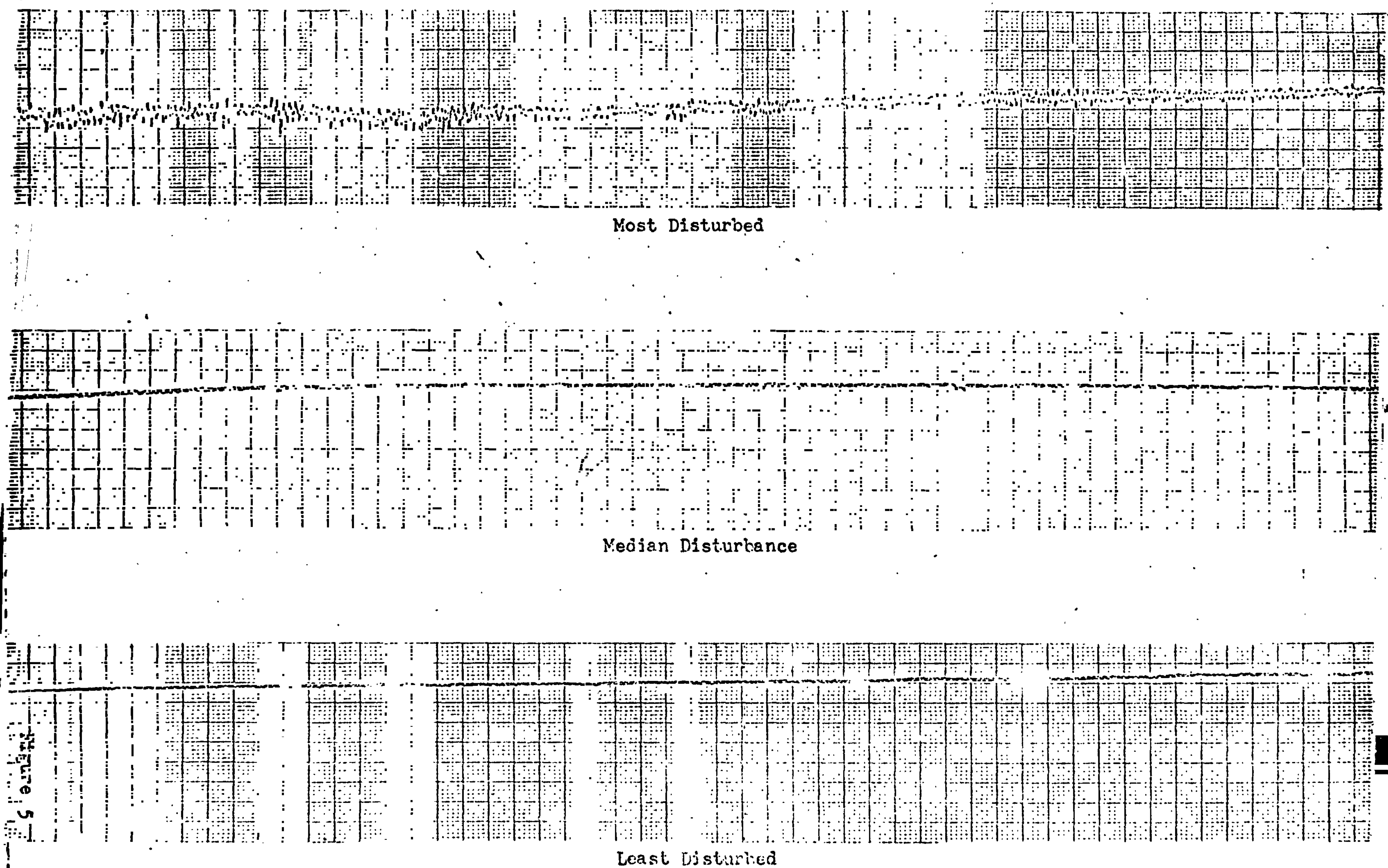
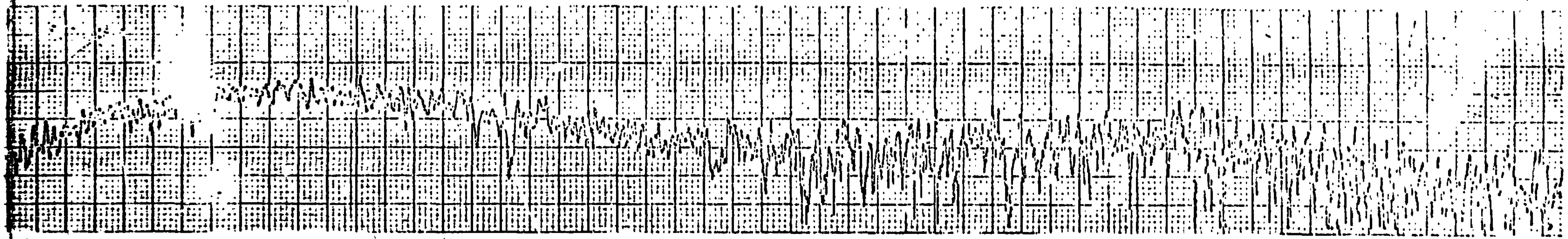
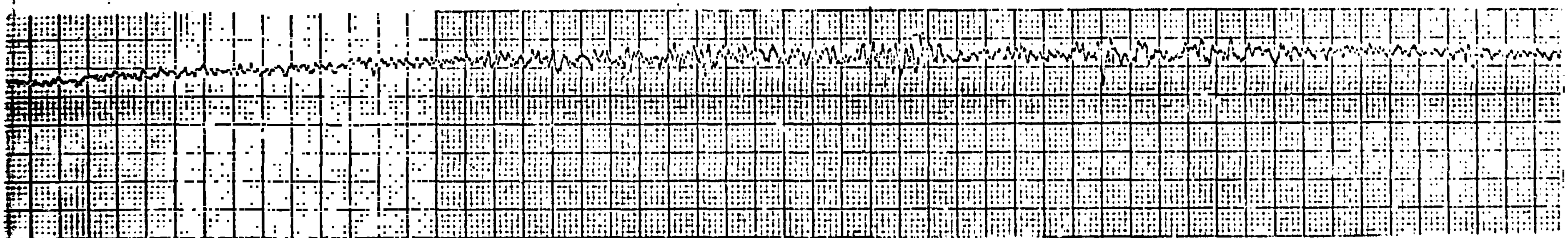


Figure 5

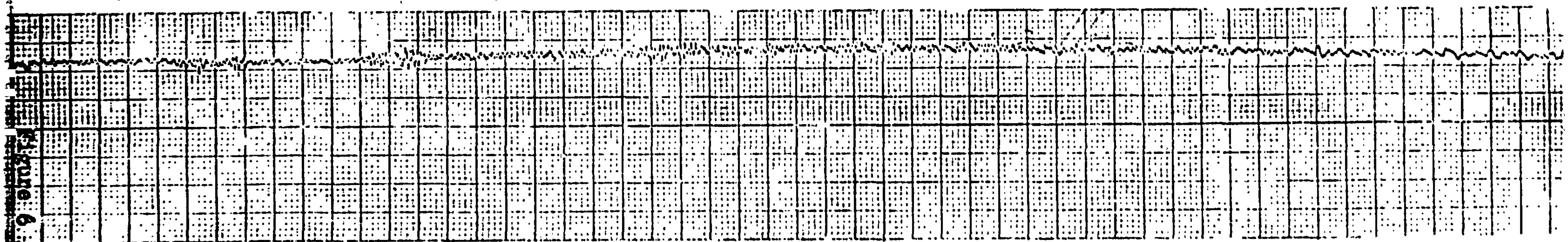
Three 136 Mc/s AGC Records
from Nimbus
on a Day of Moderate Geomagnetic
Activity



Most Disturbed

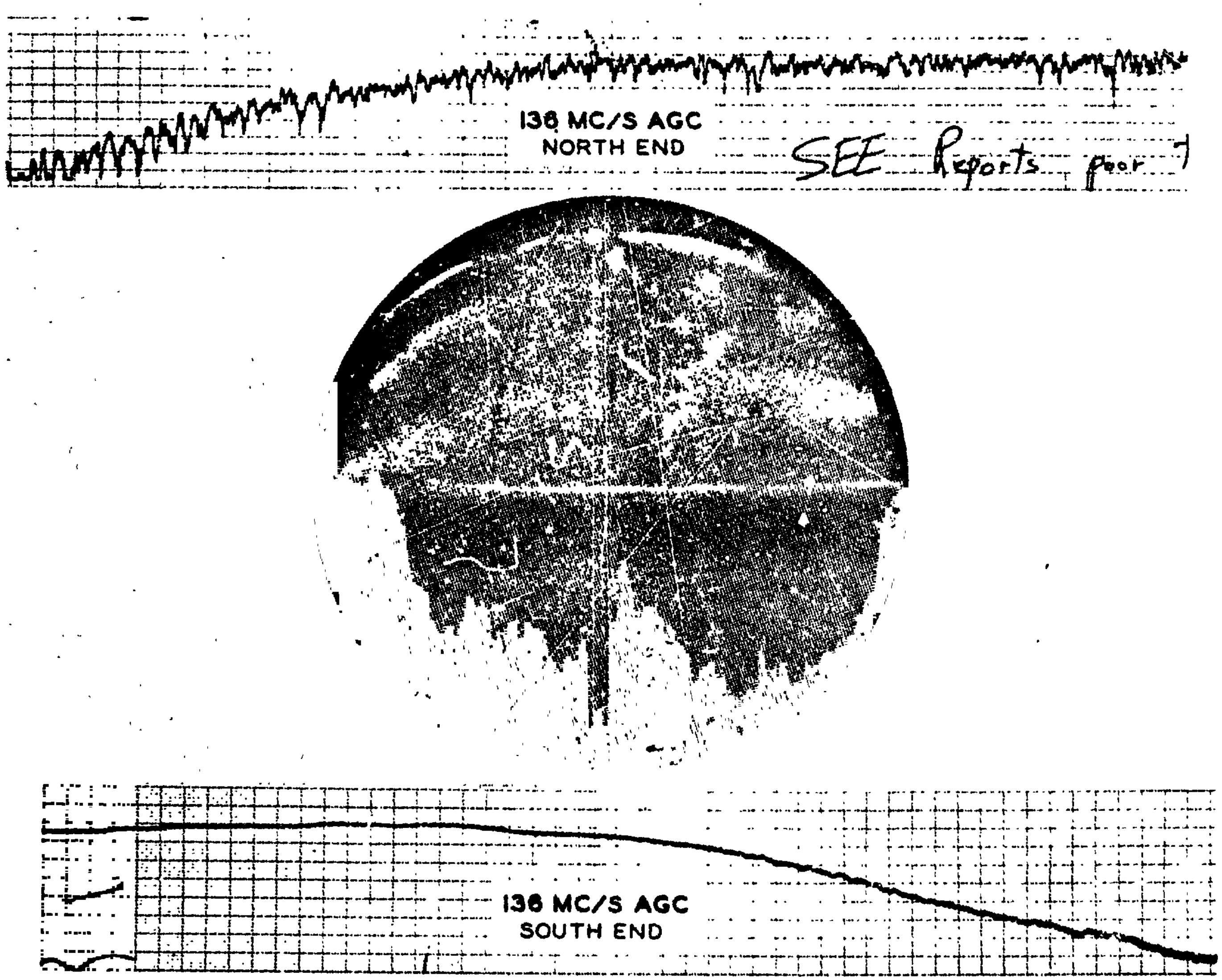


Median Disturbance



Least Disturbed

Figure 6.



Nimbus Orbit 280. North-South Pass over Gilmore Creek DAF.

Figure 7

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