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# COMPARISONS BETWEEN TOPSIDE AND GROUND-BASED SOUNDINGS

J. E. JACKSON



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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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J. E. JACKSON

NASA/GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

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# COMPARISONS BETWEEN TOPSIDE AND GROUND-BASED SOUNDINGS

by

John E. Jackson
Laboratory for Space Sciences
NASA Goddard Space Flight Center
Greenbelt, Maryland

## ABSTRACT

Past observations, indicating that electron density profiles derived from topside ionograms have a tendency to be slightly too low, are reviewed and discussed. This problem is then examined in the light of more recent and better controlled experiments in which vertical electron density profiles were obtained essentially simultaneously by topside and ground-based soundings. These new measurements confirmed past observations and indicated that the error had a tendency to increase with satellite altitude. From a study of the ground echoes, which are often seen on topside ionograms, it is shown that the above discrepancies can be partially attributed to systematic errors (0 to + 30 km) in the topside ionogram height markers. Horizontal electron density gradients can also contribute to this discrepancy. The errors found in the N(h) profile (although systematic) are usually too small to detract significantly from the general usefulness of topside ionograms. Also, the portion of the error due to incorrect height markers can often be calculated from a ground trace analysis and the ionogram data can be corrected accordingly.

# COMPARISONS BETWEEN TOPSIDE AND GROUND-BASED SOUNDINGS

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J. E. Jackson

NASA/Goddard Space Flight Center

## INTRODUCTION

This paper is an interim report on a problem which has puzzled the users of topside ionograms since the early days of Alouette I, namely the fact that electron density profiles derived from topside ionograms appear to be slightly too low.

This discrepancy was noticed, prior to the present study, when Alouette I N(h) profiles were compared to measurements provided by ground ionosondes, rocket tests and the incoherent backscatter technique. Although none of these observations could be considered conclusive by itself (due to various experimental limitations), the collective evidence provided by the various types of comparisons seemed to indicate that the Alouette I N(h) profiles were indeed too low. The present investigation was therefore undertaken to determine whether or not the discrepancy was real, and to explain this discrepancy if it substantiated under a more careful examination.

It should be pointed out that this relatively small error has not detracted significantly from the great usefulness of the very unique electron density distributions which have been obtained with the topside sounders. This is perhaps the main reason why the problem has received only sporadic attention from 1962 to 1967.

## EARLY OBSERVATIONS

### 1. Statistical Data on hmaxF2

The altitude of maximum electron density, hmaxF2, is a parameter which theoretically can be derived from either ground-based or topside soundings. Since much of the present paper is based upon comparisons at hmaxF2, an assessment of hmaxF2 measurements is quite pertinent to the discussion.

Based upon considerations given in appendix A, it can be stated that the routine reduction of ionograms should yield values of hmaxF2 which are typically 10km too low for ground-based soundings and typically 10km too high for topside soundings. The above statement assumes that the ionograms are of good quality, free of instrumental errors and obtained under condition of vertical propagation. It is also assumed that the conventional ionogram analysis techniques are valid.

The most accurate and extensive data on hmaxF2 are the noon mid-latitude values of this parameter (Thomas 1957, Becker 1967 and Wright 1962b). The published data, however, contain systematic errors, due primarily to various time saving procedures which had to be used in order to process vast quantities of data. To the author's knowledge a complete and up to date assessment of these errors is not available. For example, Schmerling (1960) pointed out that the hmaxF2 values published by Thomas (1957) were much too low, but he did not discuss the error quantitatively. The E-Valley effect (See Appendix A) was demonstrated quite dramatically by Titheridge (1959), and illustrated in a number of more recent papers (See, for example, Wright 1967). Yet the E-Valley has been ignored in statistical studies. A numerical assessment of these systematic errors can be made (See Appendix A) by making use of information published by Becker (1967) and Herbert (1967).

From a study of the above-mentioned statistical surveys (See Appendix A), one would expect that the Alouette I hmaxF2 values (i.e. lowest point on N(h) profile) should be at least 240 $\pm$ 15km in the Northern hemisphere, for magnetic dips between 67 and 74 degrees, at mid-day, in December, and for low sun-spot numbers. The above location and time requirements were met by the Alouette I day-time observations during December 1962 for latitudes between 35$^{o}$N and 45$^{o}$N and for longitudes between 60$^{o}$W and 90$^{o}$W. The longitude restrictions were imposed by the available data and the latitude range was selected to yield magnetic dip values between 67 and 74 degrees.

The values of hmaxF2 shown in table I were taken from the Alouette I N(h) tables published by DRTE for December 1962 and for the selected geographical area. The table is based upon the best N(h) data, i.e. it shows all the available data for which the DRTE quality index is either 4, 5 or 6. Also indicated in the table are the Local Mean Time (LMT), the magnetic index (Kp) and the Zurich Sun-Spot Number (Rz). The 31 measurements of hmaxF2 shown in the table have an average value of 212km and a standard deviation of 14km. This standard deviation is about the same as the standard deviation for the ground ionosonde data, but the average value of hmaxF2 is 28km less than the expected value of 240km. It is also seen on Table I that the quieter days (Kp=7, 10, 12) and the more disturbed days (Kp=24, 37) yield comparable values of hmaxF2.

| Day No. 1962 | LMT | Kp | Rz | hmaxF2 (Quality Index) | | | |
|---|---|---|---|---|---|---|---|
| 336 | 1330 | 7 | 29 | 212(5), | 210(4), | 202(4), | 192(4) |
| | | | | 200(6), | 199(5), | 205(5), | 206(4) |
| 343 | 1230 | 12 | 25 | 204(6), | 192(6), | 204(5), | 204(5) |
| | | | | 199(6), | 214(6), | 213(5) | |
| 347 | 1200 | 24 | 18 | 211(6), | 230(6), | 215(6), | 219(6) |
| | | | | 216(6), | 215(5), | 226(6) | |
| 352 | 1100 | 37 | 23 | 211(4), | 220(6), | 183(6), | 230(5) |
| | | | | 237(5), | 241(5), | 240(4) | |
| 363 | 1000 | 10 | 0 | 200(6), | 232(6) | | |

Table I Mid-latitude, Mid-day values of hmaxF2 for December 1962

2. Direct Comparisons

An early attempt to check the accuracy of N-h profiles derived from Alouette data was the rendez-vous experiment of 2 July 1963 (Bauer et al., 1964) in which the electron density profile over Wallops Island, Virginia, was measured simultaneously with Alouette I and with rocket instrumentation. The results of this experiment (Fig. 1) showed that the Alouette profile (obtained with 1963 analysis techniques) was about 20km too low at altitudes less than 600km.

A few attempts were also made during the early life of Alouette I at matching Alouette profiles with profiles obtained from nearly simultaneous ground-based soundings. Again altitude disagreements were noted (Bauer & Jackson, 1964: King private communications, 1963-1967; King et al., 1967).

For the sake of completeness one should also mention that comparisons with the Incoherent Backscatter Technique have also shown that the Alouette N-h profiles were too low. (Calvert, 1966; paper by Norton and Cohen in this issue.)

DISCUSSION OF THE EARLY OBSERVATIONS

The three different types of comparisons which have been used to check the accuracy of the Alouette N(h) profiles all seemed to indicate that the topside profiles were too low. Admittedly, each type of comparison has limitations which could invalidate the results obtained. The statistical comparison was based upon a relatively small number of Alouette soundings and upon ground-based observations made at similar but different locations and times. The results of comparisons based upon the incoherent backscatter technique have in the past been released only as private communications. No independent assessment and conclusion could be reached in the absence of a publication discussing these observations. The data for the rocket rendez-vous experiment were obtained at the same time but not quite at the same location, the horizontal separation being about 300km. Large horizontal separations existed also for many of the early so-called direct comparisons with ground-based sounders.

In spite of the uncertainty associated with each observation, the collective evidence (i.e. the overall consistency of the results) suggested the presence of a systematic error either in the topside ionograms or in the methods used to obtain electron density profiles from the ionograms. An investigation of N(h) reduction techniques led to the error study mentioned in the paper devoted to ionogram analysis (Jackson's paper in this issue). This work as well as the efforts of other workers on the topside sounder program led to considerable refinements in the techniques of analysis. However, these improvements did not resolve the altitude discrepancy. For example, repeating in 1968 the analysis of the Alouette ionogram taken during the rocket rendez-vous experiment led to essentially the same conclusion, namely that the Alouette profile **was** about 20km too low.

In order to eliminate as many sources of uncertainties as possible, it was decided to concentrate future efforts upon topside and ground-based soundings as nearly coincident as practical. The more recent availability of Alouette II data had also made it possible to conduct comparisons over a much greater range of satellite heights (500 to 3000km) than was previously possible. It was also concluded that the selection of the comparison data should be based upon a very critical examination of the original ionograms, keeping only the best quality data for the investigation of the problem. Finally, these data should be subjected to a much more careful analysis than is normally done for the routine reductions of ionograms, (simultaneous analysis of O and X modes on both ground and satellite ionograms; E-Valley corrections for ground ionograms.) The reduction of ionograms to N(h) profiles assumes that the electron density distribution was spherically stratified in the region over which the soundings were obtained. Under this assumption the lines of constant densities must remain parallel to the earth's surface over a circular area, typically a few hundred kilometers in diameter.

One tentative conclusion reached from the early observations and the fact that subsequent refinement in N-h analysis had failed to solve the problem, was that the discrepancies were due to departure from spherical stratification, i.e. to the presence of horizontal gradients. Thus, further studies should include an investigation of the horizontal gradients present while comparisons were made. One should attempt to determine whether or not the discrepancy is variable in magnitude and related to the magnitude of the gradients. Finally, one should find out whether or not a careful ray-tracing analysis through these gradients can explain quantitatively the discrepancy observed.

## PRESENT STATUS OF THE PROBLEM

It was stated in the introduction that this paper is an interim report. The problem has not yet been solved, but it is now receiving much more attention. The current effort includes both theoretical studies and improved experimental observations. The theoretical approach is based upon ray-tracing studies, which take into consideration ray deviations occurring in the magnetic meridian. These deviations occur even when vertical soundings are conducted into a spherically stratified ionosphere. Preliminary results (Colin, private communication) indicate that ray deviation (for the spherical stratification case) does not change significantly the virtual heights. Thus, this effect (in the absence of horizontal gradients) cannot explain the height discrepancy. Examples of ray-tracing analyses are given in a companion paper (Colin and Chan, this issue). The investigation of ray-tracing effects into a tilted ionosphere has not yet been completed. One might mention parenthetically that this type of analysis is at least two orders of magnitude more complex than the routine reduction of ionograms to N-h profiles.

More careful observations have been conducted recently using both ground-based ionosondes and the Incoherent Backscatter Technique to check the Alouette profiles. The improved experimental documentation, however, has not yet been completed, due to the much more restrictive criteria applied to the experimental data and due to the concurrent gradient study which should also be conducted. To meet the requirement of near-simultaneity of observations, comparisons are usually restricted to cases when the horizontal distances between the soundings are less than 100 km. This greater care in the selection of the data reduces considerably the number of possible comparisons. This number is reduced further by the requirement that the simultaneous data must be of very good quality. Preliminary results based upon nearly simultaneous topside and bottomside soundings have provided further confirmation of the height discrepancy. The remainder of this report is devoted to a discussion of these observations.

## DISCUSSION OF OPTIMIZED IONOSONDE OBSERVATIONS

### 1. Data Selection

Ideally, ground ionosonde and topside sounder comparison data should be obtained simultaneously at the same location. Since exact time and space simultaneity is never achieved, some tolerance must be placed on these requirements, and actual comparisons will usually require interpolations between successive ionograms. For example, the horizontal distance between two successive soundings is typically 125 km on Alouette I and 250 km on Alouette II. Unless special arrangements are made prior to the event, the ground ionograms available for comparisons are normally 15 minutes apart. If the criterion for an "overhead" pass is for the sub-satellite track (projection of the orbit on the ground) to come within 100 km of the ground ionosonde, then "overhead" daytime passes will occur about 30 times per year for a given mid-latitude station. Approximately half of these 30 opportunities yield usable simultaneous data, provided the ground station is in a geographic area extensively investigated by topside soundings. Due to the limited sounding time available, and due to the need for real-time data acquisition, topside soundings have been conducted only in selected areas with preference given to soundings over the American Continents. Since the horizontal ionospheric gradients are likely to be an important factor, the first comparisons were made under conditions of minimum gradients, which over North America, are found typically at latitudes between 30°N and 40°N. Based upon these considerations the Wallops Island (37.9° lat.) and the Fort Belvoir (38.7°lat.) ionosondes were selected for the comparison studies. Furthermore, these two sites were within 200 km of each other. Thus, satellite soundings obtained between the two locations could be checked against two nearby ground references. Satellite passes which were not within the two ground references were used also, when the subsatellite point came within 100 km of either Fort Belvoir or Wallops Island. Due to the greater difficulty of analyzing night-time ionograms, the initial comparisons were restricted to day-time observations. For Alouette II, and for the period June 4, 1966 to November 1, 1966, a total of 21 passes met the above requirements, of which only 11 were considered usable. The 8 best cases are included in this report. For Alouette I, and for the period Feb. 2, 1965 to December 16, 1965 there was a total of 26 "Wallops and Fort Belvoir" passes, 9 of which were usable, and 2 of which were included in this report.

## 2. Results Obtained

The main comparison possible from the analysis of these data is in the region near hmaxF2 where the topside and bottomside profiles should match. Actually, a true matching of the profiles is not possible because both bottomside and topside soundings stop short of the peak density. For this reason hmaxF2 is sometimes estimated by fitting a parabola at the high density end of the calculated profile. For ground-based soundings this extrapolation places hmaxF2 typically 10 km above the maximum height derived from the normal ionogram reduction. In the absence of such extrapolations, one would expect at hmaxF2 a gap between the upper and lower electron density profiles. Tentatively, the comparison profiles have been described as giving agreement if the original ionograms had well defined and equal values of critical frequencies (foF2), and if a small gap (typically 20 km) was present at hmaxF2 in the resulting composite profile. The presence of this gap, however, does not necessarily prove that the profiles are correct, since the actual width of the gap is unknown. An overlap, or absence of gap, was taken as a definite indication of error.

When the satellite was near perigee the overlap (if any) was not noticeable as illustrated by Fig. 2 which corresponds to a pass almost directly over Wallops Island. The insert to Fig. 2 shows the subsatellite track with respect to a coordinate system centered at Wallops Island (W). The tendency towards overlapping increases with satellite altitude, and when the topside sounder was at 2200 km the overlap was about 50 km as illustrated by Fig. 3. The insert to Fig. 3 shows the subsatellite track with respect to Wallops Island (W) and with respect to Fort Belvoir (B).

The profiles derived from the ground ionosondes are based upon a monotonic analysis, i.e. the altitudes shown are minimal. Thus, the discrepancy is actually greater than 50 km. Although percentage-wise the 50 km overlap is only 3 percent of the distance from the satellite to the height of maximum density, this discrepancy is several times greater than the observational error. Two of the ionograms used to obtain Fig. 2 are shown in Fig. 4 and 5. Two of the ionograms used to obtain Fig. 3 are shown in Fig. 6 and 7. The comparisons were based whenever possible upon an averaging between successive ionograms as illustrated by Fig. 8. A summary of all the comparisons made is given in Table II. The profiles near hmaxF2 are shown on Fig. 9, except for the two cases already illustrated by Fig. 2 and 3. The overlap correlates neither with the magnetic activity, nor with the sunspot number. The only correlation seems to be with satellite altitude, suggesting that the overlap is a cumulative effect proportional to the length of the propagation path.

The component of the horizontal gradient in the orbital plane can be obtained from the analysis of successive ionograms. Consecutive N-h profiles obtained during four of the comparisons passes are shown in Fig. 10 (overlap at hmaxF2) and 11, (no overlap) in terms of heights of constant densities versus latitude. To give a realistic representation, the latitude was selected to give horizontal distances (x) on approximately the same scale as the vertical distances (h). Actually, for a true representation, the horizontal scale should have been expanded by a factor of 1.11. The term horizontal gradient was introduced earlier by association with the concept of non-spherical stratification. From this rather loose definition it is not clear whether the horizontal gradient

## TOPSIDE-BOTTOMSIDE COMPARISONS

| No. | Satellite Altitude (Km) | Agreement | Closest Approach (Km) Wallops | Closest Approach (Km) Ft.Belvoir | Ionograms Used* Topside North | Ionograms Used* Topside South | Ionograms Used* Bottomside Before | Ionograms Used* Bottomside After |
|---|---|---|---|---|---|---|---|---|
| 1 | 520 | yes | 0 | 130 | X | X | X | X |
| 2 | 530 | yes | 10 | 125 | X | X | X | X |
| 3 | 700 | yes | 30 | 160 | X | X | X | X |
| 4 | 800 | yes | 40 | 170 | X | X | X | X |
| 5 | 1070 | yes | 80 | 210 | XX | | X | X |
| 6 | 1370 | hint of overlap | 20 | 150 | | [X] | X | |
| 7 | 2000 | 75 Km. overlap | 135 | 30 | X | X | XX | X |
| 8 | 2200 | 75 Km. overlap | 180 | 15 | XX | | X | XX |
| 9 | 1026 | 17 Km. overlap | 50 | 110 | X | X | [X] | |
| 10 | 1003(VLF) | 30 Km. overlap? | 20 | 140 | X | X | [X] | |

*Alouette II ionograms are typically 250 Km. apart; Alouette I ionograms are typically 125 Km. apart. Bottomside soundings are 15 min. apart. Except when indicated by [X], the best procedure was to use topside data north and south of ground ionosonde, and bottomside data before and after satellite pass. Blanks show that ionograms were either not available or not needed.

## ADDITIONAL DATA FOR ABOVE COMPARISONS

| No. | Satellite | Year | Day No. | GMT (37.9°) | LMT (Satellite) | ΣKp | S.S.No. | Sun Zenith Angle |
|---|---|---|---|---|---|---|---|---|
| 1 | AL-2 | 66 | 254 | 1551/17 | 10:49/29 | 13 QQ | 42 | 36.5 |
| 2 | AL-2 | 66 | 264 | 1440/04 | 9:38/16 | $16^{+}$Q | 89 | 48.3 |
| 3 | AL-2 | 66 | 239 | 1736/05 | 12:34/17 | 11 Q | 90 | 29.0 |
| 4 | AL-2 | 66 | 234 | 1810/45 | 13:08/57 | 8 QQ | 38 | 29.8 |
| 5 | AL-2 | 66 | 224 | 1919/39 | 14:17/51 | $22^{+}$ | 36 | 37.3 |
| 6 | AL-2 | 66 | 165 | 1528/38 | 10:26/50 | 9 Q | 31 | 25.1 |
| 7 | AL-2 | 66 | 180 | 1347/41 | 8:45/53 | $11^{+}$ | 47 | 44.8 |
| 8 | AL-2 | 66 | 185 | 1314/23 | 8:12/35 | 19 | 53 | 51.3 |
| 9 | AL-1 | 65 | 89 | 1616/07 | 11:14/19 | $4^{+}$ Q | 9 | 35.9 |
| 10 | AL-1 | 65 | 268 | 1645/17 | 11:43/29 | $20^{-}$ | 13 | 39.1 |

Table II

refers to the slope of the stratification (i.e. dh/dx on Fig. 10 and 11) or to the rate of change of the density N in the x direction (dN/dx). The two interpretations are related as follows:

$$\frac{dN}{dx} = \left(\frac{dN}{dh}\right) \left(\frac{dh}{dx}\right)$$

It should be noted that under either interpretation the gradient is zero when the stratification is spherical. Since the slope of the constant density lines, or ionospheric tilt, is a basic parameter controlling the refraction of a vertical sounding wave, the slope of these lines will be taken as a measure of the horizontal gradient. The magnitudes of the horizontal gradients are comparable for the four passes shown in Fig. 10 and 11. The gradient dh/dx averaged over 10 degrees of latitude is generally less than 0.1, but random fluctuations can yield local gradients several times greater than the average. The gradients also exhibit variations as a function of altitude. These variations, which even include reversals in direction over the altitude range, are more clearly seen when data are available over a great height range, as is the case for the passes of Fig. 11. These observations suggest that height discrepancies might be due to cumulative errors caused by fluctuations in gradients along the propagation paths.

A complete evaluation of the effects of horizontal gradients should include a study of East-West gradients. Statistical considerations, based upon studies of diurnal effects (Bauer and Blumle, 1964) and the assumption that time variations can be converted to equivalent longitude variations, suggest however that the East-West gradients are less important than the North-South gradients. Thus horizontal gradients measured along the satellite orbit should provide information adequate for first order corrections of gradient effects.

ACCURACY TESTS BASED UPON GROUND TRACE ANALYSIS

As indicated earlier, the absence of overlap does not necessarily imply that the profile heights are correct. The correctness of the total distribution can sometimes be checked by making use of the ground echoes obtained on topside ionograms at frequencies above foF2. These ground reflections have a delay (virtual distance - satellite altitude) which is determined by the entire electron density distribution below the satellite. Since the delay occurs mostly in the region of maximum density, the value of this delay is essentially a measure of the thickness Ym of the F2 region. The ground trace can therefore be used to detect discrepancies near hmaxF2. For frequencies well above foF2, the ground echoes are relatively insensitive to horizontal gradients and to analytical approximations made near the reflection point. Thus the interpretation of ground echoes is relatively free of the uncertainties inherent to conventional ionogram analysis.

The observed and calculated ground traces for the profile shown in Fig. 2 are indicated on Fig. 12a. The calculated trace is based upon the profile shown by the solid curve, i.e. upon the initial N(h) analysis. It is seen that the observed trace is 30 km lower than the calculated trace. The ionogram analysis was repeated assuming that this discrepancy was due to a systematic error on the ionogram, i.e. that the indicated virtual range was 30 km too low. The resulting "corrected" profile is shown as a dashed line on Fig. 2. The ground trace was then calculated for the corrected electron density distribution and compared to the "corrected" observed ground trace. As shown by Fig. 12, this correction resulted in excellent agreement between observed and calculated ground traces.

One would infer from this exercise that there was a systematic error of 30 km on the topside ionogram. Repeating the above procedure with the topside ionogram for day 264 (see Fig. 13a and 13b) led to a very similar result. In this case the systematic error was 25 km. The above procedure is rather laborious, and it requires that both the topside and the bottomside profiles be available. A procedure has been devised whereby a systematic error can be detected from the ground trace alone. The principle is as follows.

For frequencies well above foF2, the ground trace delay (D) is of the form $D = K/f^2$, i.e. the quantity $Df^2$ approaches a constant value K. The function $Df^2$ decreases monotonically as shown by the solid curves of Fig. 14, which correspond to the corrected and uncorrected profiles of Fig. 2. On Fig. 14 the frequency was normalized to foF2, since such a normalization tends to standardize the shape of the $Df^2$ function (particularly when this function is examined in terms of Ym). Also shown on Fig. 14 is the $Df^2$ function based upon the observed ground trace. It is seen that curve 3 does not decrease monotonically. However, by decreasing the virtual range by various fixed amounts (curves 4, 5 and 6) one can eventually obtain a $Df^2$ variation which exhibits the proper behavior.

From the $Df^2$ analysis, one would conclude that the correction should be at least 30 km (curve 6) but definitely less than 40 km (curve 6). Thus from an examination of the ground trace alone one would conclude that the required correction is 35 km, which is very close to the result of the more elaborate analysis. The test illustrated by Fig. 14 was conducted on the ionograms used for the comparison study, whenever a ground trace was available, and performed also on a number of additional ionograms selected randomly. From a total of 8 ionograms examined (4 of these from Alouette I), not a single case was found indicating that the virtual range was too small. On one Alouette I ionogram the virtual range appeared to be correct (i.e. within $\pm$ 5 km), but on the other three the virtual range was too great by typically 10 to 20 km. The systematic errors seemed slightly greater on Alouette II, ranging from 12 to 35 km.

The ground trace was not available for the comparison shown on Fig. 3, however it seems unlikely that the 50 km discrepancy can be explained by systematic errors. A virtual height error of about 60 km would be required in this case, corresponding to about twice the maximum error found from the ground trace study. It should also be noted that the comparisons at hmaxF2 were not significantly affected by the type of lamination assumed in the N(h) analysis. The parabolic in log(N) and the linear in log(N) techniques yielded profiles which near hmaxF2 differed at most by 6 km. The 50 km discrepancy shown on Fig. 3 might therefore be due to a combination of systematic errors and gradient effects.

## CONCLUSION

Although the experimental documentation is not completed, it appears that the Alouette electron density profiles are definitely too low. The altitude error, however, is only a few percent of the total propagation path. The discrepancies noted when the topside sounder was at low altitudes (Alouette II perigee data) could be explained by systematic errors in the virtual range scale. The magnitude of these systematic errors is not sufficient to explain the 50 to 75 km discrepancies noted when the topside sounder was at altitudes in excess of 2000 km. It is possible in this case that the error may be due in part to irregularities (horizontal gradients) between the sounder and the reflection point. Another possibility not discussed in the report is that cumulative errors arise in the analysis due to one of the many assumptions made in the magneto-ionic theory (cold plasma treatment of the ionosphere, WKB approximation, idealized reflection condition, group velocity representation of the signal velocity, etc...). Although these approximations have been accepted for several decades, a complete evaluation of their effects has not been done in the topside ionosphere, where, for example, at the higher altitudes waves can travel for hundreds of kilometers in a very slowly changing medium where the reflection condition is approached almost asymptotically.

# APPENDIX A

## COMMENTS ON THE DETERMINATION OF HMAXF2 FROM IONOGRAMS

### 1. Mid-day Ground-Based Measurements

There are two basic problems associated with the calculation of hmaxF2 from ground-based soundings. First, the ionograms exhibit at least one major discontinuity due to the fact that the electron density does not increase monotonically with altitude from the E to the F region (E-Valley problem). Second, ionograms are incomplete at both ends of the frequency range (No echoes for f < 1.0 MHz; No echoes in the immediate vicinity of hmaxF2). These problems introduce errors in the analysis of both day-time and night-time ionograms, and consequently in the derived values of hmaxF2. Additional errors can be introduced by ionogram reduction techniques, particularly in extensive statistical surveys where time saving procedures have been used at the cost of reduced accuracy. Since the comparisons with Alouette results have been based upon mid-day observations, the discussion of the above problems will be restricted to mid-day ionograms.

#### The E-Valley problem

Most, if not all, of the statistical day-time studies of hmaxF2 have been based upon the monotonic N(h) assumption, which ignores the effect of the E-Valley uncertainty. A shallow E-Valley, where the minimum electron density is only 10 per cent less than the density at Emax, is representative of mid-day conditions (Herbert 1967, p. 1271 Errors introduced by a monotonic calculation for mid-day conditions (Titheridge 1959, fig. 1, p. 111; Wright 1967, fig. 5 p. 1166; Becker 1967, table 5, p. 1227) cause the calculated values of hmaxF2 to be 10 to 20Km too low.

#### The Low Frequency cut-off

The absence of echoes for frequencies less than 1.0 MHz introduces an additional uncertainty in the N(h) analysis, which can cause the N(h) profile to be either too high or too low. The effect, however, is small at hmaxF2 and typically ± 1 km (based upon the author's own calculations).

The Absence of Echoes near hmaxF2

According to Becker and Stubbe (1962 section 3, p. 38) the maximum echo frequency on an ionogram is at least one per cent smaller than the true critical frequency. This causes the last calculated point (maximum N(h) value) to be lower than hmaxF2 by at least (0.14)Ym where Ym is the half thickness of the F2 region (Becker 1967, table 2, p. 1219). The error is due primarily to the missing virtual heights, since very large virtual heights would theoretically be required in order to carry out the calculations to within 1 or 2km of an idealized parabolic layer maximum.

Errors due to Analysis Techniques

In addition to the above-mentioned sources of errors, which are due to the ionograms themselves, other errors can arise from special techniques devised to process large volumes of data. For example, the results published by Thomas (1957) were based upon virtual heights read to the nearest 0.1 MHz, and this caused the values of hmaxF2 given by Thomas to be much too low (Schmerling, 1960). This routine scaling could easily cause the highest frequency scaled to be 2 per cent less than the true critical frequency and yield a value of hmaxF2 which is too low by (0.199)Ym (based upon Becker, 1967, table 2, p. 1219).

Practical considerations led Becker to develop a manual-optical-graphical technique in order to conduct his early statistical studies of hmaxF2. This technique is less accurate than Becker's more recent machine technique. Thus reference data from Becker's work should be taken, if possible, from his most recent publications.

2. Mid-day hmaxF2 data for low sunspot number and winter conditions

Ground-based observations which should be comparable to the Alouette I, December 1962, mid-day values of hmaxF2 can be found in publications by Thomas (1957), Becker (1967) and Wright (1962b). The data published by Becker and Stubbe (1962, fig. 2) are less accurate than Becker's 1967 results (Stubbe, private communication) and the earlier publication was therefore not considered in the present discussion. Thomas showed that the minimum values of hmaxF2 occur at mid-day, in winter and when the solar activity is minimum.

The average value of hmaxF2 at Slough (dip=68°, latitude=51.5°N) for the ten international quiet days of December 1953 ($\bar{R}$=2.5) at mid-day (1100 to 1300 hrs.) was 219.4Km. Becker's graph of the 27-day running mean noon values of hmaxF2 at Lindau (dip=67.6°, latitude=51°N) for the period July 1963 to June 1964 show that the minimum value of hmaxF2 occurred in December 1963 ($\bar{R}$=11.3) and was equal to 220Km. From the data published by Wright, one would also infer that a typical winter noon value of hmaxF2 during sunspot minimum is 220Km at Washington (dip=70°, latitude=38°N) and also at Anchorage (dip=74°, latitude=61°N). The minimum hmaxF2 value of 220Km thus seems applicable for dip values between 67° and 74° and for geographic latitudes between 38°N and 61°N. The scatter in the data published by Thomas indicate that the standard deviation for the noon values of hmaxF2 is about ± 15Km. Wright (1962a, fig. 15) shows that the standard deviation of hmaxF2 was 15Km at noon for both New Foundland and Puerto Rico, based upon one year of data (May 1959 to April 1960).

The above results should be examined in the light of the earlier comments. Specifically, the error due to a monotonic analysis is present in the three sets of results discussed above. A conservative allowance for this effect raises the above values of hmaxF2 from 220 to 230Km. Becker and Wright use extrapolation for their hmaxF2 calculations and therefore, their results would require no further correction. The December 1963 results published by Thomas should be increased by (0.199)Ym, i.e. by at least 10Km, based upon representative Ym values (Becker, 1967, fig. 2).

3. <u>Alouette values of hmaxF2</u>

In some respects the analysis of topside ionograms is less subject to errors than the analysis of ground-based ionograms. The topside profile is monotonic and the starting point of the analysis (N at the satellite) is accurately known. The lack of values near hmaxF2, however presents the same problem as on ground-based ionograms. In fact, on topside ionograms the definition of hmaxF2 is typically poorer than it is on ground-based ionograms. Thus the error is more likely to be (0.199)Ym than (0.14)Ym, i.e. 10Km for winter noon, low solar activity. Thus the minimum altitude derived from a topside ionogram should be equal to hmax + 10Km, i.e. 240Km (based upon Becker and Wright) or 250Km (based upon Thomas). The lowest of these two estimates was used for the comparison with the topside sounder results.

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Norton and Cohen's paper on comparisons between Alouette profiles and profiles from the Jicamarca incoherent backscatter station."

## FIGURE CAPTIONS

Fig. 1. Comparison of charged particle profiles obtained simultaneously by rocket, satellite, and ground-based incoherent backscatter measurements.

Fig. 2. Comparison between electron density profiles obtained from Alouette II and from ground-based soundings. (11 September 1966, 1551/17 GMT). It can be seen from the insert that the satellite passed almost directly above Wallops Island (center of coordinate system). Also indicated are the positions of the satellite when the topside soundings were the closest to Wallops Island. The corrected topside profile (based upon the ground trace study is shown as a dashed line).

Fig. 3. Comparison similar to that shown on Fig. 3, but for a much higher satellite altitude. In this case the sub-satellite track came very close to Fort Belvoir (small circle B in insert). Data obtained on 4 July 1966, 1314/23 GMT. Profiles from the Ft. Belvoir (B) and Wallops Island (W) ionosondes have been shown to provide an indication of East-West gradients.

Fig. 4. Alouette II ionograms for 11 September 1966, 1151/19 GMT.

Fig. 5. Wallops Island ionogram for 11 September 1966, 1100 EST.

Fig. 6. Alouette II ionogram for 4 July 1966, 1314/27 GMT.

Fig. 7. Fort Belvoir ionogram for 4 July 1966, 0815 EST.

Fig. 8. Matching of N-h profiles at hmaxF2 for the 11 September 1966 comparison.

Fig. 9. Comparison between Topside Sounder profiles and the corresponding ground ionosonde profiles for various satellite altitudes.

Fig. 10. Constant density contours in orbital plane for two of the topside-bottomside comparisons made when Alouette II was at low altitude.

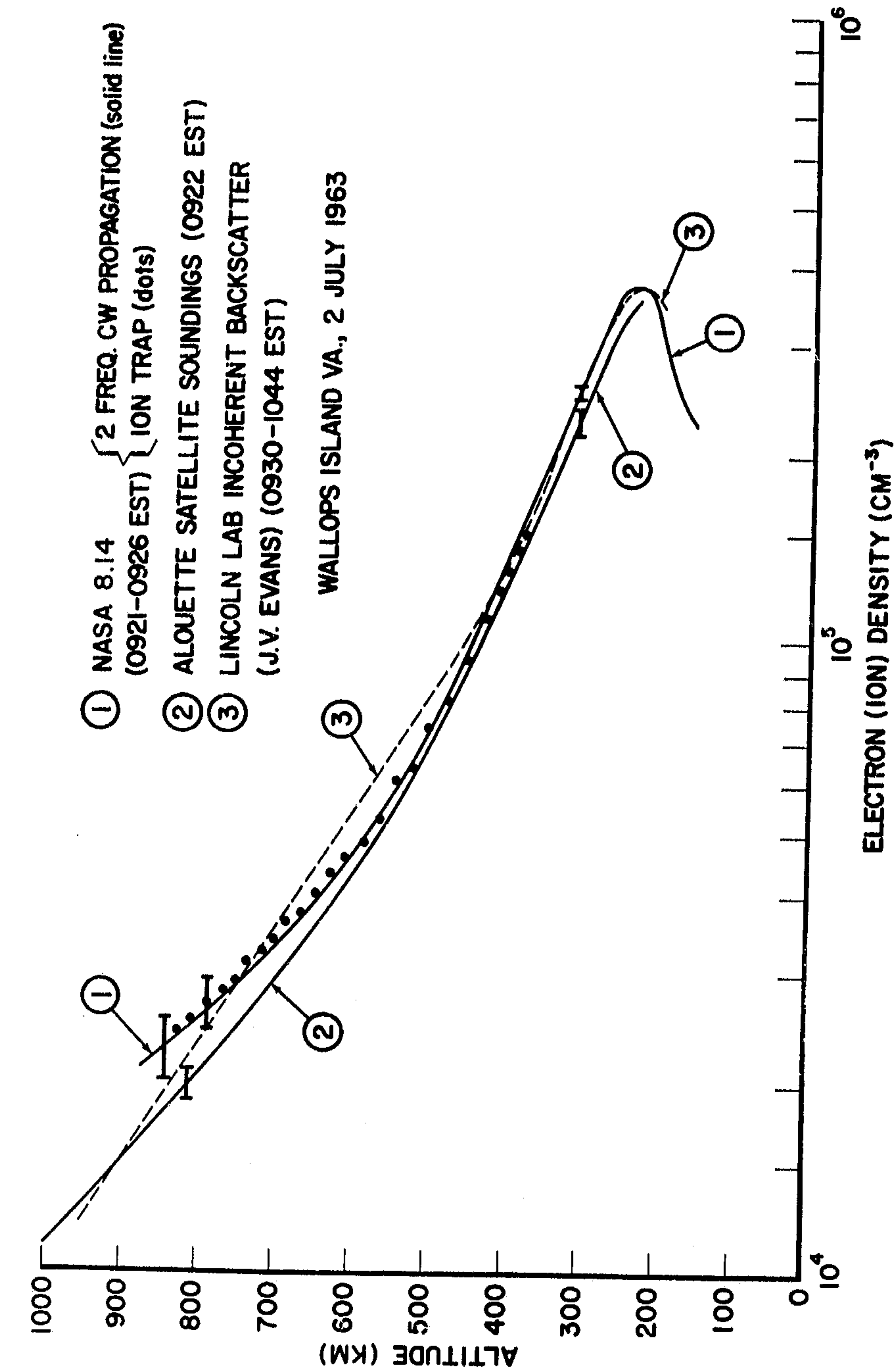
Fig. 11. Constant density contours in orbital plane for two of the topside-bottomside comparisons made when Alouette II was at high altitude.

Fig. 12. (a) Calculated and observed ground traces (b) calculated and observed ground traces, reducing the virtual range data by 30 km.

Fig. 13. (a) Calculated and observed ground traces (b) calculated and observed ground traces, reducing the virtual range data by 25 km.

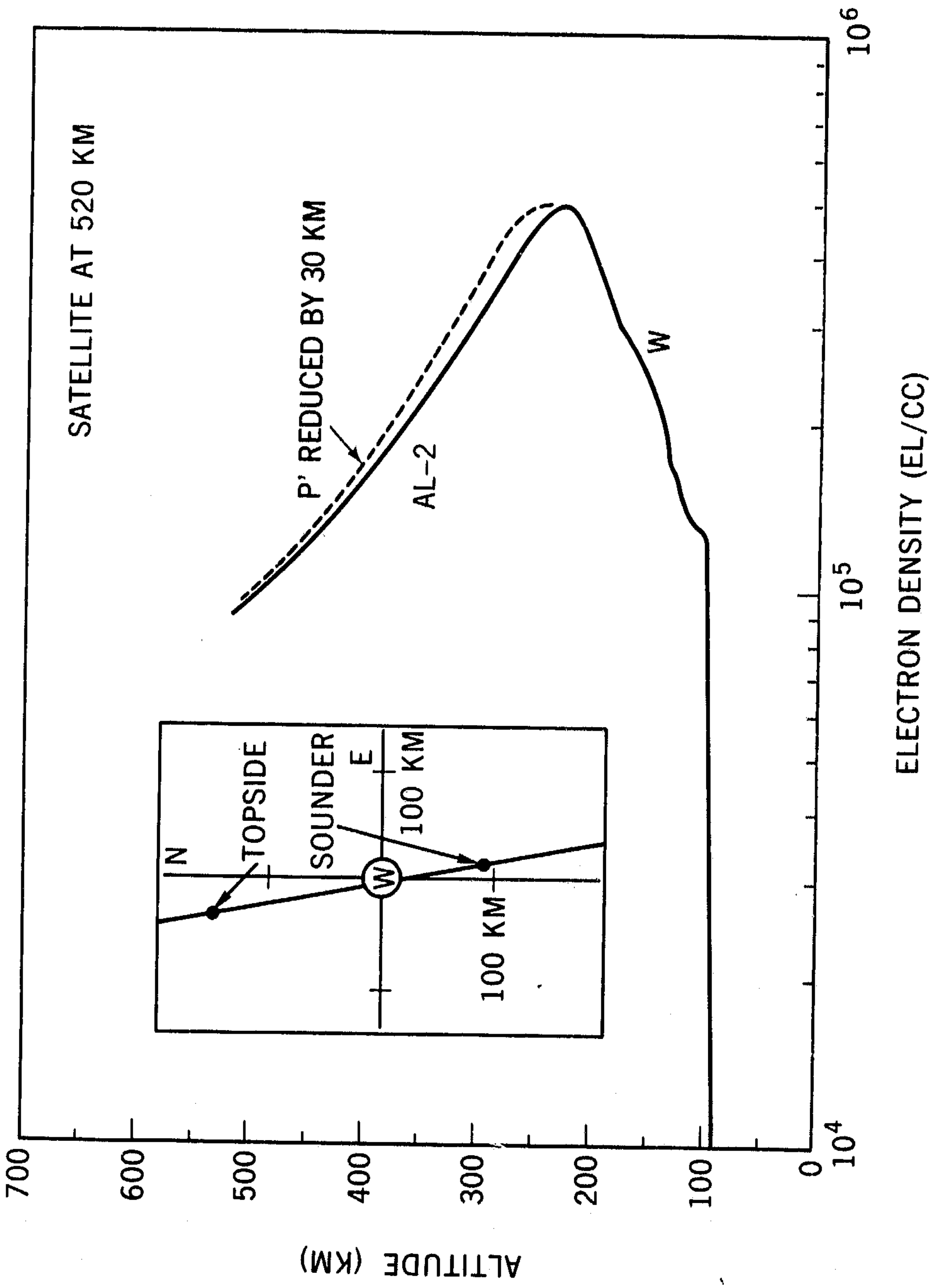
Fig. 14. Use of the $Df^2$ test for detecting systematic errors in the virtual range data. If the virtual range is correct the $Df^2$ function should decrease monotonically towards a constant value as shown by the theoretical curves 1 and 2.

Fig. 1



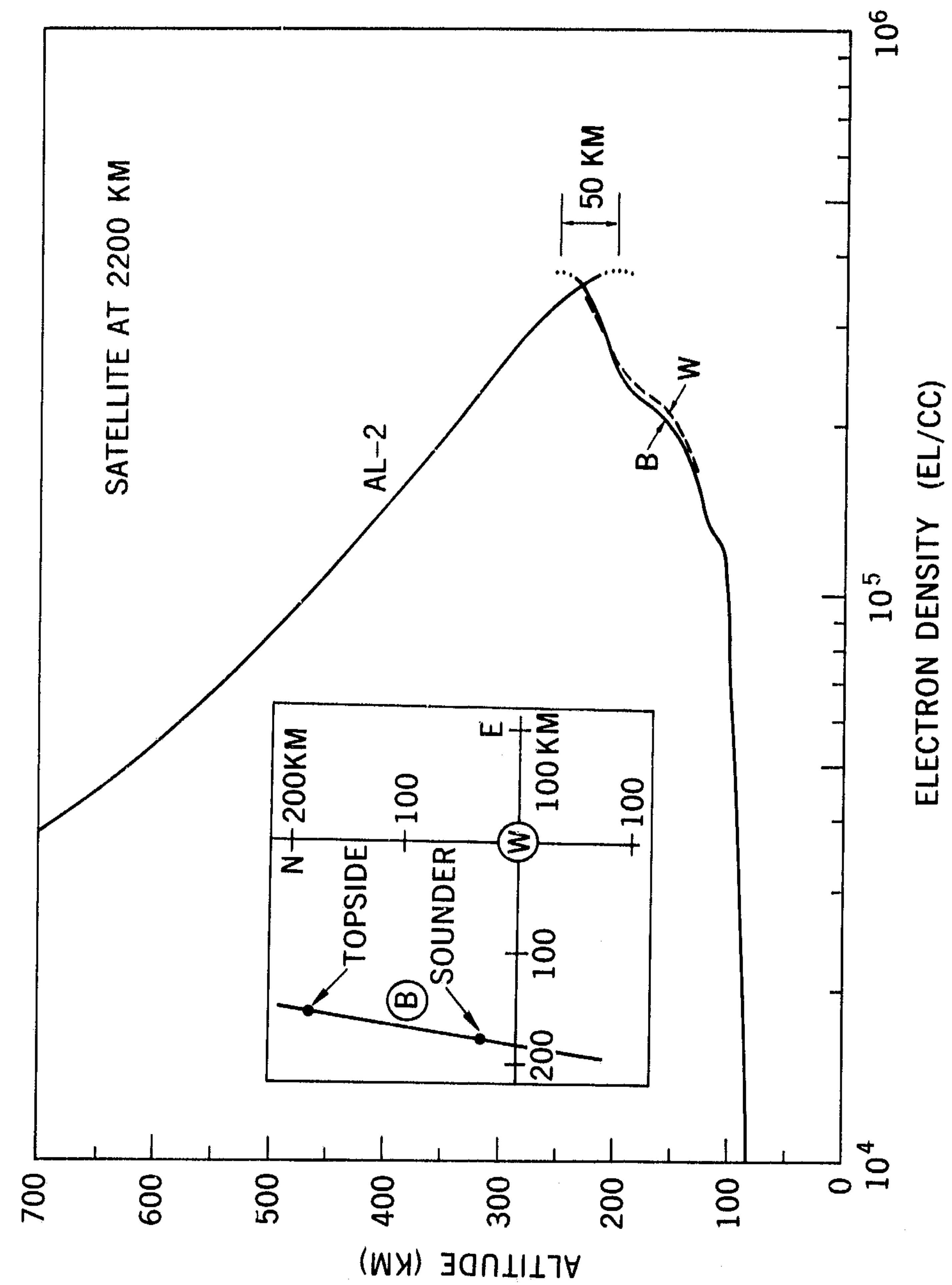
① NASA 8.14 (0921-0926 EST) {2 FREQ. CW PROPAGATION (solid line) / ION TRAP (dots)
② ALOUETTE SATELLITE SOUNDINGS (0922 EST)
③ LINCOLN LAB INCOHERENT BACKSCATTER (J.V. EVANS) (0930-1044 EST)
WALLOPS ISLAND VA., 2 JULY 1963
ALTITUDE (KM)
1000
900
800
700
600
500
400
300
200
100
0
$10^4$
$10^5$
$10^6$
ELECTRON (ION) DENSITY ($CM^{-3}$)

Fig. 2

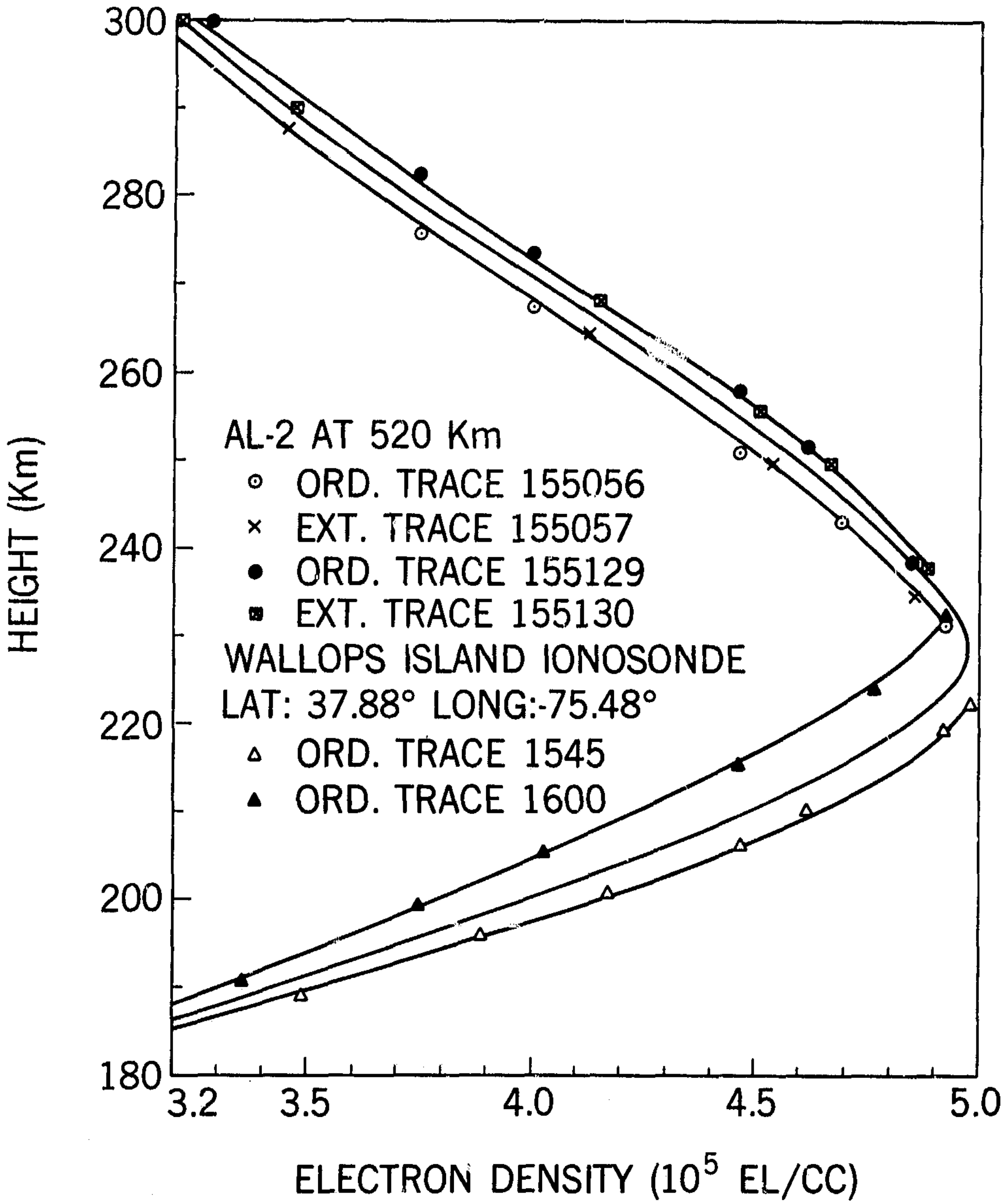


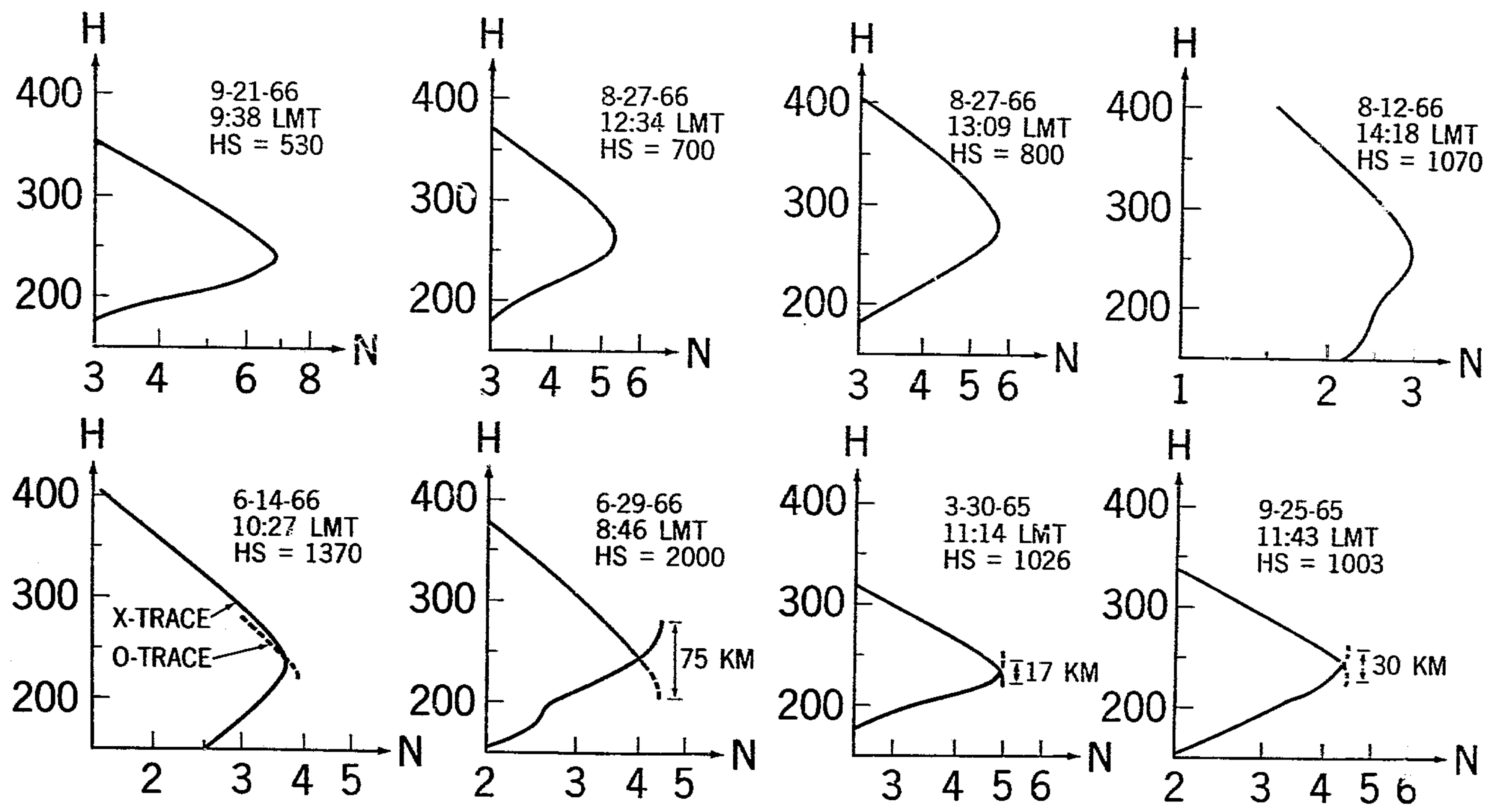
SATELLITE AT 520 KM
P' REDUCED BY 30 KM
AL-2
W
TOPSIDE
SOUNDER
N
E
100 KM
100 KM
ALTITUDE (KM)
ELECTRON DENSITY (EL/CC)
0
100
200
300
400
500
600
700
$10^4$
$10^5$
$10^6$

Fig. 3



SATELLITE AT 2200 KM
AL–2
50 KM
W
B
N
200KM
100
E
100KM
100
W
TOPSIDE
SOUNDER
B
100
200
ALTITUDE (KM)
700
600
500
400
300
200
100
0
ELECTRON DENSITY (EL/CC)
$10^4$
$10^5$
$10^6$


300
280
260
240
220
200
180
HEIGHT (Km)
3.2
3.5
4.0
4.5
5.0
ELECTRON DENSITY (10^5 EL/CC)
AL-2 AT 520 Km
ORD. TRACE 155056
EXT. TRACE 155057
ORD. TRACE 155129
EXT. TRACE 155130
WALLOPS ISLAND IONOSONDE
LAT: 37.88° LONG:-75.48°
ORD. TRACE 1545
ORD. TRACE 1600




H = HEIGHT IN KM

N = ELECTRON DENSITY IN UNITS OF $10^5$ EL/CC

HS = SATELLITE HEIGHT IN KM

Fig. 9

Fig. 10

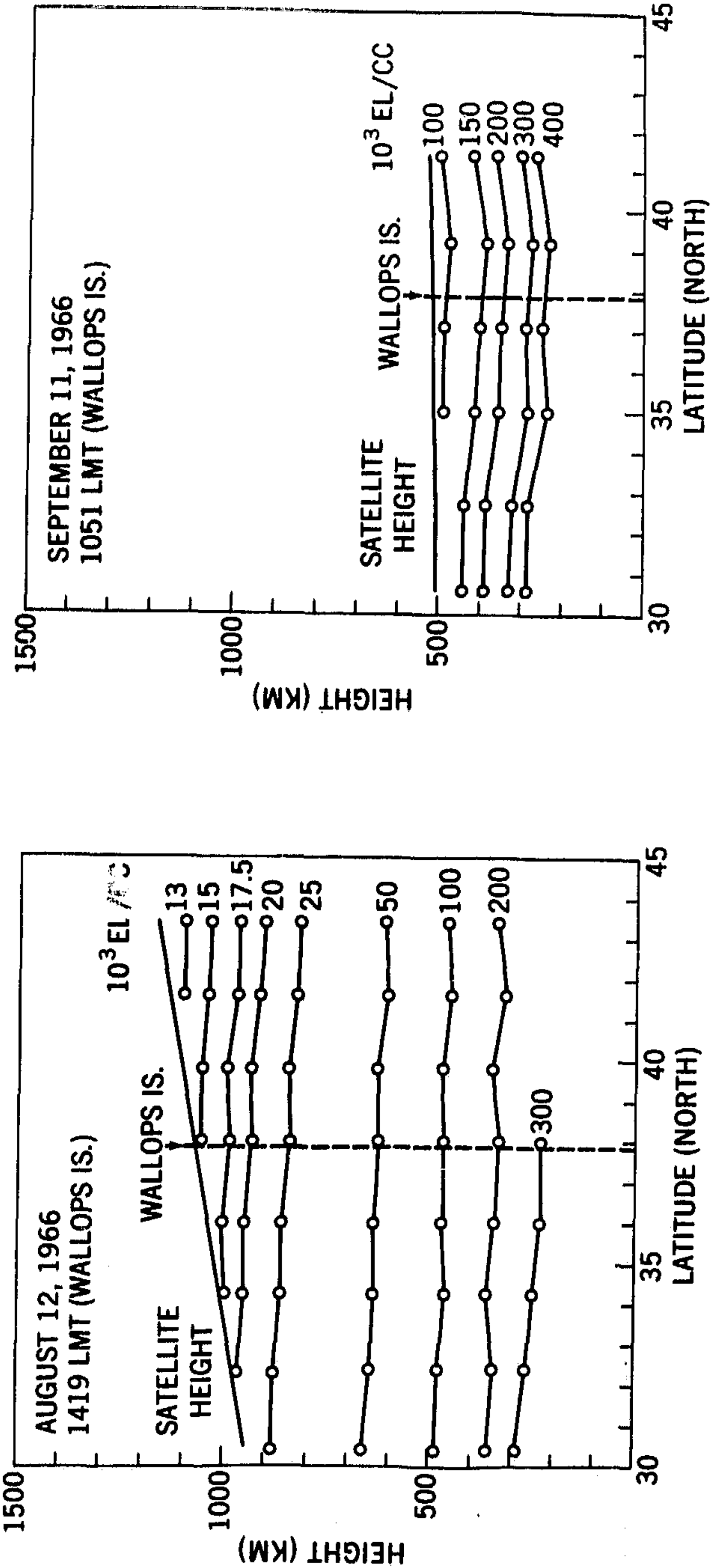

SEPTEMBER 11, 1966
1051 LMT (WALLOPS IS.)
SATELLITE HEIGHT
WALLOPS IS.
$10^3$ EL/CC
100
150
200
300
400
HEIGHT (KM)
LATITUDE (NORTH)
AUGUST 12, 1966
1419 LMT (WALLOPS IS.)
13
15
17.5
20
25
50
100
200
300
1500
1000
500
30
35
40
45

Fig. 11

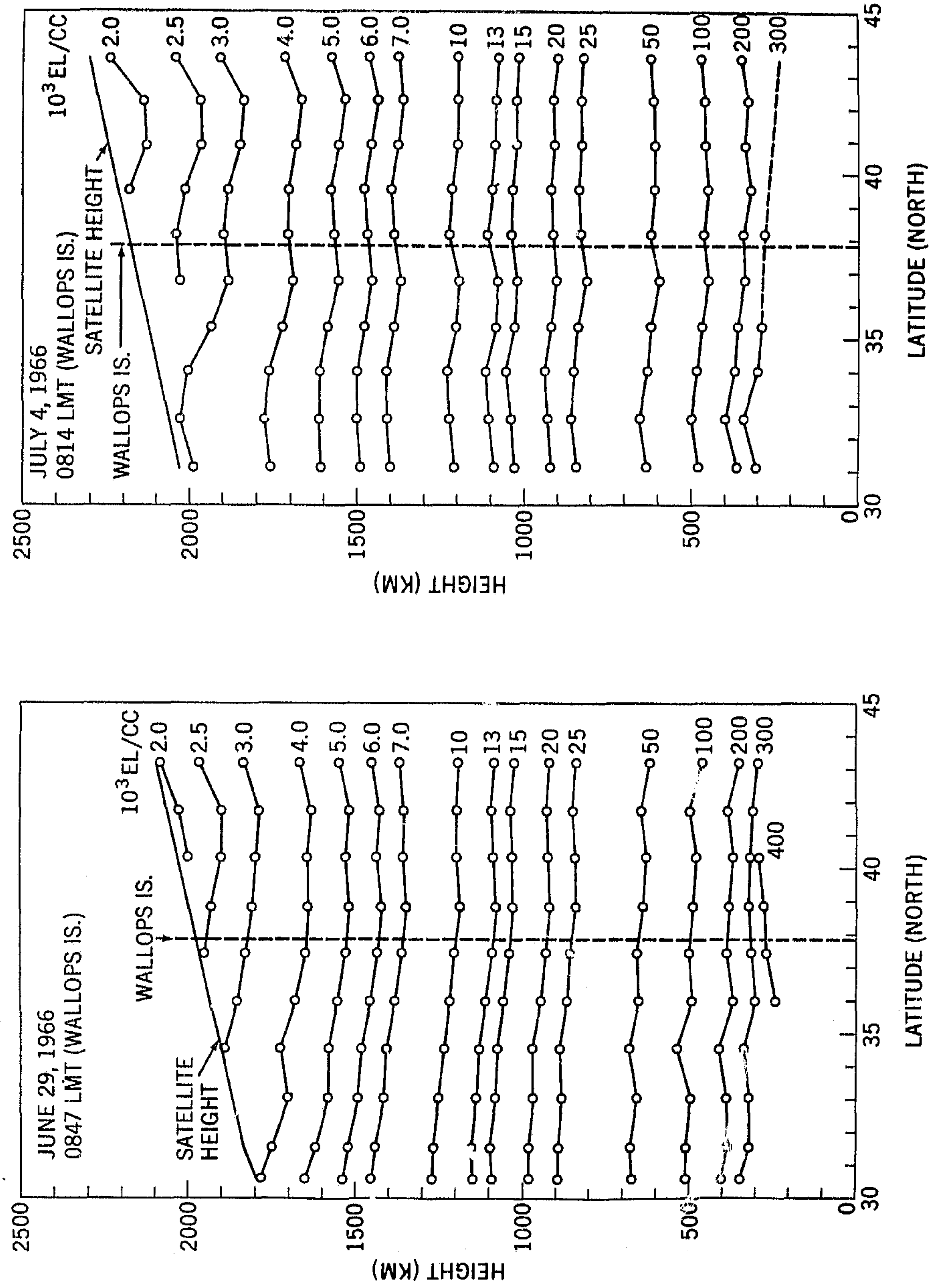

JULY 4, 1966
0814 LMT (WALLOPS IS.)
WALLOPS IS.
SATELLITE HEIGHT
10³EL/CC
2.0
2.5
3.0
4.0
5.0
6.0
7.0
10
13
15
20
25
50
100
200
300
HEIGHT (KM)
2500
2000
1500
1000
500
0
30
35
40
45
LATITUDE (NORTH)
JUNE 29, 1966
0847 LMT (WALLOPS IS.)
WALLOPS IS.
SATELLITE HEIGHT
10³EL/CC
2.0
2.5
3.0
4.0
5.0
6.0
7.0
10
13
15
20
25
50
100
200
300
400
HEIGHT (KM)
2500
2000
1500
1000
500
0
30
35
40
45
LATITUDE (NORTH)

Fig. 12

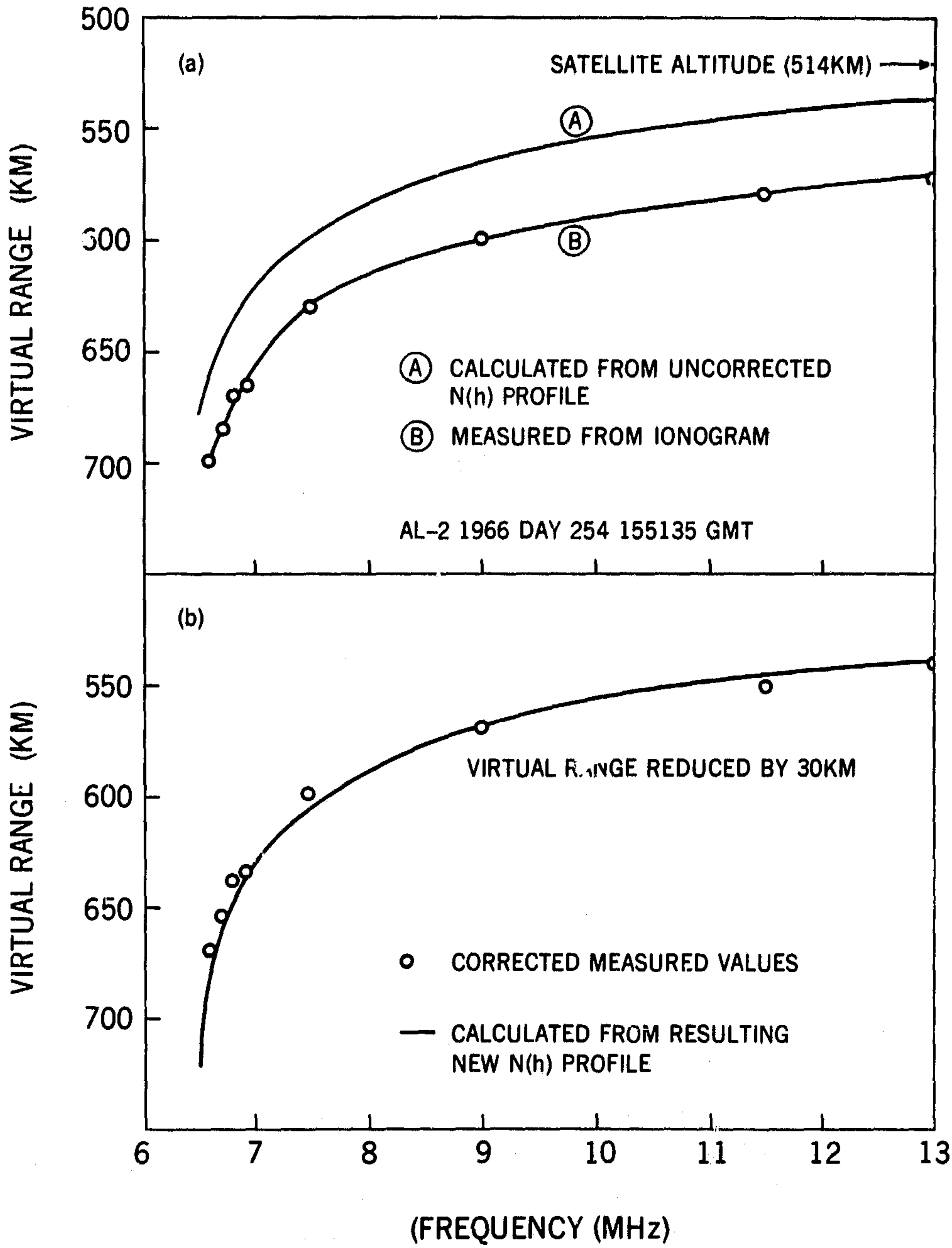
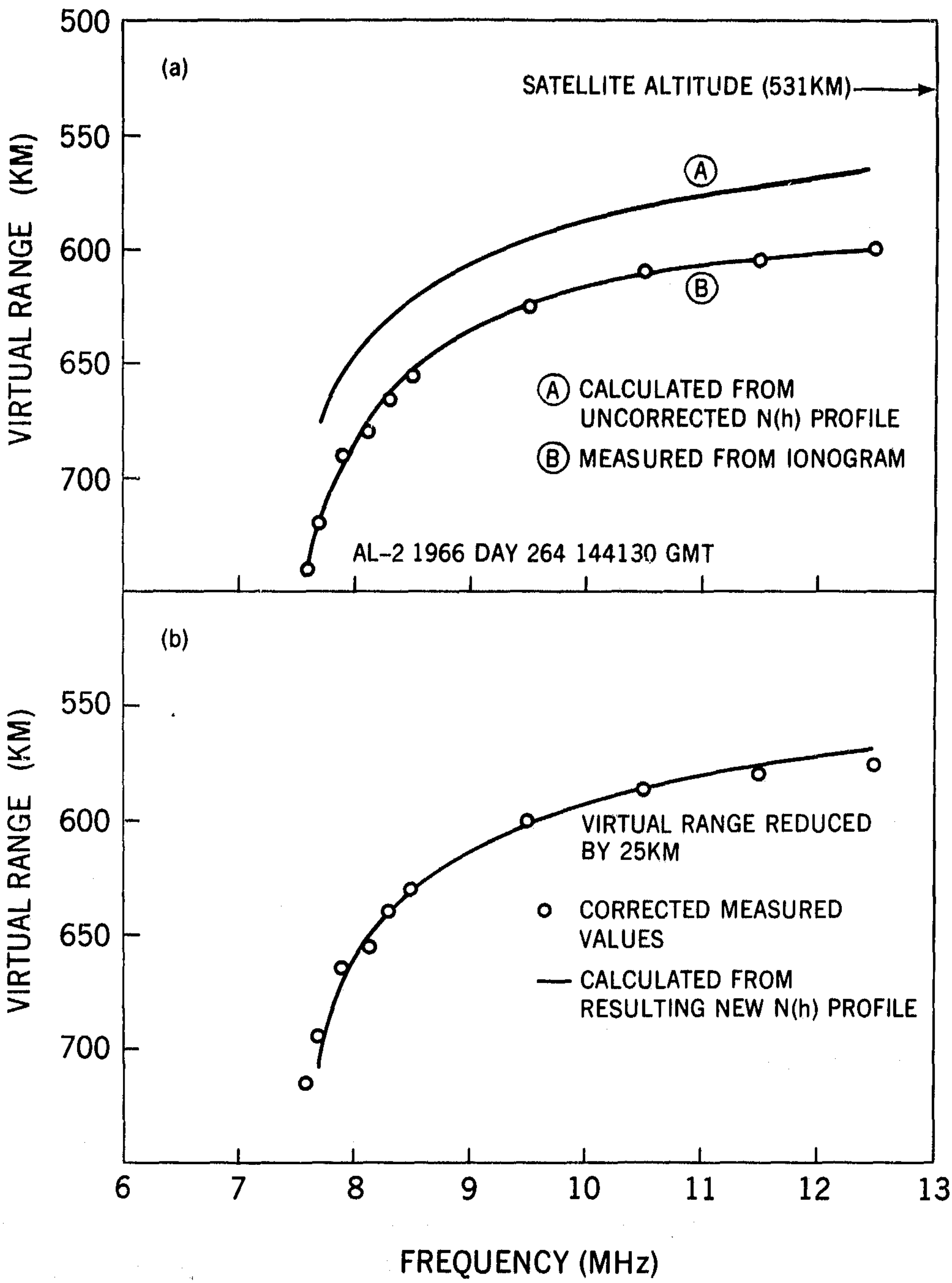
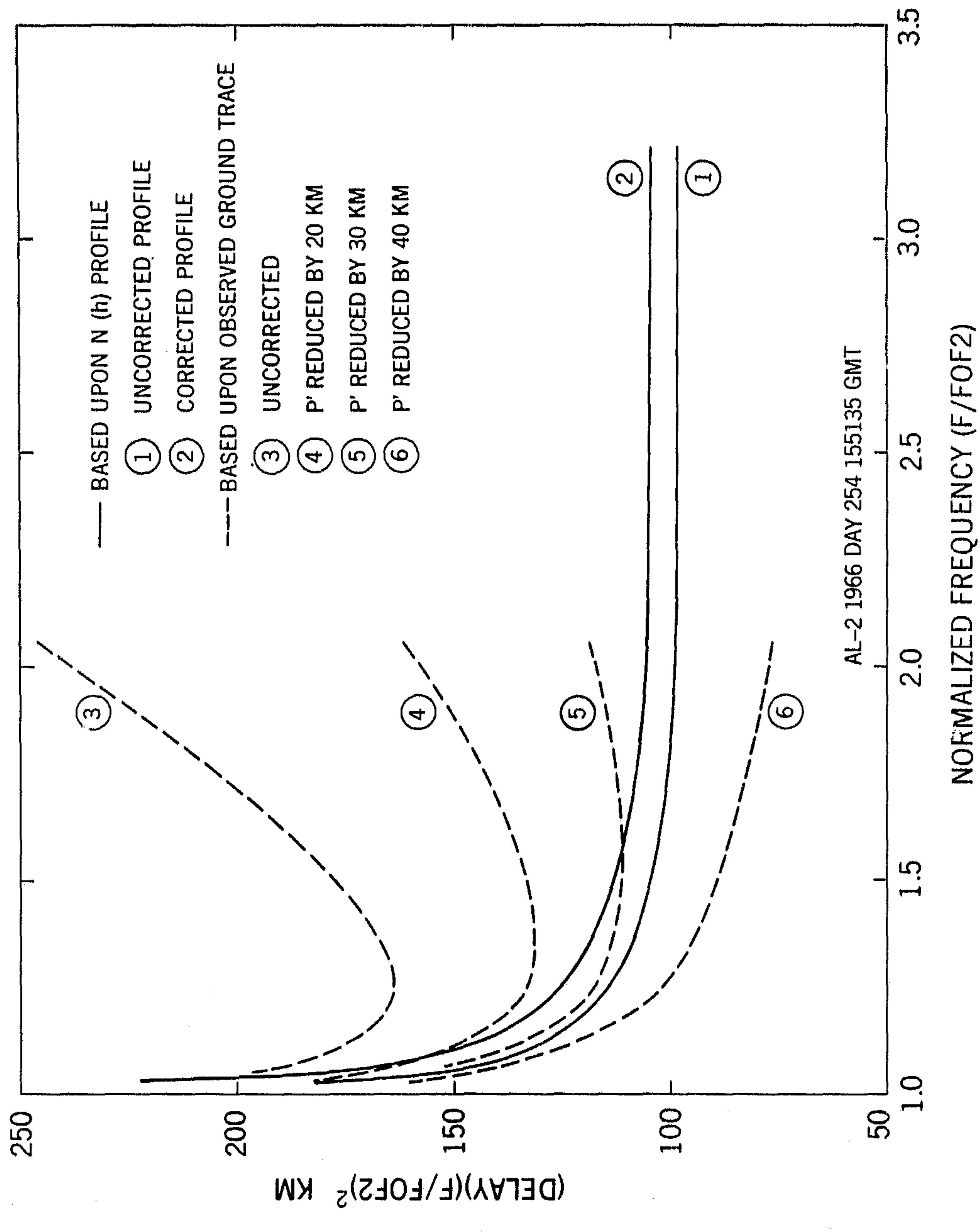

(a)
SATELLITE ALTITUDE (514KM)
A
B
A CALCULATED FROM UNCORRECTED N(h) PROFILE
B MEASURED FROM IONOGRAM
AL-2 1966 DAY 254 155135 GMT
VIRTUAL RANGE (KM)
500
550
600
650
700
(b)
VIRTUAL RANGE REDUCED BY 30KM
CORRECTED MEASURED VALUES
CALCULATED FROM RESULTING NEW N(h) PROFILE
VIRTUAL RANGE (KM)
550
600
650
700
6
7
8
9
10
11
12
13
(FREQUENCY (MHz)

Fig. 13



(a)
SATELLITE ALTITUDE (531KM)
A
B
A CALCULATED FROM UNCORRECTED N(h) PROFILE
B MEASURED FROM IONOGRAM
AL-2 1966 DAY 264 144130 GMT
VIRTUAL RANGE (KM)
500
550
600
650
700
(b)
VIRTUAL RANGE REDUCED BY 25KM
CORRECTED MEASURED VALUES
CALCULATED FROM RESULTING NEW N(h) PROFILE
VIRTUAL RANGE (KM)
550
600
650
700
6
7
8
9
10
11
12
13
FREQUENCY (MHz)

Fig. 14



— BASED UPON N (h) PROFILE
① UNCORRECTED PROFILE
② CORRECTED PROFILE
--- BASED UPON OBSERVED GROUND TRACE
③ UNCORRECTED
④ P' REDUCED BY 20 KM
⑤ P' REDUCED BY 30 KM
⑥ P' REDUCED BY 40 KM
AL-2 1966 DAY 254 155135 GMT
NORMALIZED FREQUENCY (F/FOF2)
(DELAY)(F/FOF2)² KM
1.0
1.5
2.0
2.5
3.0
3.5
50
100
150
200
250
1
2
3
4
5
6