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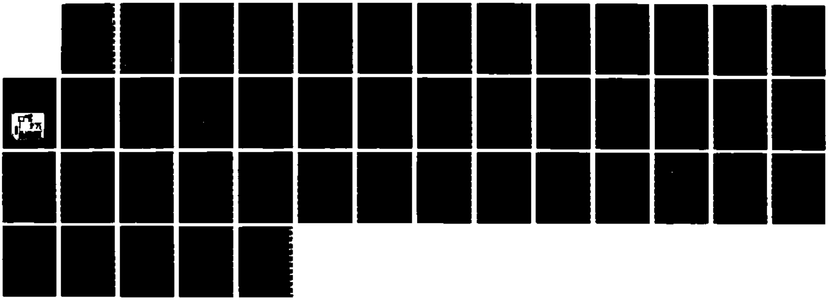

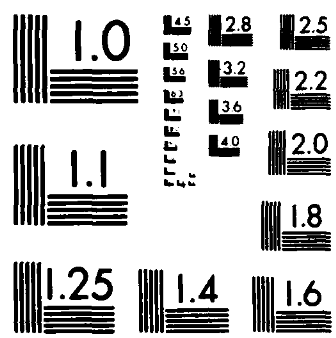
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AFGL-TR-86-0030

IONOSPHERIC PROPAGATION STUDIES DURING THE PRECISION TARGETING EXPERIMENTS

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January 1986

Scientific Report No. 2

Approved for public release; distribution unlimited.

AIR FORCE GEOPHYSICS LABORATORY
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-86-0030	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) IONOSPHERIC PROPAGATION STUDIES DURING THE PRECISION TARGETING EXPERIMENTS		5. TYPE OF REPORT & PERIOD COVERED Scientific Report No. 2
		6. PERFORMING ORG. REPORT NUMBER ULRF-431/CAR
7. AUTHOR(s) Gary S. Sales, Claude G. Dozois, Bodo W. Reinisch, Klaus Bibl		8. CONTRACT OR GRANT NUMBER(s) F19628-83-C-0092
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Lowell, Center for Atmospheric Research, 450 Aiken Street, Lowell, Massachusetts 01854		10. PROGRAM ELEMENT PROJECT, TASK AREA & WORK UNIT NUMBERS 62101F 464308AD
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory Hanscom AFB, Massachusetts 01731 Contract Monitor: J. B. Waaramaa/LIS		12. REPORT DATE January 1986
		13. NUMBER OF PAGES 44
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Ionosphere Over-the-Horizon Radar High Frequency Propagation Ionosonde		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) In support of the Rome Air Development Center's Precision Targeting Experiment during March and April 1985, the University of Lowell Center for Atmospheric Research installed and operated a Digisonde 256 vertical incidence ionospheric sounder at Erie, Colorado. The sounder continuously measured the local ionospheric layer parameters, including ionospheric tilts, during two five-hour flights of the Air Force Geophysics Laboratory's aircraft.		

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20. ABSTRACT

The data has been scaled and analyzed to provide a description of the ionosphere as it affected the HF radio waves transmitted from the SRI-International's over-the-horizon radar facility in Los Banos, California.

Comparison is made between the results simulated using ionospheric models, the backscatter ionograms and the oblique ionogram data over the same propagation path.

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ACKNOWLEDGEMENT

The authors wish to thank the staff of the Center for Atmospheric Research who participated in the experiments and the analysis, especially Messrs. David F. Kitrosser, Gary R. Fuller, Eric Li and William T. Kersey. The many helpful discussions on data samples with Mr. Jurgen Buchau of AFGL and Mr. Eli Tichovolsky of RADC are greatly appreciated.

1.0 INTRODUCTION

1.1 Objectives

The Precision Targeting Experiment (PTE) was designed primarily to develop a data base for deducing the actual target range (ground range) from the radar range (slant range) for aircraft detections using an over-the-horizon radar system. This calibrated data base will be used to evaluate the performance of existing methods of converting radar slant range to ground range, including the accuracy with which this process can be accomplished. New methods will then be developed which can achieve equal accuracy, but with much greater processing speed.

Two aircraft missions were flown on 5 March 1985 and 17 April 1985. The primary purpose of the aircraft was to serve as a target for the OTH-B radar. The aircraft carried a transponder which enhanced its cross-section. Since the purpose of this experiment was range conversion accuracy and not detection it was appropriate to use the transponder.

The frequency management of the radar and the timing of the aircraft flight was designed to produce a variety of propagation conditions that would serve to test the accuracy of range conversion under operational conditions.

The ionosphere permits the signals from these radar systems, using HF (6-30 MHz) radio waves, to propagate over the horizon and to detect a distant moving target by backscattering a small fraction of the transmitted signal. The propagation path, via the ionosphere, introduces additional time delay over the great circle path between the radar and the target. This additional time delay results from the increased distance introduced by propagating up to the reflecting layer and then down again, and from the fact that the wave propagates at a speed less than the speed of light along the ionospheric portion of the path. If the observed time delay for the backscattered signal from the target is multiplied by the speed of light, an effective distance (slant range) is obtained which is always greater than the true ground range. Attempts to deduce the ground range from the slant range by using a simple model in which reflection occurs at some estimated altitude can be only partly successful. Better knowledge of the structure of the ionosphere is required. Improved corrections are obtained by an iterative method starting with a model of the ionosphere or through direct ionospheric measurement. Although this direct approach is not always possible for operational radar systems, the method will be applied here on an experimental basis to determine the limits set by the ionosphere and the range conversion process.

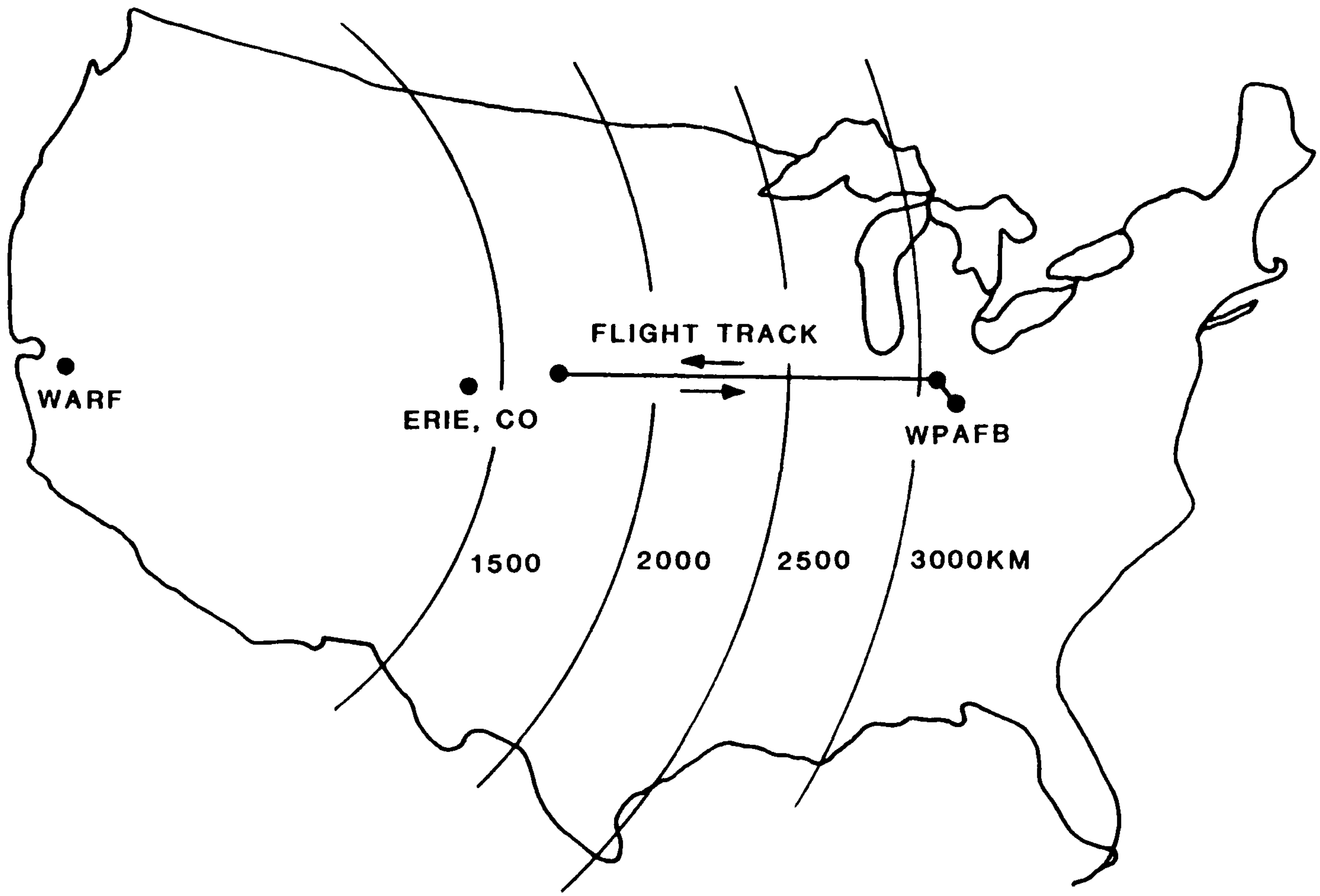
This direct approach involved the measurement of all the ionospheric parameters at a site near the midpoint of the propagation path between the radar and the aircraft target. ULCAR was responsible for producing this midpoint reference data using the Digisonde 256 ionospheric sounder, and operating the sounder for periods that included both aircraft flights. In addition to the usual vertical incidence ionospheric parameters this midpoint sounder made angle of arrival measurements, so that ionospheric tilts could be identified and factored into the ray analysis for an improved range conversion process.

1.2 Approach

The requirement to locate a Digisonde at the midpoint of the radar propagation path from Los Banos, CA (37° N, 121° W) to the AFGL aircraft could be met only approximately since the range from the radar to the aircraft was always changing. The aircraft flew an almost straight path from Wright-Patterson AFB at Dayton, Ohio, a distance of 3200 km from the radar, along a radial that brought it to within 1800 km range of the radar.

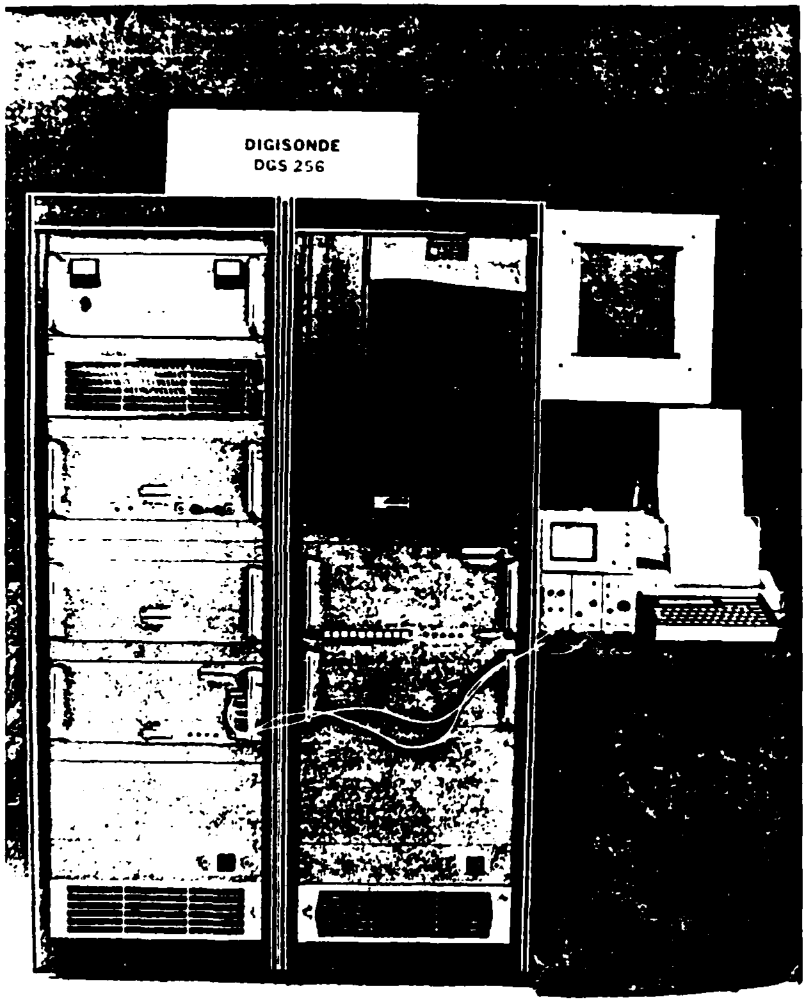
The location of the midpoint site was necessarily a compromise and logistic support was a factor to be considered. With the cooperation of the Institute for Telecommunication Sciences the use of their Erie, CO site (40° N, 104° W) was arranged and the Digisonde established there before the first mission. This site is 1485 km from the Wide Aperture Radar Facility (WARF) system along an acceptable flight path for the aircraft, some 18° north of east as seen by the radar. Figure 1 shows the locations of the radar, the Digisonde and the flight path of the aircraft. Figure 2 shows the Digisonde 256 as used for the Precision Targeting Experiment, and the configuration of the four receiving antennas used to determine ionospheric tilts.

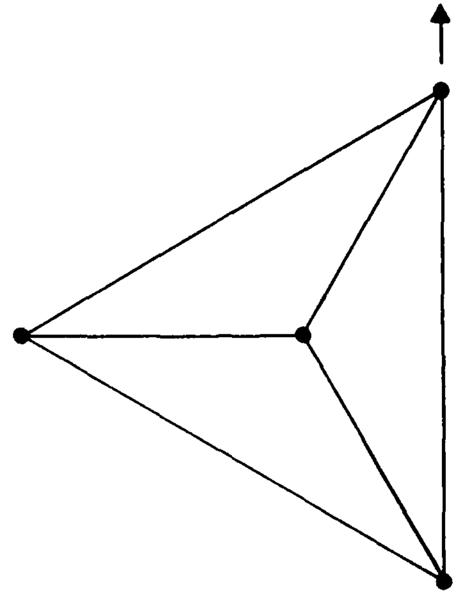
Vertical ionograms were taken continuously for more than one week for each of the two missions. It was essential to provide background data for each flight, particularly since the level of geomagnetic activity changed and clearly affected the propagation conditions. This background data will be used to put the results for the flight periods in the proper context. Drift mode data was interlaced with the vertical ionograms and taken continuously during the flight periods, with selected data at other times.



FLIGHT TRACK - PRECISION TARGETING EXPERIMENT
5 MAR 85 AND 17 APR 85

FIGURE 1





Digisonde 256 System and Antenna Configuration

FIGURE 2

2.0 DATA COLLECTION AND REDUCTION

2.1 Data Collection

This report covers the first two flights of the proposed three missions for the Precision Targeting Experiment. The first two missions took place on 5 March 1985 and 17 April 1985. These flights and the period around each flight will be designated the March and April campaign, respectively. The data collection schedules for these two campaigns are indicated in Figure 3. As part of this preliminary analysis, the level of geomagnetic activity has been included in the figure. The ΣK indices were derived from the Fredricksburg K indices published in the NOAA-USAF Preliminary Report and Forecast of Solar Geophysical Data.

The vertical ionograms were made every five minutes, stepping from 1 to 7 MHz and taking approximately 1.5 minutes to complete. The remainder of the five minute interval was used to make the tilt measurements, operating the Digisonde in the so-called drift mode (Bibl et al., 1981).

Periodically, Smith transmission curves appropriate for the range of the aircraft at the particular time were used on the Erie vertical ionogram and the scaled transmission frequency forwarded to the radar as an aid in frequency management. Two examples are shown in Figure 4. The first was taken on 5 March 1985 at 1854 UT and the second on 17 April 1985 at 2109 UT. In both cases the aircraft-range was somewhat greater than 3000 km. These are very typical of the early part of the flight period when foF2 was not much greater than foF1. On the 5 March ionogram the F1 layer is stratified, indicating the presence of an additional transient layer often designated as the F0 layer. In this particular case with the MUF(3000) curves overlaid, the highest MUF is determined by the F0 layer with a frequency greater than 15 MHz. For the April mission the 16 MHz MUF(3000) curve is

PTE DATA SCHEDULE

MAR 85

Calendar Day	1	2	3	4	5	6	7	8	9	10	11
Julian Day	060	061	062	063	064	065	066	067	068	069	070
ΣK	17	26	18	16	30	26	24	27	6	17	13

Flight

Ionogram Analysis

Tilt

APR 85

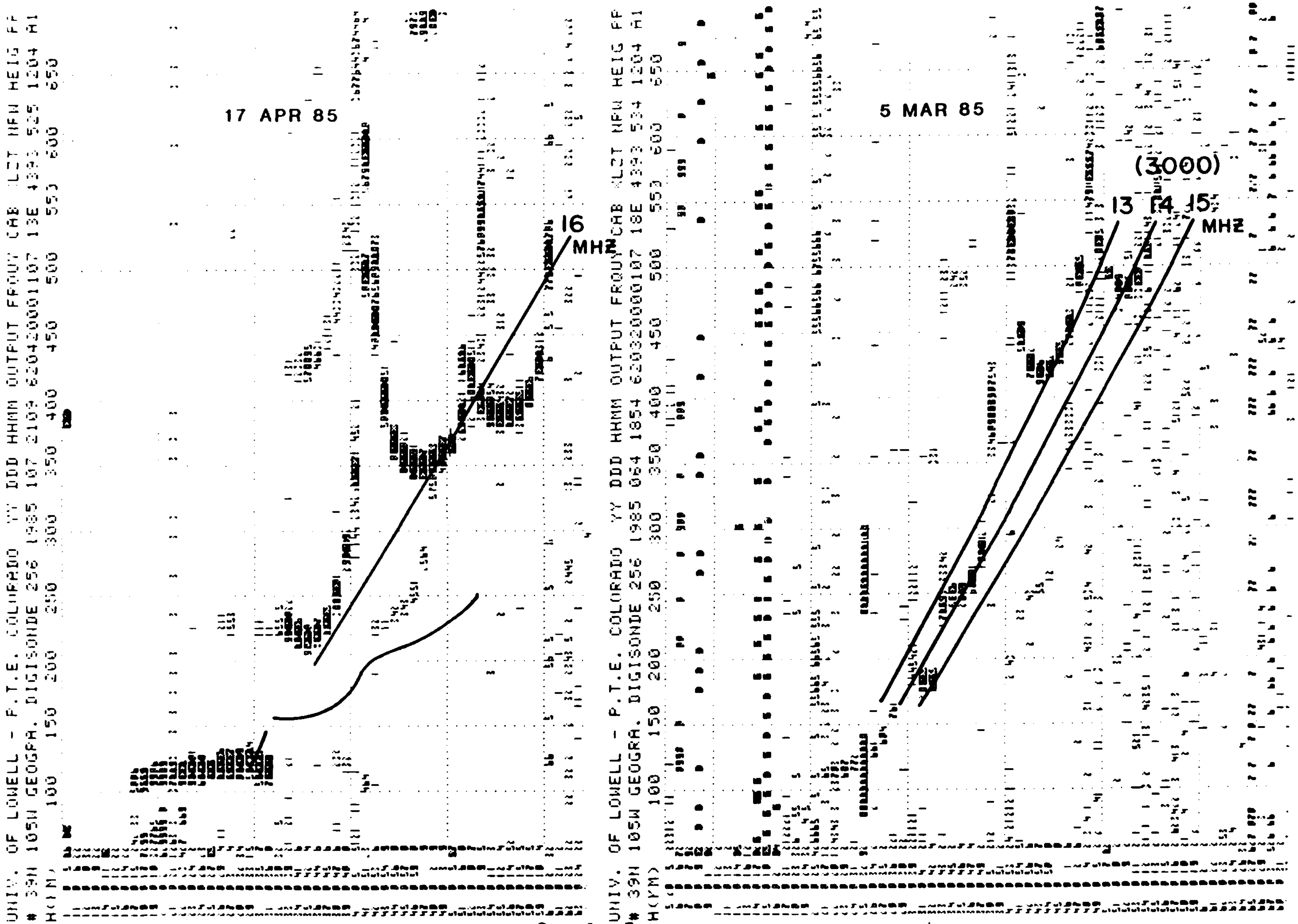
Calendar Day	15	16	17	18	19	20	21	22
Julian Day	105	106	107	108	109	110	111	112
ΣK	9	16	12	9	23	33	42	22

Flight

Ionogram Analysis

Tilt

Figure 3



Sample Ionograms

FIGURE 4

overlaid to indicate the small difference between MUFF1 and MUFF2 at that particular time.

2.2 Data Reduction

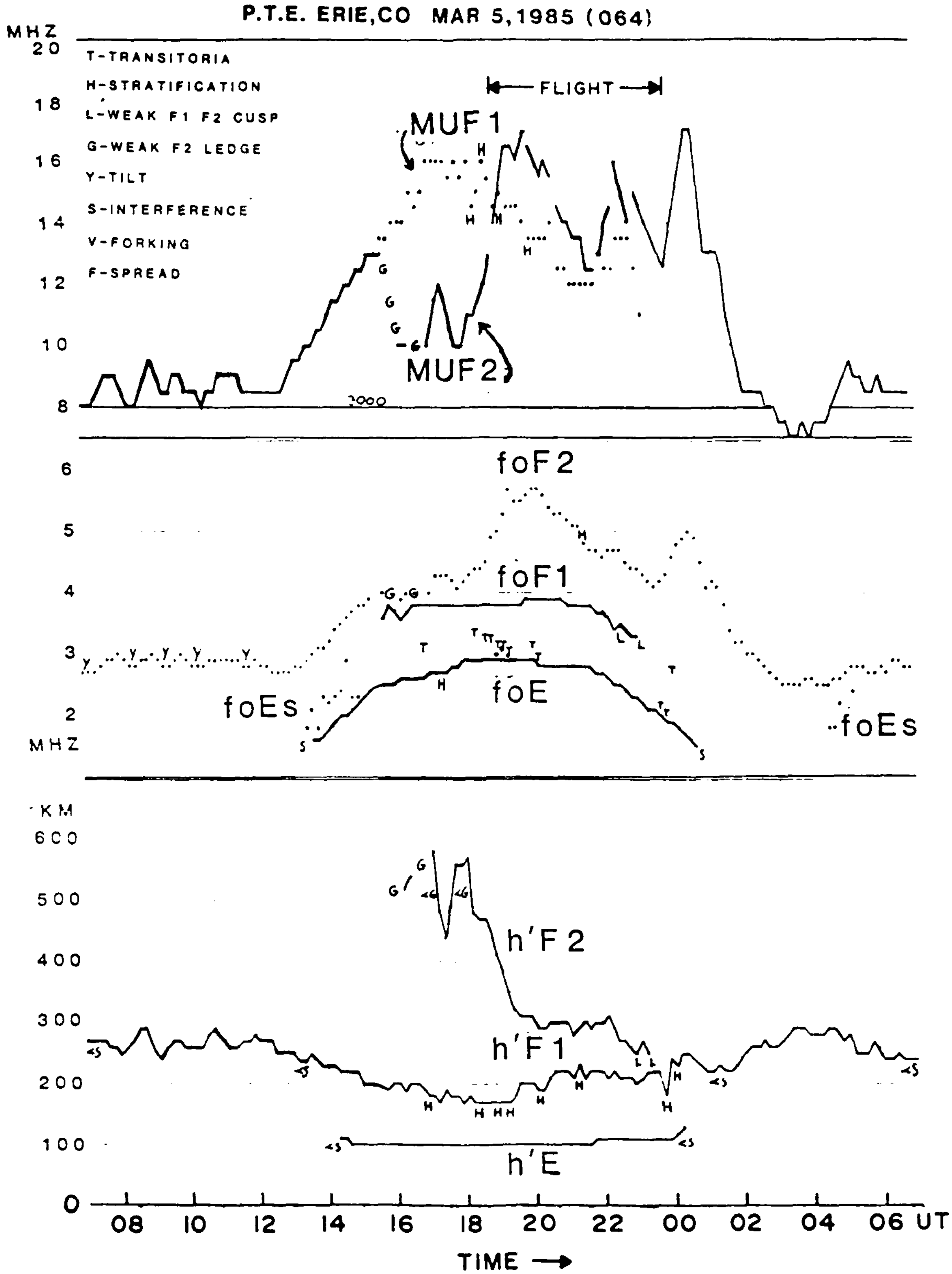
2.2.1 Vertical Sounding

The usual ionospheric parameters were scaled for the two campaigns. For the March campaign the data included in this report covers the period from 4 March 1985 through 9 March 1985. For the April campaign the period covered was from 16 April 1985 through 20 April 1985. The scaled data for the flight days are shown in Figures 5 and 6.

The vertical parameters are unaffected by the aircraft range. However, the maximum usable frequency (MUF) was scaled as a function of the range of the aircraft. For all times when the aircraft was not flying, the MUF was scaled for the usual 3000 km range. During the flight the scaling range was adjusted in steps of 200 or 400 km depending on the range of the aircraft.

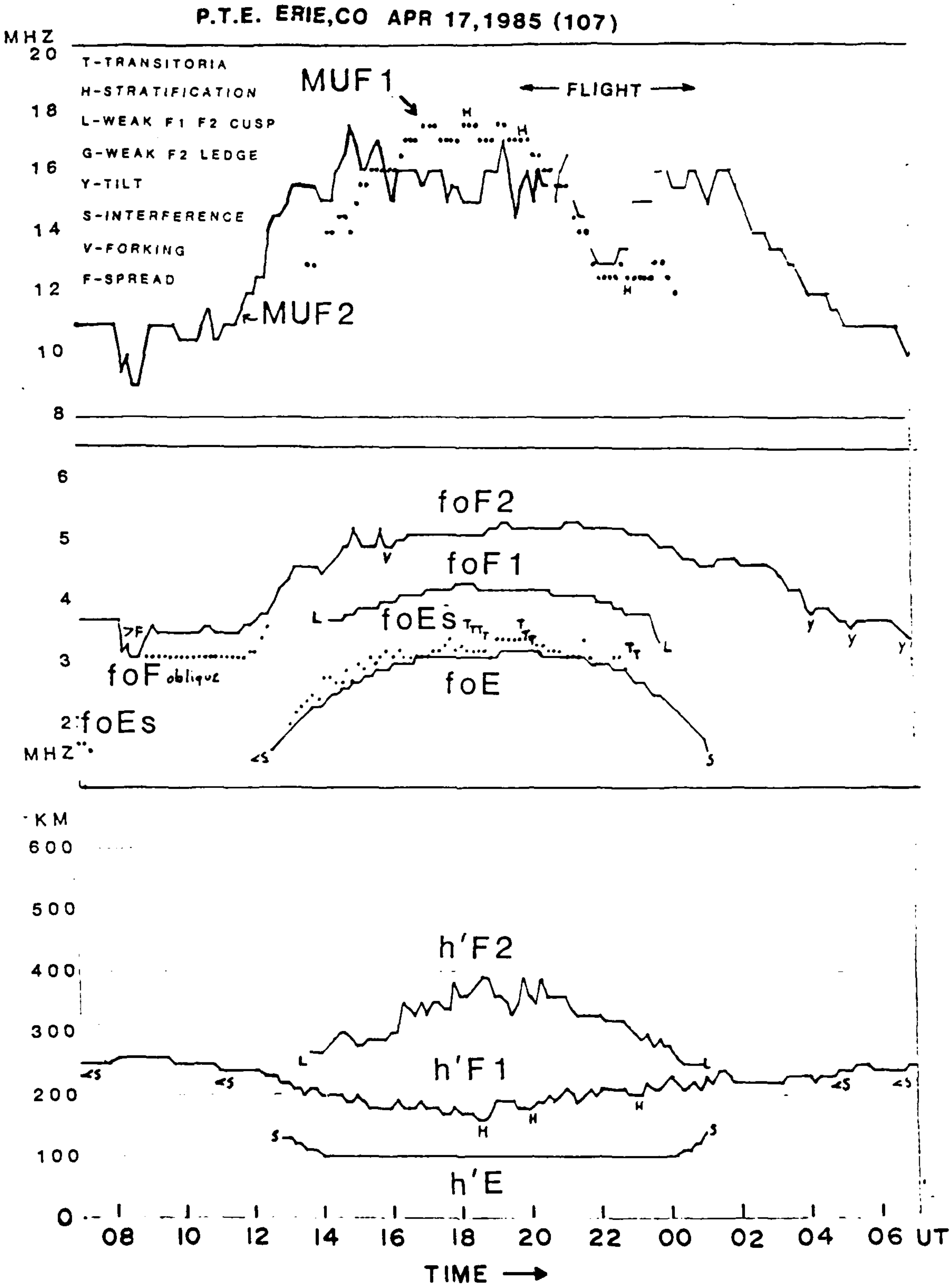
There were significant differences in the ionospheric parameters between the two flight days, particularly for the F2 layer. These differences were clearly related to the level of geomagnetic activity on these days, with 5 March a "disturbed" day and 17 April a "quiet" day. This subject will be addressed later in this report.

The five-hour flight periods are indicated in Figures 5 and 6. The changing MUF during that period is a combination of both the changing range to the aircraft and the changing ionosphere, especially of the critical frequency and the height of the reflecting layer. More detailed plots of the scaled MUF data for the flight periods are shown in Figures 7 and 8. These flight data were collected and analyzed by AFGL, while the radar data was collected by SRI-International and provided by RADC (this includes the data presented



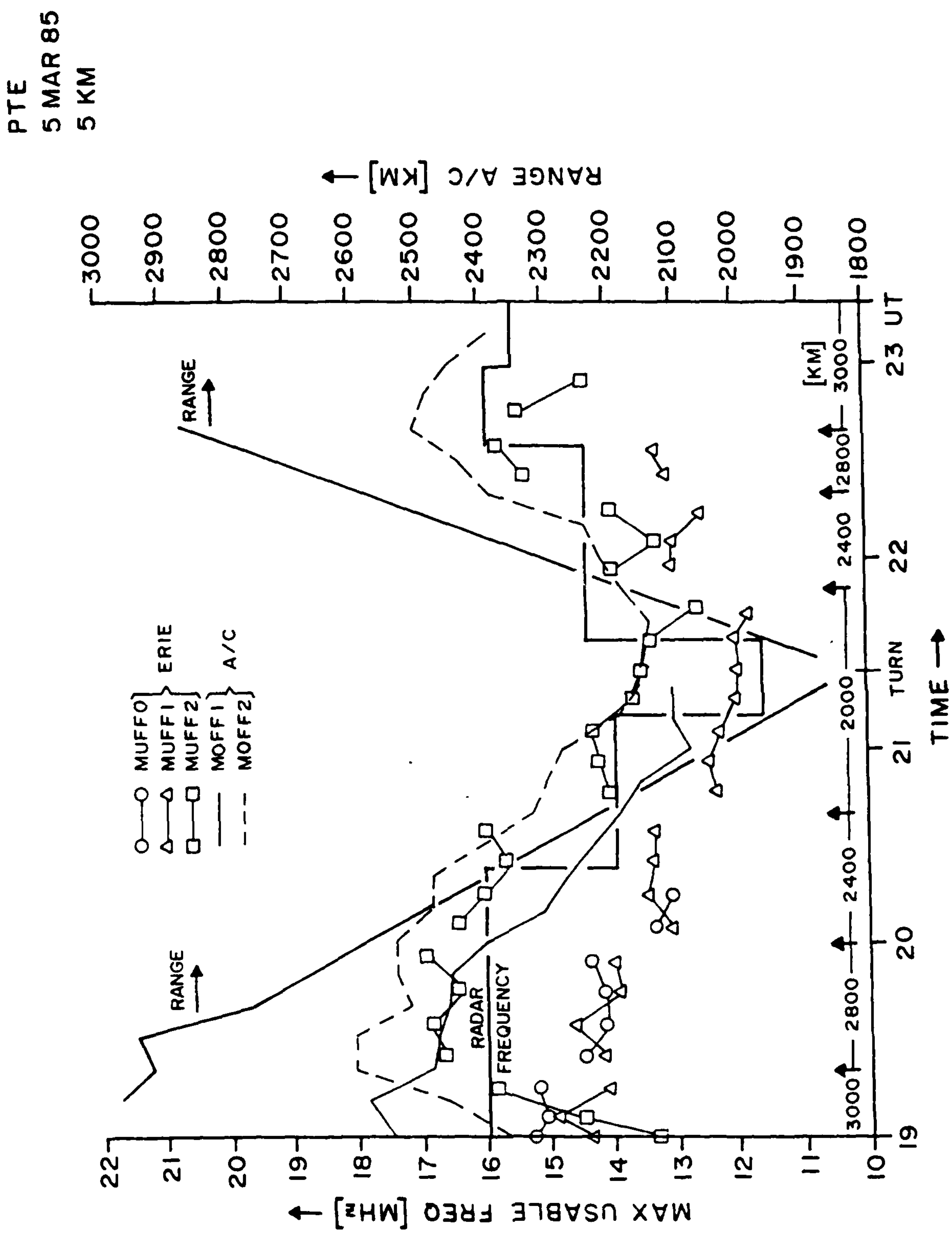
Scaled Layer Parameters - 5 Mar 85

Figure 5



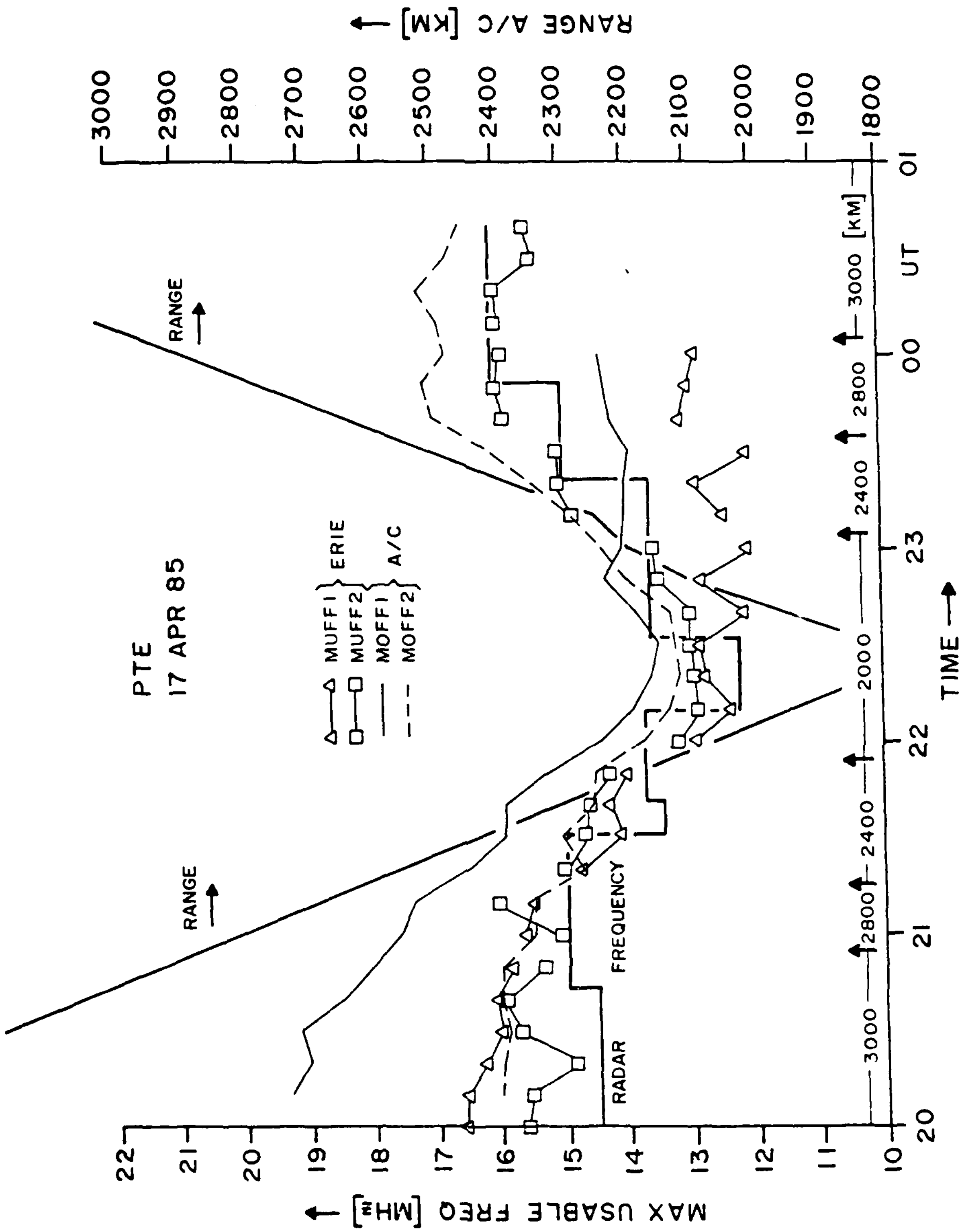
Scaled Layer Parameters - 17 Apr 85

Figure 6



Scaled Oblique Ionogram Data - 5 Mar 85

Figure 7



Scaled Oblique Ionogram Data - 17 Apr 85

Figure 8

in Figures 13 and 19). Both the F1 and F2 layer MUFs were scaled from the vertical incidence ionograms, and are labeled MUFF1 and MUFF2, respectively. Indicated on each plot is the interval over which a particular MUF distance was used and these can be compared to the actual aircraft range, also shown in these figures. In Figure 8, for the April mission, the "kink" in the range plot at around 2300 UT was caused by the planned touch-and-go executed by the KC-135 aircraft at Offutt AFB near Omaha, Nebraska.

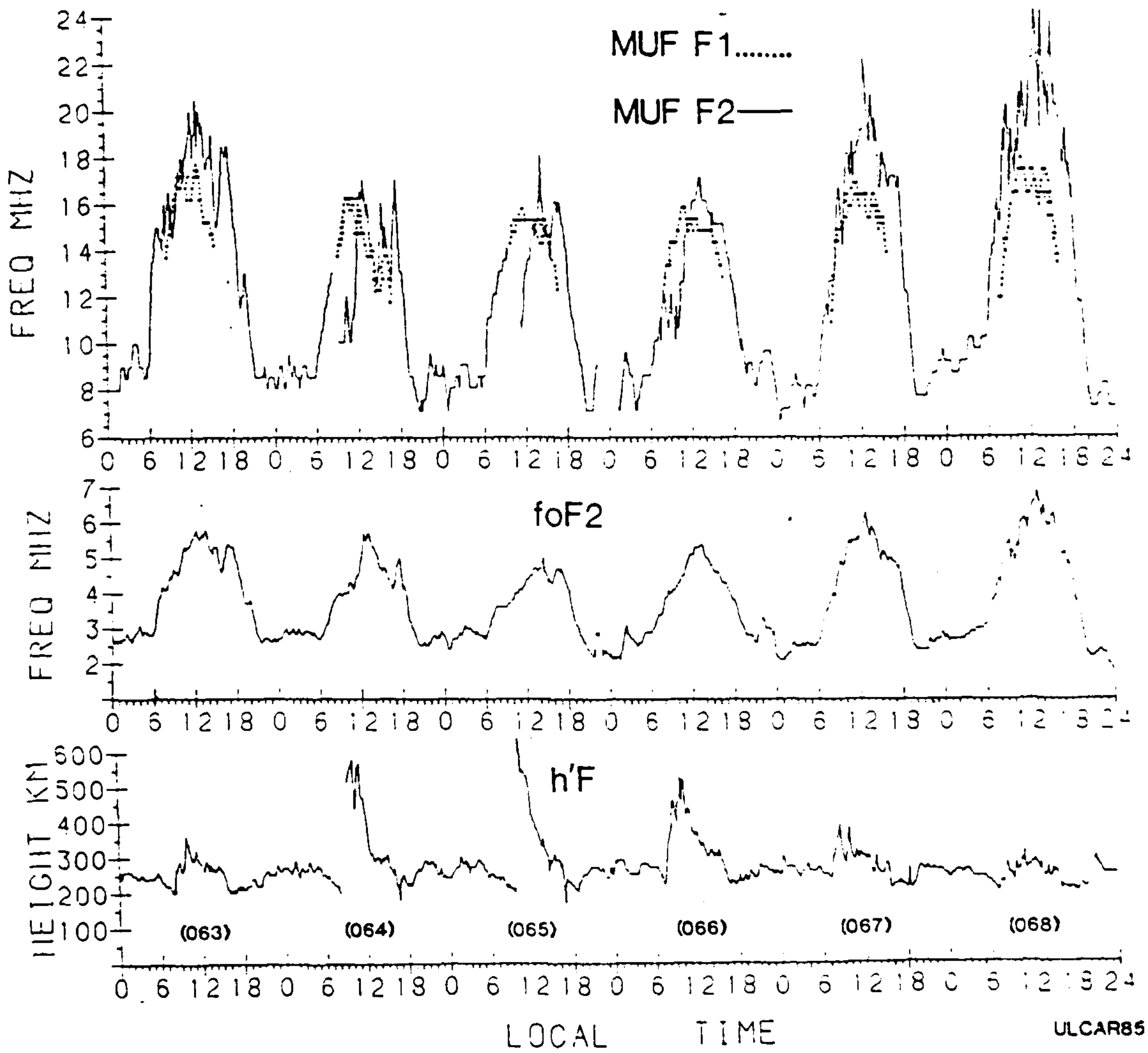
Superposed on these plots for later analysis is the radar operating frequency and the actual maximum observed frequency (MOF) observed aboard the aircraft by receiving the wideband sounder transmissions from the radar site.

Finally a composite plot is presented of the MUF curves and the F2 layer parameters for each campaign (Figures 9 and 10), covering the days for which the data was scaled. This data will serve for the comparison between magnetically quiet and disturbed days and indicate how the radar frequency management and performance might be affected by these changing conditions.

2.2.2 Ionospheric Tilt Measurement

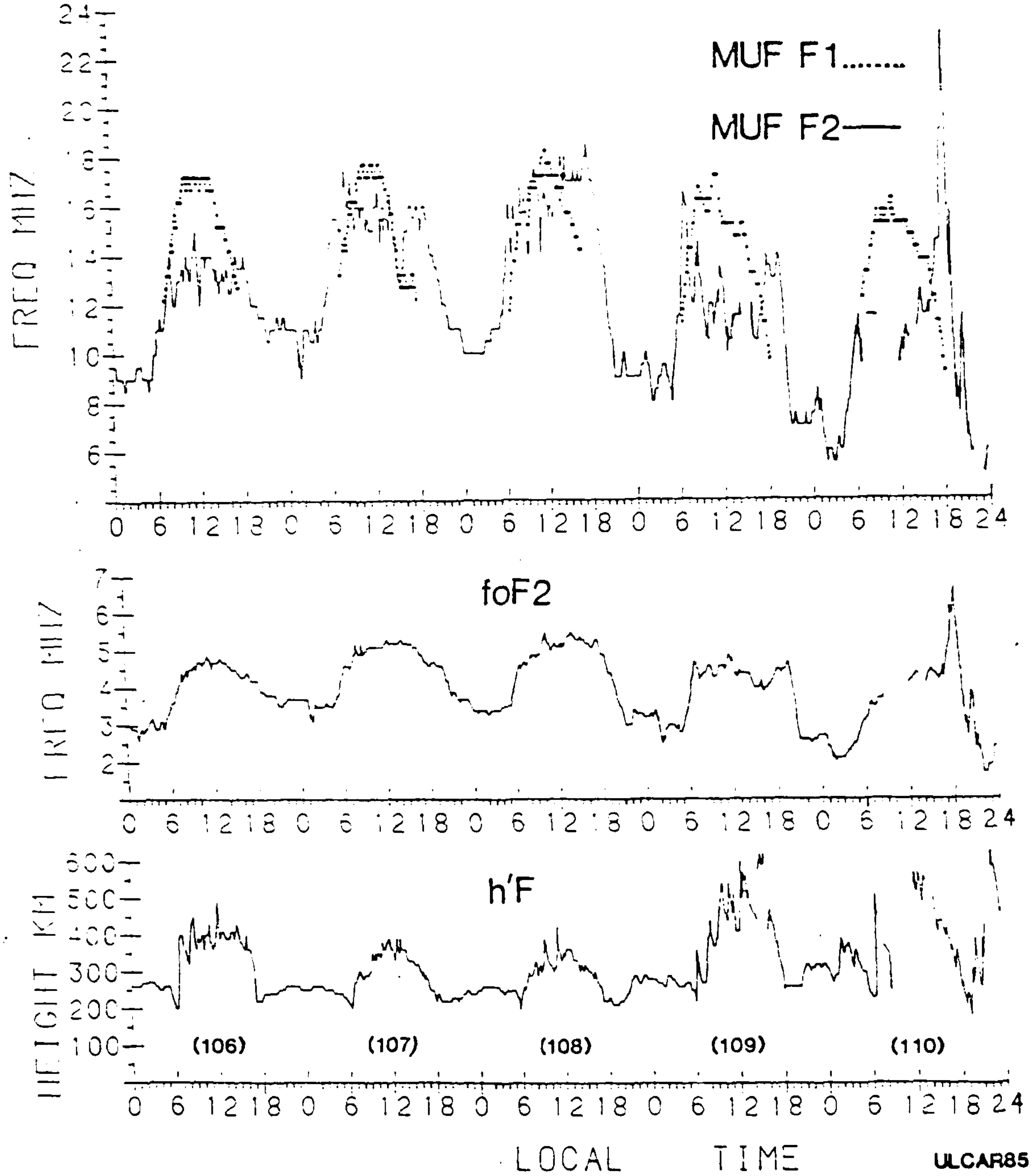
As indicated in Figure 3, many hours of tilt data were gathered during both campaigns. For this report the analysis has been restricted to the period of the actual aircraft flight. The Digisonde 256 system can simultaneously sound at four frequencies and these soundings used to determine the magnitude and direction of the ionospheric tilt. During these particular missions the system was operated at only two different frequencies, each using two different height gates.

A complete sky map of the reflecting sources is made at each frequency and each 10 seconds, approximately. This



PTE 1 Erie, Colorado - Scaled Layer Parameters
Mar 4-9, 1985

Figure 9



PTE 2 Erie, Colorado - Scaled Layer Parameters

Apr 16-20, 1985

Figure 10

SKY MAP

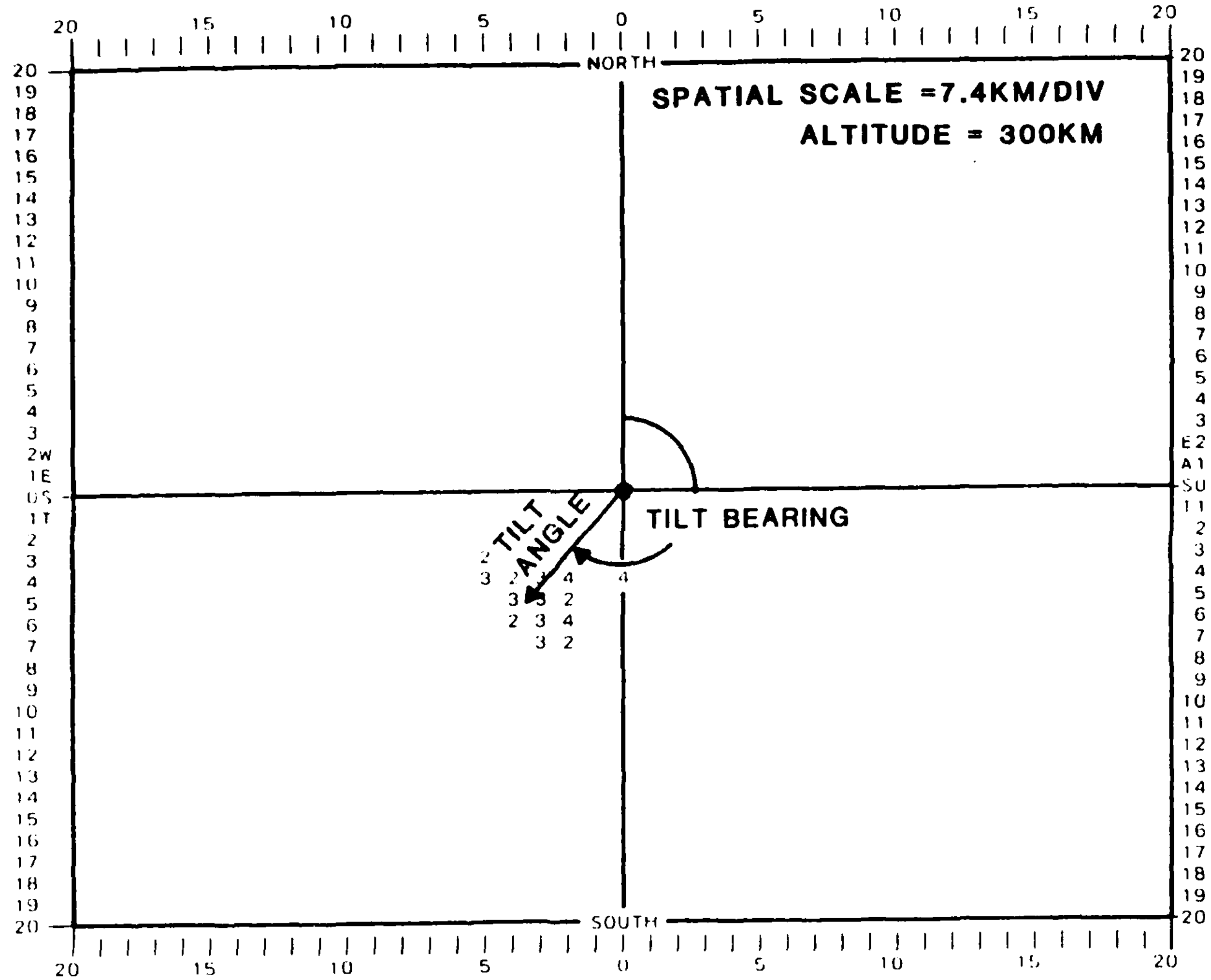


FIGURE 11

process is repeated some 19 times, filling most of the five minute interval between ionograms. The 19 cases, at each frequency, are superposed as shown in Figure 11.

The details of the production of these maps have been published elsewhere (Dozois, 1984) and will not be repeated here, except to say that these sky maps represent the reflection sources as seen looking up from the ground with the zenith direction at the center. The location of the source is measured in units of the spatial scale factor adjusted for the frequency and height of reflection. In Figure 11 the map indicates the scaled Doppler frequency shift associated with each observed source. These maps are produced once each five minutes.

Figure 11 is very typical of the entire data set for the five hours of the aircraft flights. Except for a small number of extraneous points, most sources are clustered very tightly at a particular location in the sky. Using this data, a single location has been defined for each five minute interval and the tilt angle and azimuth, as indicated in Figure 11, of the median source relative to overhead and north has been determined. This was done by smoothing the data and determining the center of gravity of each cluster. Then the tilt angle and azimuth of that center of gravity was calculated. Figure 12 shows the tilt measurement operating frequency relative to the layer critical frequencies for the two missions.

Except for the first hour of the March mission and the first hours of the April mission, all of the tilt measurements were made for the F2-layer.

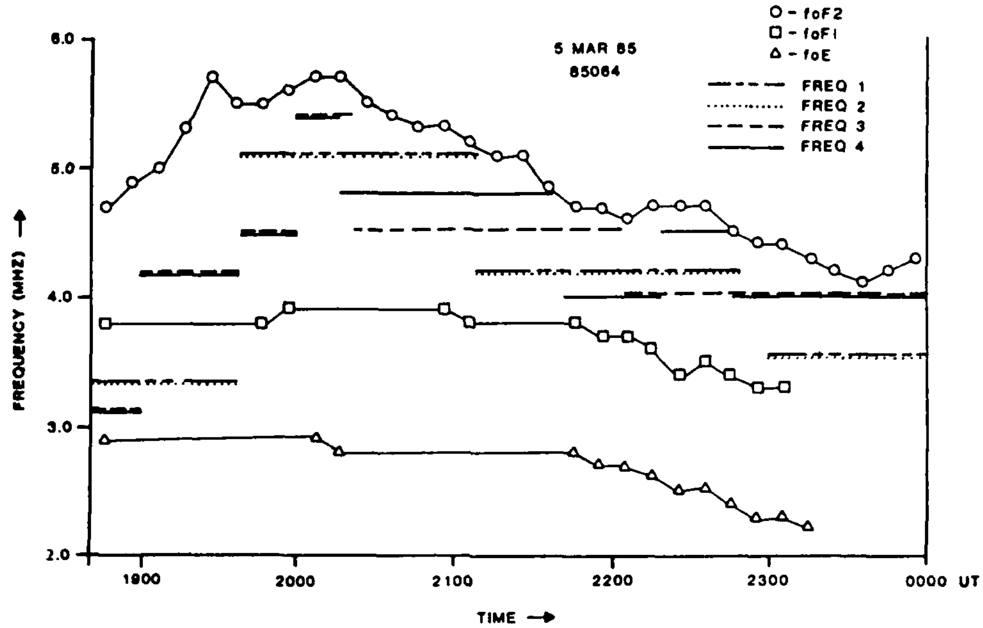


FIGURE 12A

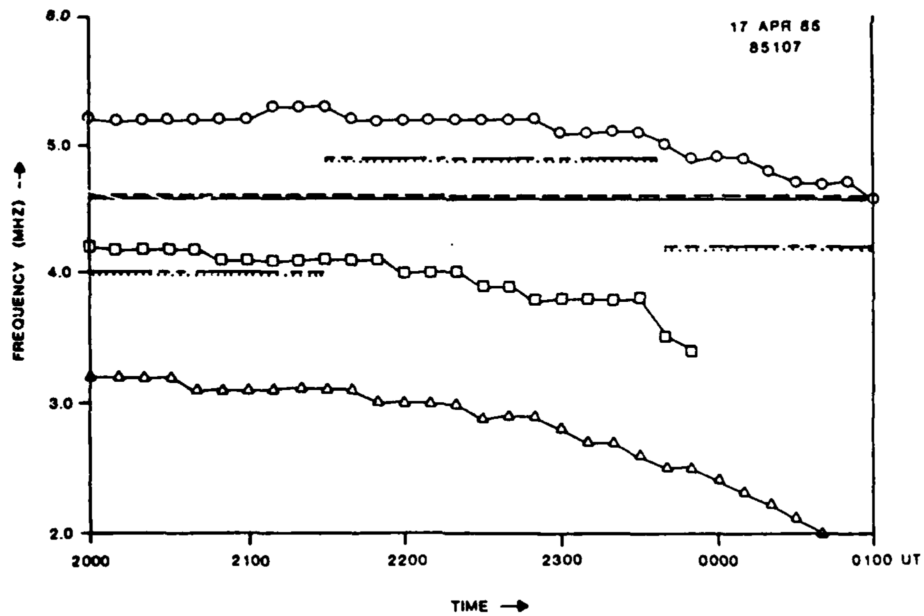


FIGURE 12B

Tilt Mode Operating Frequencies

3.0 ANALYSIS

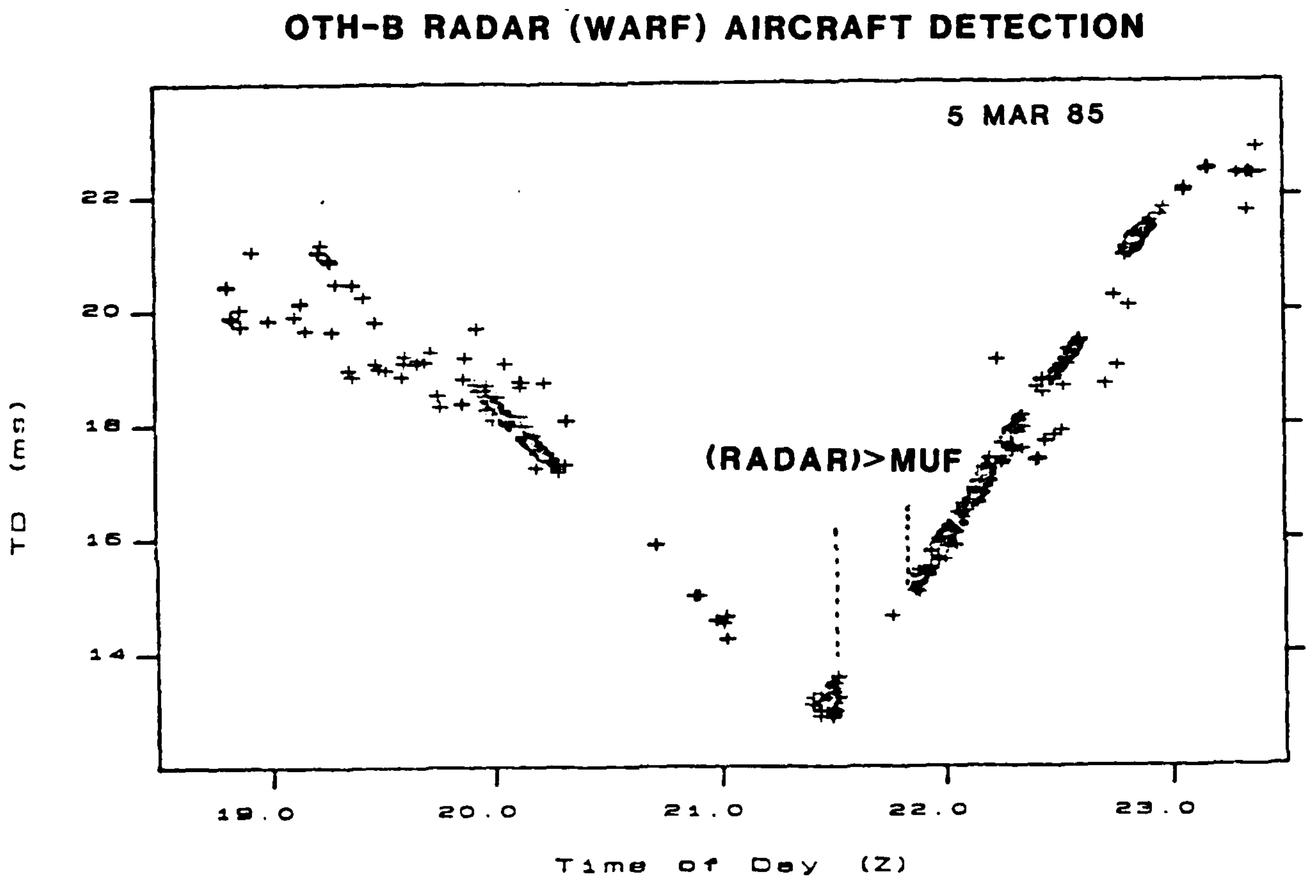
3.1 March Campaign

3.1.1 Vertical Incidence Sounding

The mission on 5 March 1985 took place on a geomagnetically active day with a $\Sigma K = 30$ using the Fredricksburg indices. The flight which began shortly before 1900 UT was preceded by a significant geomagnetic storm effect, with the virtual height decreasing from above 500 km down to the normal 300 km in just over one hour. The F2 critical frequency increased from just above 4 MHz to 5.8 MHz in the same time. This combination of effects, that is low foF2 and high h'F2, resulted in the MUF(3000) being as low as 10 MHz and remaining below 13 MHz until the beginning of the flight. Shortly after takeoff the MUF increased to over 16 MHz. This magnetically active condition repeated on the next three days to varying degrees (see Figure 9). The virtual height and critical frequency curves indicate that the storm effects continued to subside through the eighth of March, with normal conditions returning on 9 March with a $\Sigma K = 6$.

The dip in the MUFF2 curve between 1900 UT and 2300 UT is primarily caused by the change in the range to the aircraft. This same effect is better seen in Figure 7 where the mission time is expanded. Figure 7 also shows the MOFF2 and MOFF1 as measured directly aboard the aircraft receiving the wideband soundings from WARF. These were scaled aboard the aircraft and also used to assist the radar in frequency management during the flight. The solid curve indicates the radar operating frequency during the flight. The radar operating frequency was kept 1 to 2 MHz below MOFF2 most of the time. Occasionally the operating frequency approached the MOF (c.f. 2020 UT and 2110 UT), indicating that the aircraft was approaching the skip range. At these times the frequency was usually changed by about 2 MHz and the operation continued. During the period 2130 to 2210 UT the operating frequency exceeded the MOF by more than 1 MHz and aircraft detection should have been impossible during this period. The SRI-International WARF detection data in Figure 13, show that there was virtually no aircraft detection between 2130 and 2150 UT. However, there are other times when detection became poor and the radar frequency was correct in terms of the MUF. Questions as to target amplitude and subclutter visibility must also be looked at in detail. During the entire mission MOFF2 > MOFF1 as seen by the aircraft. This was not always the case for the April mission.

Finally, for the entire mission, a set of scaled MUF's was produced from the Erie vertical ionograms using the Smith propagation curves for the appropriate range to the aircraft. This data is also superposed on Figure 7 for comparison with the measured MOF's. The MUFF2 and the MOFF2 curves agree reasonably well throughout the flight, with typically less than one megahertz difference. However, this difference is systematically displaced in one direction, with MUFF2(Erie) < MOFF2(aircraft). The same is true for MUFF1. However, the difference is greater; more than 2 MHz until 2100 UT. Another problem is that MUFF1(Erie) was derived throughout the flight, while from the aircraft there was no F1 propagation mode to scale after 2130 UT. For almost two hours the vertical ionogram indicated that an F1 mode should exist when none could be found at the aircraft. These differences between midpoint scaling and actual MUF measurements need further analysis. These differences may affect the process of range conversion. Range conversion requires the identification of the propagation mode and some estimate of the equivalent virtual height of the oblique ray.



WARF Aircraft Detection - 5 Mar 1985

Figure 13

3.1.2 Tilt Measurements

Although 5 March 1985 was a geomagnetically disturbed day with unusually low values of foF2, beginning around sunrise and ending just after the beginning of the mission at around 19 UT, the foF2 decreased steadily throughout the flight and was otherwise well behaved. There seems to be no significant difference between the March and April tilt data.

Figure 14 shows the tilt angle and bearing angle for the March mission from frequencies 1 and 3. Most of the time frequency 2 is the same as 1 and 4 is the same as 3. The frequency data in Figure 12 shows that until 1920 UT the tilt measurements on frequency 1 are in the F1-layer and then in the F2-layer. Frequency 3 is always in the F2-layer, sometimes above and sometimes below frequency 1. Using these two frequencies, the tilt data simultaneously measured the horizontal gradient in the ionosphere at two different altitudes.

Over the period of the flight the magnitude of the tilt as measured at Erie varied between 1.5 degrees to 6 degrees, with an overall median tilt of approximately 3 degrees clearly towards the south. There seems to be some trend in the analyzed data, with the bearing seeming to shift from east of south during the early hours of the flight to the west of south during the second half of the flight. Dividing the data into two halves separated at 2130 UT indicates a significant shift from 2.6° to 3.4°, while the bearing shifts from 160° T to 190° T during the five hours of this mission. This variation of tilt direction from SSE before 22 UT to SSW after 22 UT agrees qualitatively with the expected behavior as the maximum F2-layer moves from east of Erie, CO to the west. Superposed on this general trend is a somewhat random variation, with periods of tens of minutes to one hour and a magnitude ±1 degree. The source of these fluctuations may be gravity waves passing over the site. This question needs additional study.

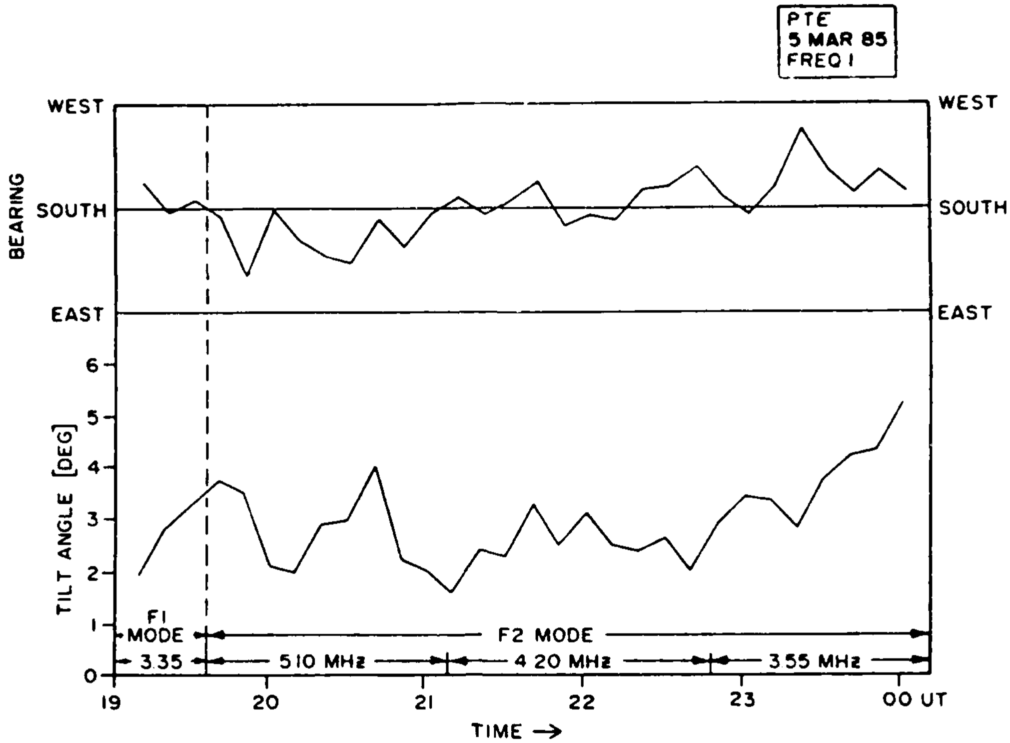


FIGURE 14A

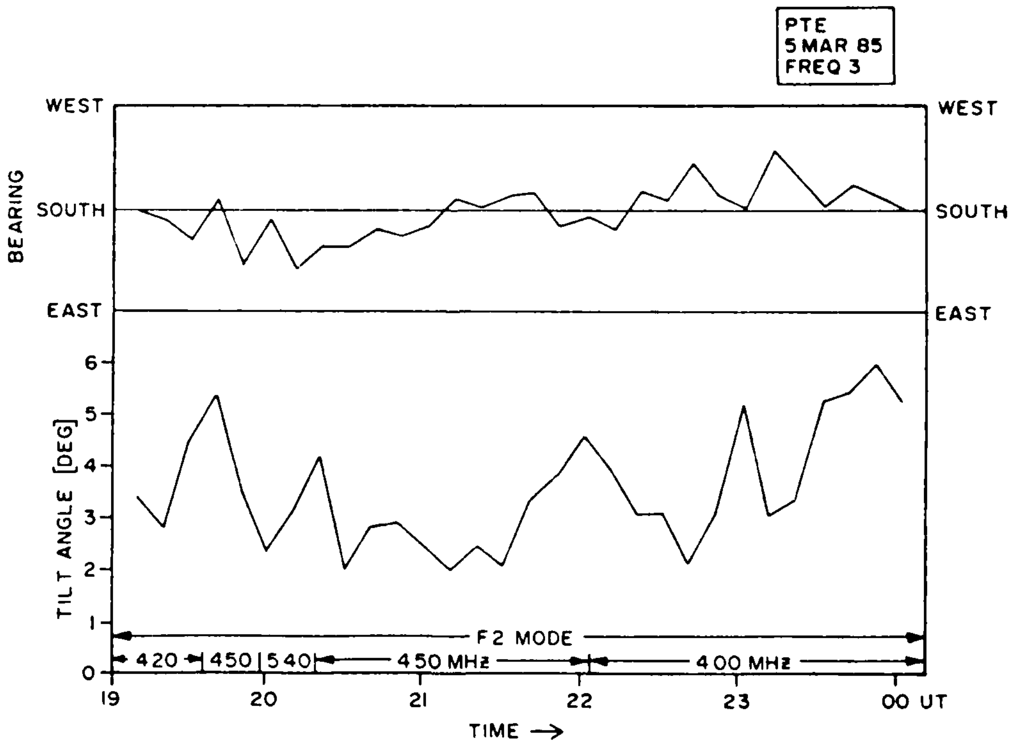


FIGURE 14B

Ionospheric Tilt Angle and Bearing - 5 March 1985

Figure 14

These observed tilts can be compared to those predicted by IONCAP for March with a sunspot number (SSN) equal to zero. An SSN = 0 was selected to produce a reasonably good fit to the observed critical frequencies during the flight.

Figure 15 is a contour map of the ionosphere around Erie, covering 8° longitude × 6° latitude. The contours indicate constant plasma frequency at an altitude of 240 km at 22 UT. The horizontal and the vertical gradients were computed and a tilt angle $\tau = \arctan[(dN/dx) \cdot (dN/dz)^{-1}]$ determined. This was done for a variety of altitudes and times during the flight period and an almost constant value of 1.5° southward was obtained for the hours of the March mission.

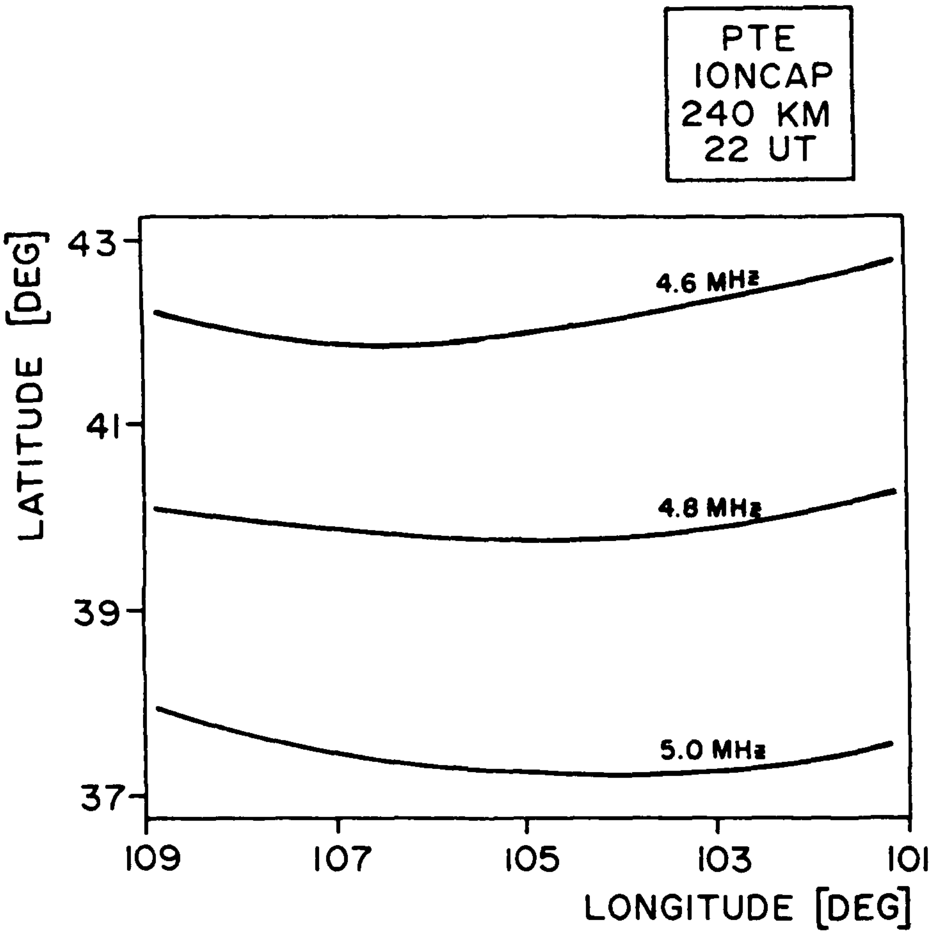
This is good qualitative agreement, though IONCAP probably underestimates gradients because it is a smoothed global model.

3.2 April Campaign

3.2.1 Vertical Incidence Sounding

The aircraft mission on 17 April, in contrast to the March campaign, took place at the end of a quiet magnetic period. A disturbed geomagnetic period began on the day after the flight.

A detailed comparison between the MOF's observed aboard the aircraft and the derived MUF's from the Erie vertical ionograms must await the true height analysis of those ionograms. Then the electron density profiles can be input to IONCAP and the propagation modes determined. As is typical for low SSN and late spring, the F1 modes can be seen to dominate the propagation (c.f. Figure 8). In the early part of the flight, at 21 UT, just after local noon, the relatively high foF1 = 4.2 MHz and low h'F1 of 180 km results in a high MUFF1 which exceeds the MUFF2. This is shown clearly in Fig-



Horizontal Gradient in Plasma Frequency

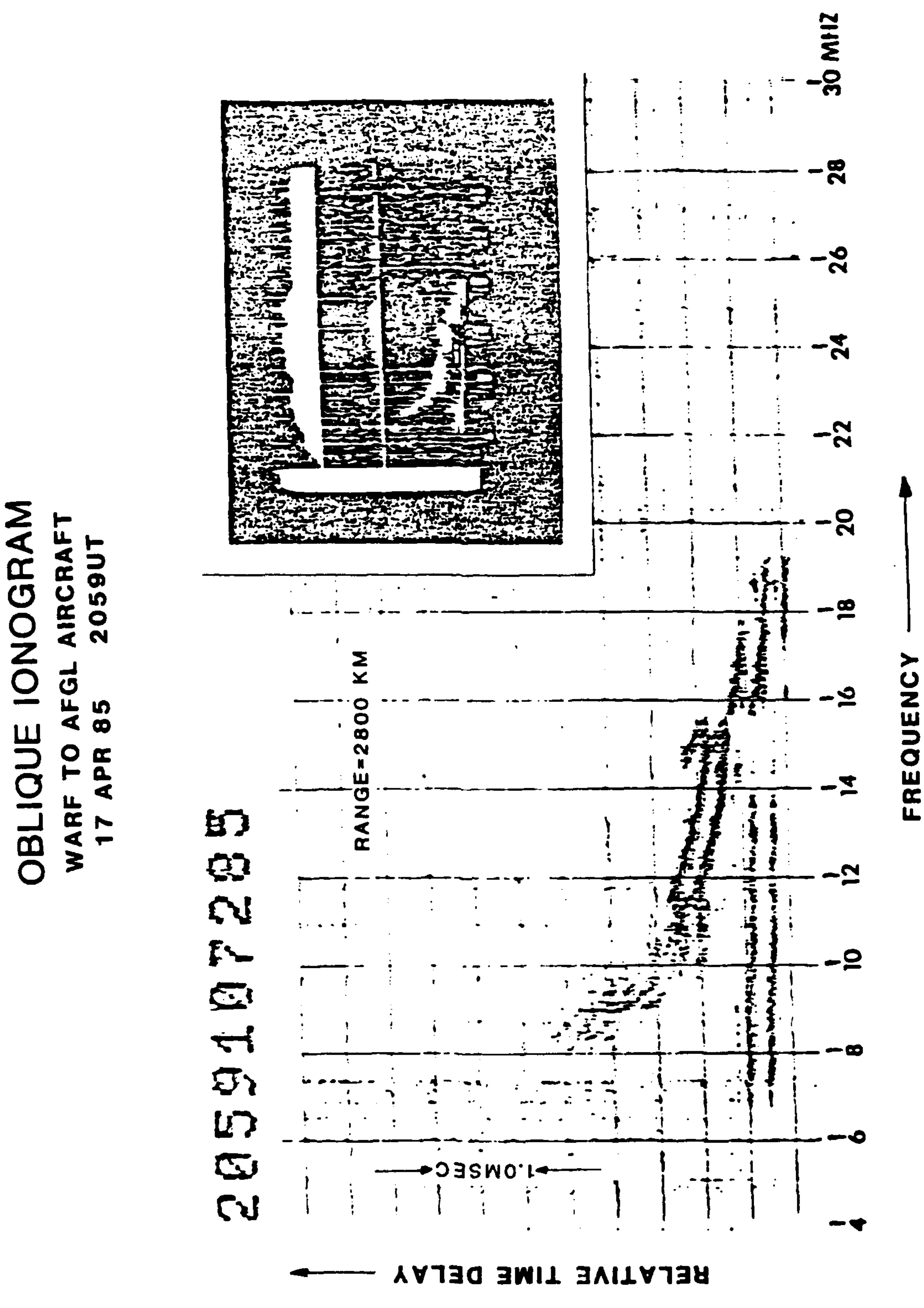
Figure 15

ure 16 for the oblique ionogram from the WARF to the AFGL aircraft. The double traces on the ionogram result from an artifact of the transponder aboard the aircraft.

The scaled MOFF2 is 15.5 MHz while MOFF1 is approximately 17.8 MHz. Fortunately it was possible to find, using IONCAP, a profile which closely matched the measured values at Erie. This was done by setting the SSN = 0 and the time to 20 UT and using that ionosphere for 21 UT when the aircraft range was approximately 2828 km. The synthesized ionogram is shown in Figure 17. The modes shown on the synthesized ionogram compared well with the measured oblique ionogram. In both cases the dominant mode in terms of frequency is the 1F1. However, the IONCAP simulation indicates that the 1F1 signal strength is some 10 dB below the 1F2 mode and would probably not be a factor in aircraft detection by the WARF radar. In fact, as seen in Figure 18a, the leading edge of the backscatter ionogram made at the WARF does not show the presence of the F1 mode, except possibly for a small area at 17 MHz and 20 ms time delay.

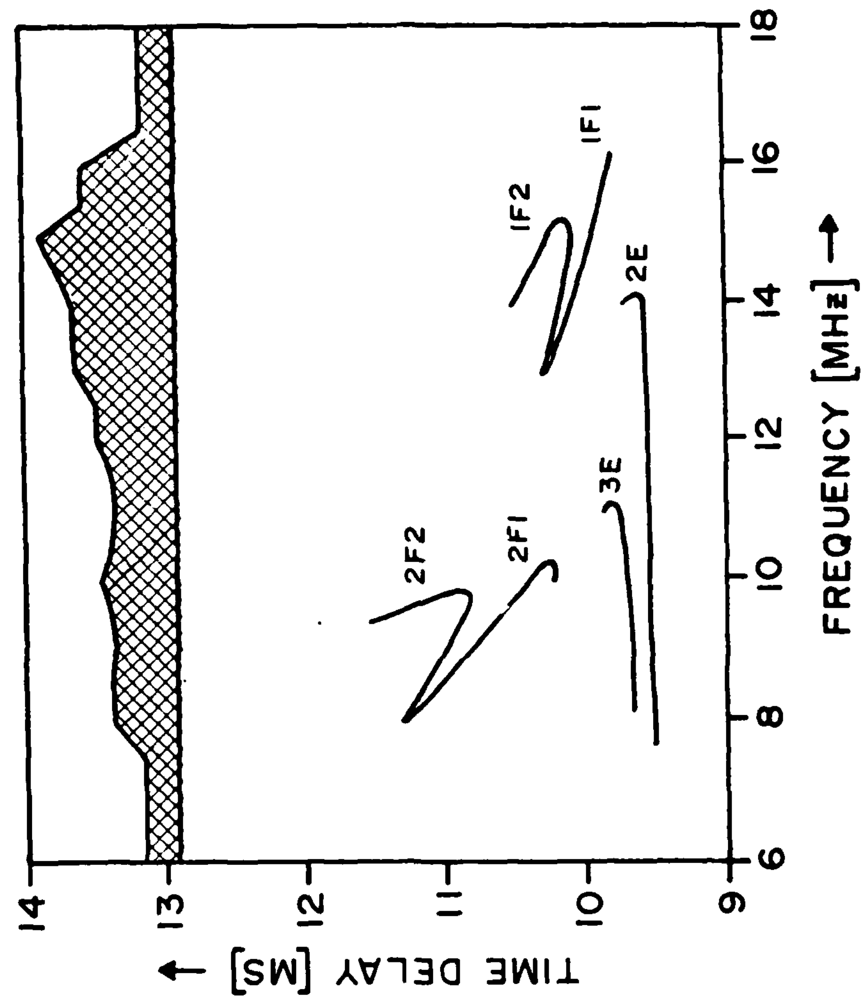
Using the ionospheric profile at 20 UT and SSN = 0 as a best fit to the Erie data at 21 UT, a backscatter ionogram was synthesized (Figure 18b) which can be compared to the WARF backscatter ionogram (Figure 18a). The contours indicate the signal-to-noise ratio computed using IONCAP. This simulation included the IONCAP estimate of the sporadic-E layer and this was included in the computation.

The 1F1 mode is approximately 10 dB weaker than the 1F2 mode. Detailed comparison is made difficult by the AGC used on the original WARF backscatter ionogram. When the Erie electron density profiles become available a detailed comparison will be possible, and then the effect of gradients can also be calculated.



Sample Oblique Ionogram - WARF to AFGL Aircraft

Figure 16



Synthesized Oblique Ionogram

Figure 17

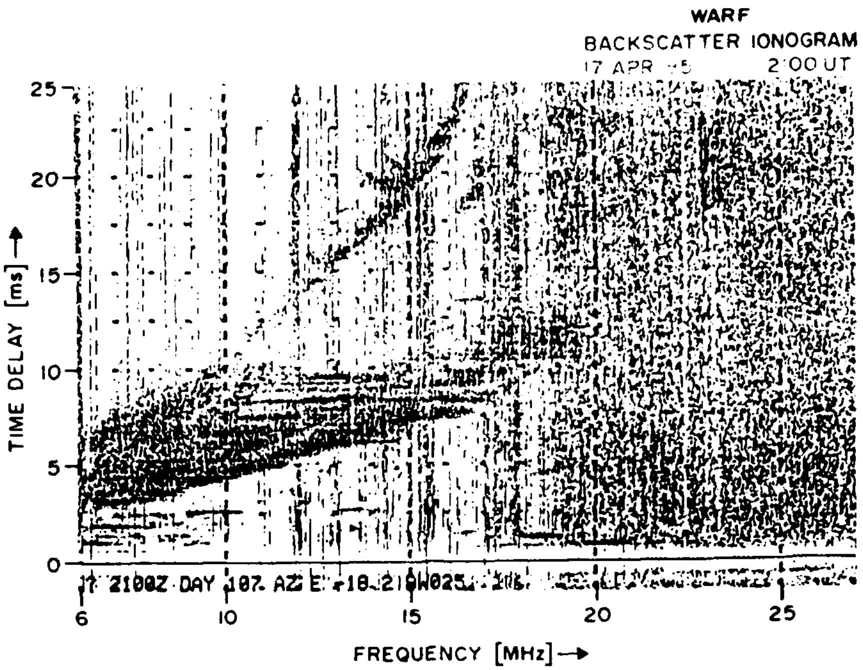


FIGURE 18A

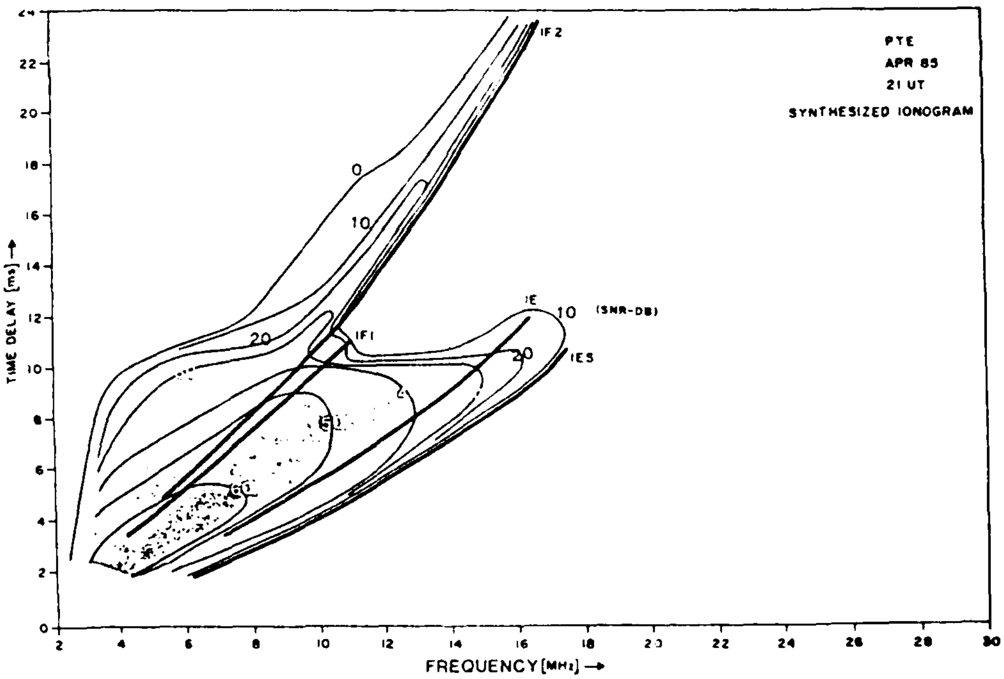


FIGURE 18B

Backscatter Ionogram - Actual and Synthesized

Figure 18

Using the vertical incidence ionograms from Erie to adjust IONCAP, a synthesized oblique ionogram can be generated making it possible to interpret the WARF detection data during the period 2045 through 2130 UT. Figure 19 for the above time period indicates two targets moving towards the radar with a time delay difference of approximately 500 μs. During that period the radar operating frequency was 14.5 and then changed to 15.0 MHz (c.f. Figure 8) halfway through the period. Examination of Figures 16 and 17, the actual and synthesized ionograms, shows that the two returns at the AFGL aircraft with 0.5 ms delay were most likely the 2Es and low rays of the 1F2 mode. The 1F1 mode is too close in time delay, and the signal strengths in the synthesized ionogram are more comparable for the 2Es and low 1F2 mode.

3.2.2 Tilt Measurements

The April mission was analyzed in exactly the same manner as the March mission. The data is presented for frequency 1 and 3 for the flight period from 20 UT on 17 April to 0130 UT on 18 April. All tilt measurements were in the F2 layer as shown in Figure 12B, except for the period from 2000 to 2128 UT at frequency 1. These particular measurements were in the F1 layer.

The April data (Figure 20) closely resembles the data for the March mission (Figure 14), with a median tilt of 2.6° and a median bearing of 195° T. The slight shift from east to west during the March mission is not apparent during April. Again the fluctuations have periods of ten minutes to one hour, and gravity waves are the likely source of these fluctuations.

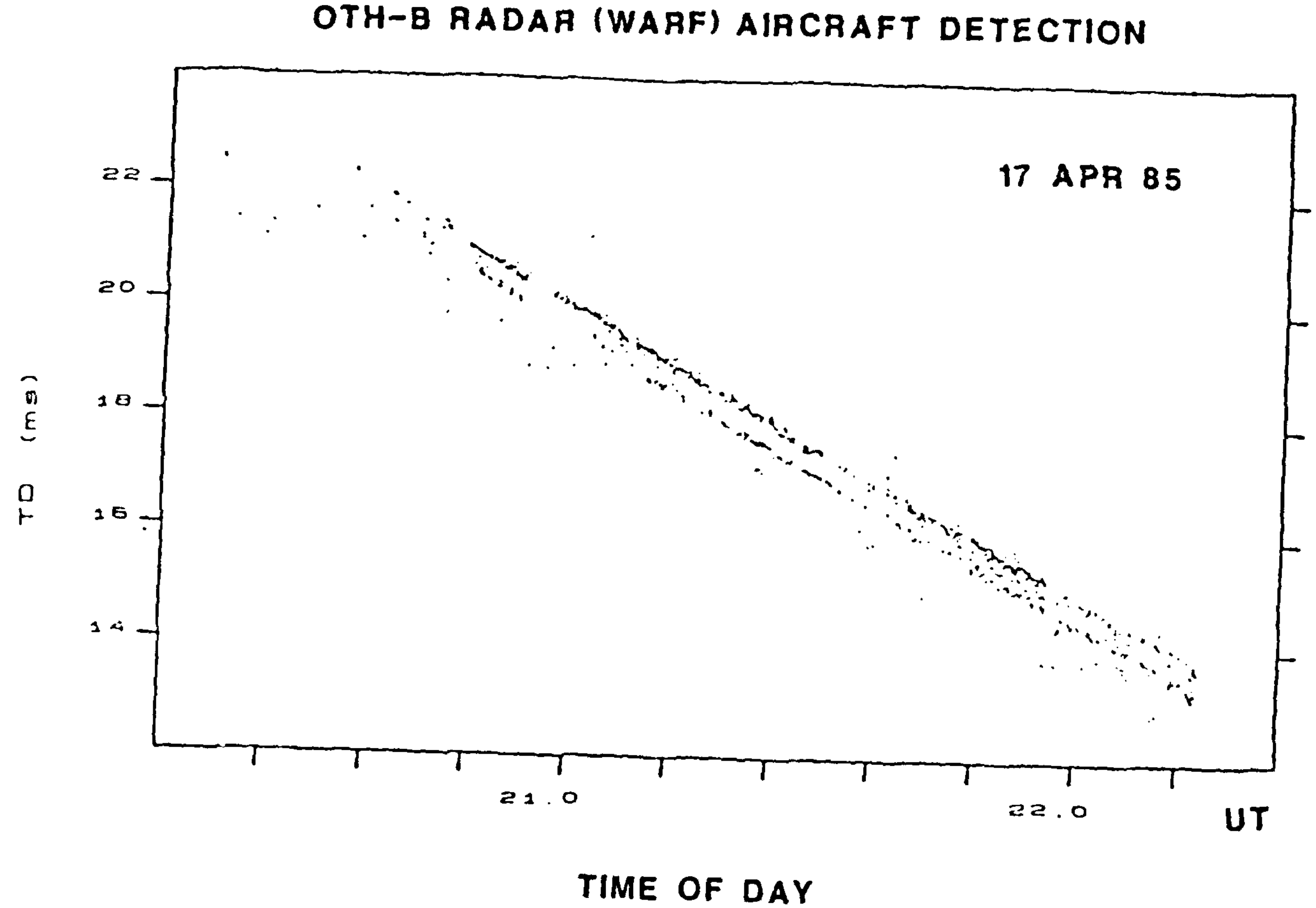

OTH-B RADAR (WARF) AIRCRAFT DETECTION
17 APR 85
TD (ms)
22
20
18
16
14
21.0
22.0
UT
TIME OF DAY

Figure 19

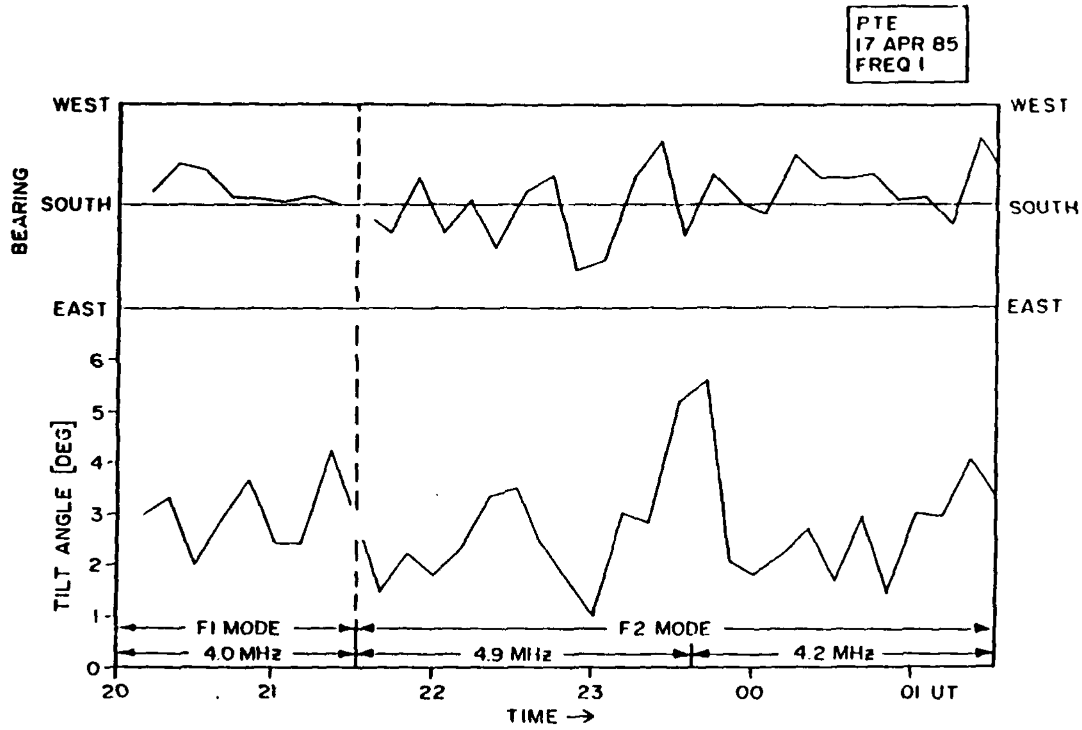


FIGURE 20A

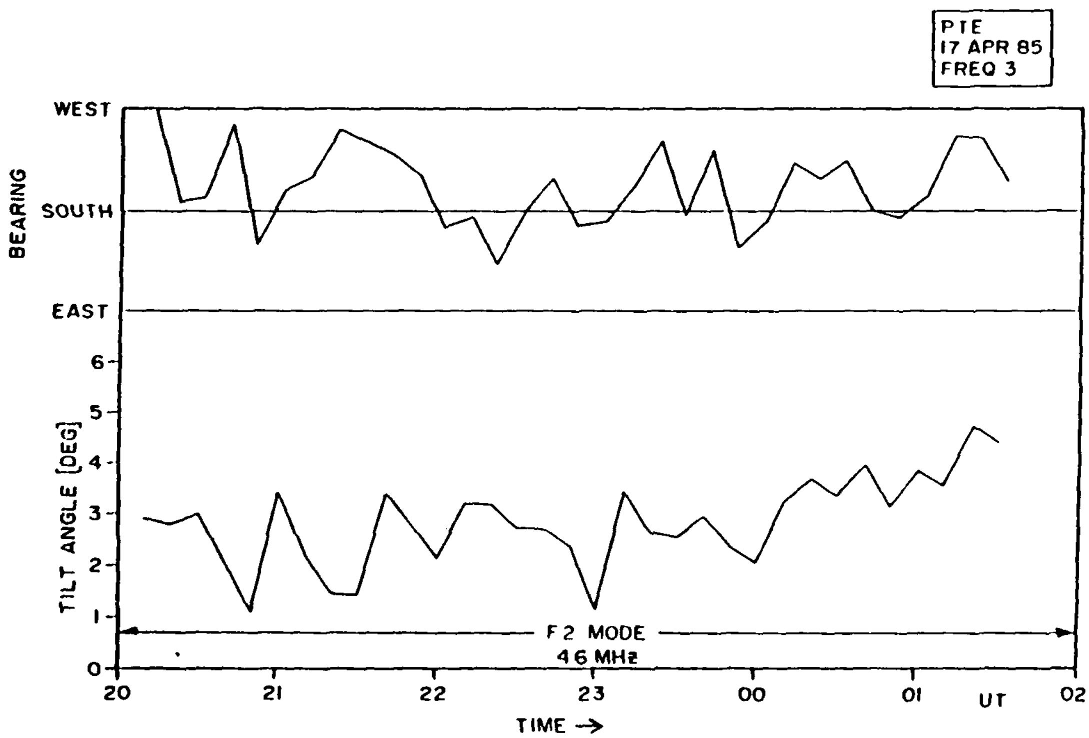


FIGURE 20B

Ionospheric Tilt Angle and Bearing Measurements - 17 Apr 85
Figure 20

4.0 CONCLUSIONS AND RECOMMENDATIONS

In terms of propagation analysis, data from the two campaigns of the Precision Targeting Experiment has provided a unique opportunity to compare vertical incidence, backscatter and oblique soundings over the same path. IONCAP has been useful for describing the propagating modes, since agreement could be found between the actual measurements and the median ionospheric model. IONCAP was modified to produce both oblique and backscatter ionograms for comparison with the sounding data, and the interpretation of the mode structure was facilitated by the comparison between IONCAP and the data.

The general daytime ionospheric structure during both campaigns was typical of low sunspot conditions, with relatively low densities in the F2 layer and a competition for propagation control by the F1 layer over the F2 layer. In spite of the geomagnetic storm effects on 5 March 1985, the ionosphere during the actual mission had largely recovered and was not significantly different from during the April mission.

On the basis of comparison between the operating frequencies of the radar and the measured maximum usable frequencies, the frequency management of the radar was found to be very effective. Naturally this experiment had the advantage of both mid-point vertical incidence sounding with MUF overlays, and oblique soundings to the AFGL aircraft.

Complete analysis of the propagation modes and the effect of tilts on the coordinate registration process will have to wait for the true height reduction of the vertical incidence ionograms from the three sites.

The tilt measurements were successfully analyzed and presented in a very compact form. Because of the relatively stable ionosphere, only small fluctuations of the order of a few degrees and periods of tens of minutes were present. It would be advantageous to process some of the long term (24 hour) tilt data to investiage the diurnal characteristics of the tilted ionosphere and its effect on HF radio waves.

5.0 REFERENCES

Bibl, K., B. W. Reinisch and D. F. Kitrosser, "General Description of the Compact Digital Ionospheric Sounder - Digisonde 256," University of Lowell Center for Atmospheric Research, 1981.

Dozois, C. G., "A High Frequency Radio Technique for Measuring Plasma Drifts in the Ionosphere," AFGL-TR-83-0202, Scientific Report No. 6, ULRF-424/CAR, ADA140509, 1983.

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