NRL Report 6590
Copy No.

Tilt Behavior of the Ionosphere

[Unclassified Title]

J. M. Headrick

Radar Techniques Branch
Radar Division

and

D. L. Lucas

Bell Aerosystems Company

September 15, 1967

APPROVED FOR PUBLIC
RELEASE - DISTRIBUTION
UNLIMITED

NAVAL RESEARCH LABORATORY
Washington, D.C.

CONTENTS

Abstract	iv
Problem Status	iv
Authorization	iv
INTRODUCTION	1
MONTHLY MEDIAN PROFILES	1
DAILY AND HOURLY VARIATION OF VIRTUAL HEIGHT	3
DAILY AND HOURLY TILT VARIATIONS	4
DISCUSSION	12
REFERENCES	12

ABSTRACT

A tilted ionosphere, i.e., earth eccentric contours of electron density, affects ionospheric radar performance. Expected tilt behavior influences radar antenna design, and the existing tilt condition at any time dictates frequency and launch angle requirements. A sample of the north-south refracting region was examined for tilt effects; this region is considered to be defined by ionosonde records spaced 1100 km apart. A simple method is used to derive some virtual tilts. Noon and midnight tilt values for one month show considerable variation and deviation from the monthly median. For nearly half the time, the tilt angle can be reduced to zero by appropriate frequency selection; and in general, the no-tilt condition determines the maximum one-hop range. Hourly tilts, examined for one day of the month, were found to be variable and somewhat dependent upon frequency. In addition, the hourly tilts seem to indicate a daily cyclical behavior. For optimum long-range performance the example studied indicates that radar needs to be quite flexible, that a continuous assay of the propagation path is required with appropriate adjustment to the instantaneous conditions, and that launch angles as small as possible are needed.

PROBLEM STATUS

This is an interim report on the problem; work on other phases of the problem is continuing.

AUTHORIZATION

NRL Problem R02-42
Project RADC USAF MIPR (30-602)64-3412

Manuscript submitted June 8, 1967.

TILT BEHAVIOR OF THE IONOSPHERE
[Unclassified Title]

INTRODUCTION

The term ionospheric tilt will be used to describe the condition of electron density whose contours are not concentric with the earth. On a virtual single frequency basis, the tilt can be considered to be as though rays are reflected at the appropriate virtual height from a plate not normal to an extended earth radius. The tilt effects are such that the launch and arrival angles are not equal and the maximum great-circle ground distance that can be spanned with one hop is reduced. Sometimes a tilt condition can be identified by noting an abnormally long distance to the leading edge of the earth echo, which indicates that two ionospheric refractions have occurred between the earth launch and subsequent earth arrival. Such large-scale tilt effects are frequently associated with sunrise and sunset on east-west paths and on transequatorial paths. In addition to diurnal large-scale bulges in the ionosphere, there exists, both in time and in area, finer grain roughness or eccentricity in ionization density.

Tilt behavior is certainly a factor in hf radar performance because the vertical-plane launch angle required for a particular distance depends on the tilt angle; thus, it establishes the extent of launch angles required. Addressing the selection of the launch angle, probably the most promising method for obtaining improved radar performance is to increase vertical-plane antenna directivity far beyond current practice. For this method to be effective, the existing tilt at any time must be predictable; or if the tilt is unpredictable, means must be provided to recognize the tilt and to adapt to the appropriate launch angles.

Tilt angle variations, also, affect the extent of launch angles for the long-range, one-hop radar transmission. The 1F long distance coverage of 3500 km or longer provides an appreciable advantage over the 2F mode. Power losses between 10 and 20 db for the radar circuit can be avoided, and in addition target location for both distance and azimuth is more accurate for the one refraction case. However, if a consistent going-away upward-tilt can be expected, radar coverage around 3500 km must be achieved by a 2F mode; and an antenna capable of small launch angles would be superfluous. If, on the other hand, every up-tilt can be expected to be followed both in time and distance by a down-tilt, then small launch angles can always provide useful long-range coverage–sometimes in the 5000 km region. Tilt angle variations, if appreciable, will require a wide extent of launch angles.

In a paper given at the 1966 ARPA OHD meeting (1) and in an NRL report (2), a radar performance prediction method was described and applied to a radar site at about 35° geomagnetic latitude, looking north. The tilt behavior studied in this report is intended to apply to a similar propagation path.*

MONTHLY MEDIAN PROFILES

So far, the best exhibits of monthly median profiles, that have been found, were made by J.W. Wright, et al. (3). These profiles have been computed from monthly median virtual

*Some of the basic data used in this report were previously discussed at an ARPA Advisory Meeting; and were used in Ref. 2 to indicate tilt sense and variability. The treatment, here, is intended to be more exact and complete.

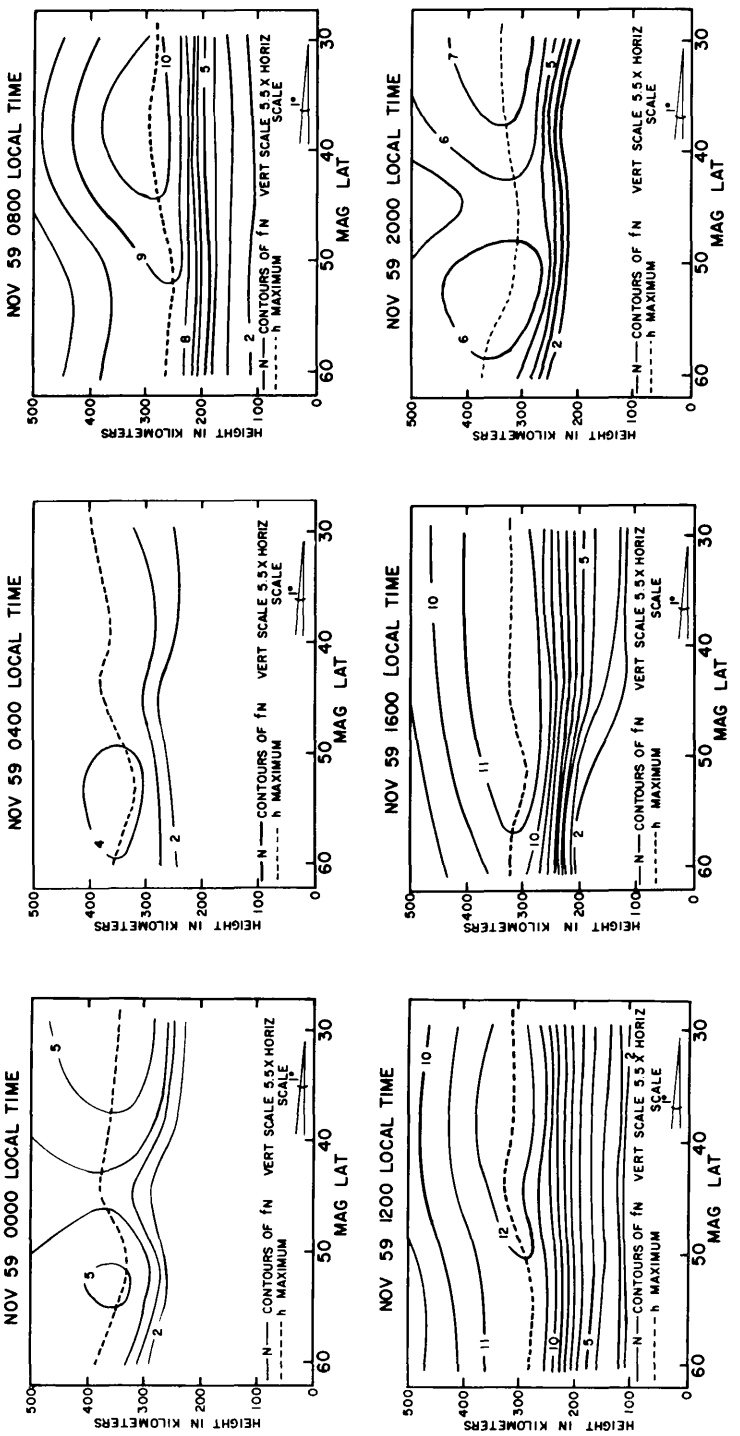

Fig. 1 - Monthly median contours of plasma frequency and height of maximum ionization vs geomagnetic latitude

height versus vertical frequency (h′ vs f) traces which were deduced from daily ionosonde records at different latitudes nominally along the 75th meridian. These median true height reductions are available at hourly intervals for all months of the year. Figure 1, an example, shows plasma frequency contours and the height of maximum ionization versus geomagnetic latitude for November 1959 at 6-hour intervals. For a radar located at 35°, influential part of the ionosphere for a long 1F path lies between 45° and 55°. Inspection of Fig. 1 suggests that during the November 1959 monthly median day, tilts will vary in sense with time. Furthermore, it seems evident that amount and direction of tilt can be a function of both frequency and range. Such profiles change from month to month and from year to year; however, the set shown is a fair example. Although the data were taken for the 75th meridian, it is probably reasonable to expect similar profiles to occur elsewhere at corresponding geomagnetic latitudes.

Actual h′ vs f traces for June 1965 are available from ionosondes located at Wallops Island about 50° geomagnetic latitude, and Cape Kennedy, about 40° geomagnetic latitude.* These traces will be used later for a more detailed study of tilt behavior. In Fig. 2 the monthly median profiles are shown for midnight and noon. If these contours are taken to represent the influential part of the ionosphere for a long-range path, some monthly median tilt estimates can be made by examination. At midnight for near the maximum usable frequency (MUF), the tilt is up to the north; but for frequencies far below the MUF, the tilt is up to the south. At noon the F2 region has an up-tilt to the south, and the F1 region has a zero or down-tilt to the south.

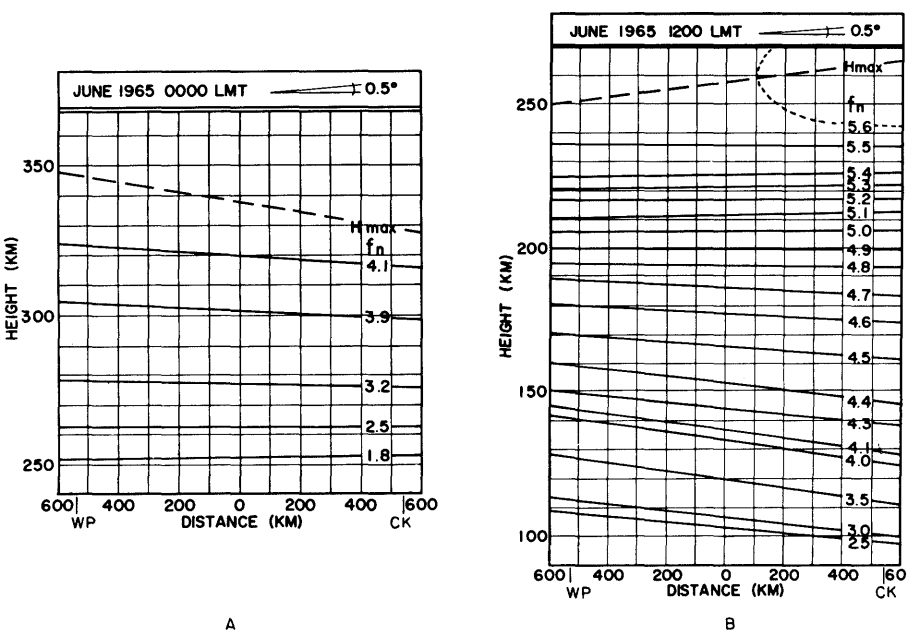

Fig. 2 - Monthly median contours of plasma frequency vs height of maximum ionization between Wallops Island and Cape Kennedy

DAILY AND HOURLY VARIATION OF VIRTUAL HEIGHT

In the previous section examples of monthly median ionospheric contours were exhibited. The ionospher's variability from day to day and from hour to hour can be

*Acknowledgment and appreciation is given to the World Data Center, ITSA, for the sounding data used.

displayed by h′ vs f ionosonde traces. Although such traces can be reduced to true height profiles and given as constant density contours, as in the prior section, only h′ vs f traces or tilts derived directly from them will be treated from hereon.

Figure 3 shows families of daily h′ vs f traces; each family is taken over the days in the month for the same hour at night. The sets are for Thule, Anchorage, Boulder, and Bogota, and they are intended to illustrate the type of variations at polar, high, middle, and equatorial magnetic latitudes. It is evident that deviations from the mean increase with increasing latitude, and it may be inferred that tilt variability and magnitude will increase as the refracting region moves toward a pole.

In Fig. 4 pairs of h′ vs f traces at Wallops Island and Cape Kennedy are shown. Six hours at night are given in one pair, and six hours in the day are given in the other pair. It can be seen that the hourly variation is not too well correlated between the two locations. Figure 5 also exhibits the pair behavior; a sequence of four hours is shown with superimposed Wallops and Kennedy h′ vs f traces. These h′ vs f traces will later be used to indicate variation of tilt with frequency.

DAILY AND HOURLY TILT VARIATIONS

A short study of the variability of tilts has been made. The experimental data have been the vertical ionospheric soundings taken at Wallops Island and Cape Kennedy; these stations are separated by about 1100 km, which is a little longer distance than a long-range propagation path spends in the refracting region. The sounding pairs have been used to derive the tilt conditions existing for a long north-south 1F path centered at about 45° geomagnetic latitude. Vertical sounding pairs for June 1965, taken daily at noon and midnight, and on one day taken hourly, have been used to determine the virtual tilt angle, the path length, and the launch angle at one terminal for grazing incidence at the other, which is the condition for maximum one-hop range.

The analysis was done for both a frequency near the MUF and one well below the MUF. The method is indicated in Fig. 6 for a frequency near the MUF at midnight. A M3000 transmission curve was used to obtain virtual heights h'_w at Wallops Island and h'_k at Cape Kennedy. It is probably evident that whereas the virtual height scalings near the MUF can be objective and repeatable, the scalings well below the MUF are rather subjective. In Fig. 6 for example $h'_w > h'_k$ at the lowest MUF for the pair and for a span of even lower frequencies. However, well below the MUF there are two frequencies where $h'_w = h'_k$ and a short span where $h'_w < h'_k$, indicating the tilt direction could be reversed. The criteria followed for well-below-the-MUF assessment at night was to go down the h′ vs f until the curve was well flattened out and in the daytime to use the F2 portion of the trace and go no further up into a cusp than for the MUF height. It was assumed that the transition between the virtual height at Wallops and Kennedy was linear. The reflection point of the propagation path has been always taken as midway with the value of $(h'_w + h'_k)/2$, and the tilt is computed from the difference in heights. This is a quite simplified approach containing several approximations and assumptions; however, it is felt that the results obtained will be truly indicative of the variations in tilt sense that can be expected. The magnitude of tilt angle, the launch angle, and distance derived from the launch angle must be considered approximate pending some verification.

Figure 7 is an exaggerated sketch to illustrate tilt effects. The solid line starting at T, reflecting from the ionosphere, and returning to the earth at a distance R with zero grazing angles at both ends represents the no-tilt case. Examples for an up-tilt and a down-tilt of the same magnitude are shown by dashed lines; note that the range R′ with

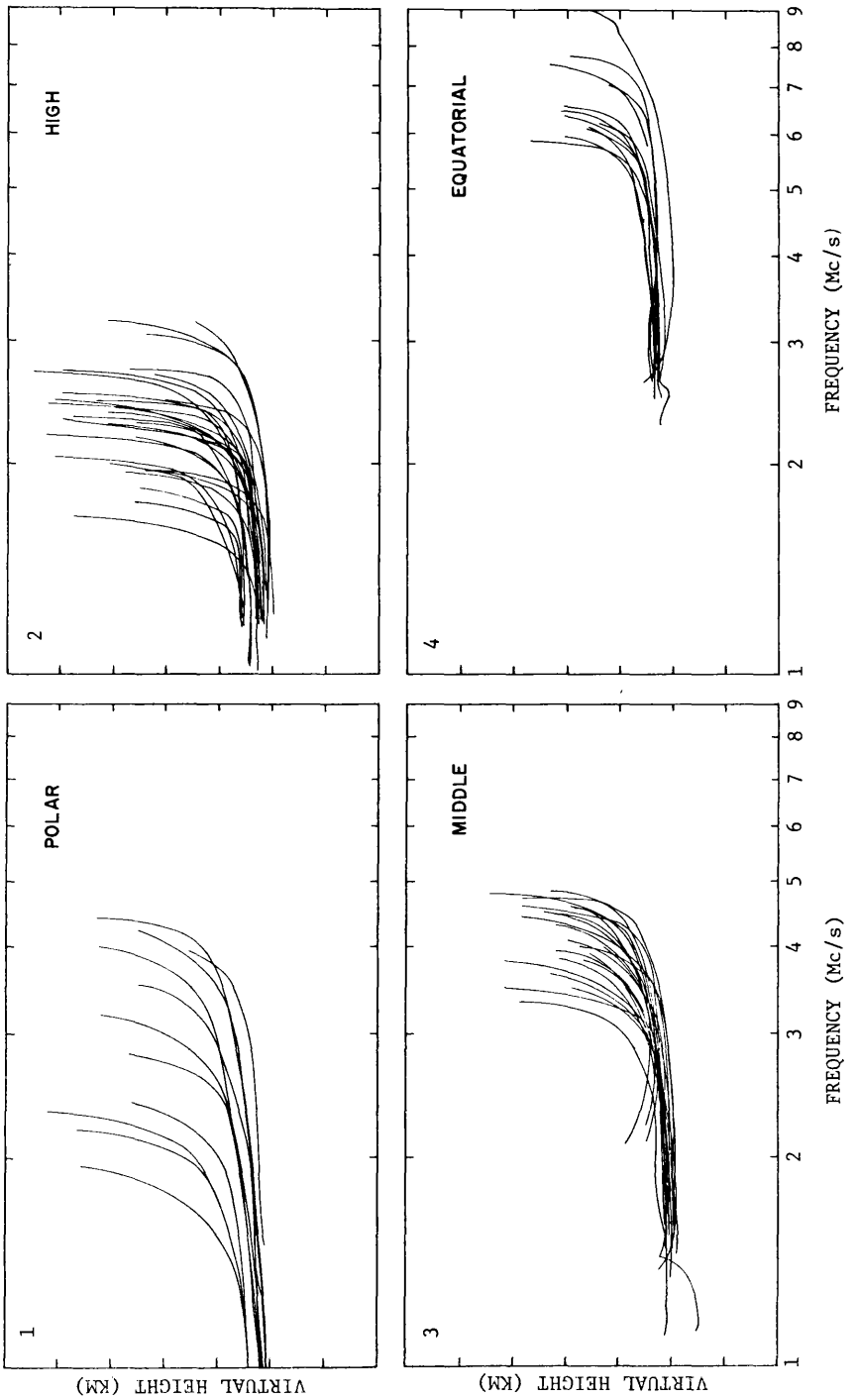

Fig. 3 - Typical nighttime daily distributions of h′ vs f traces of four different magnetic latitudes for one hour

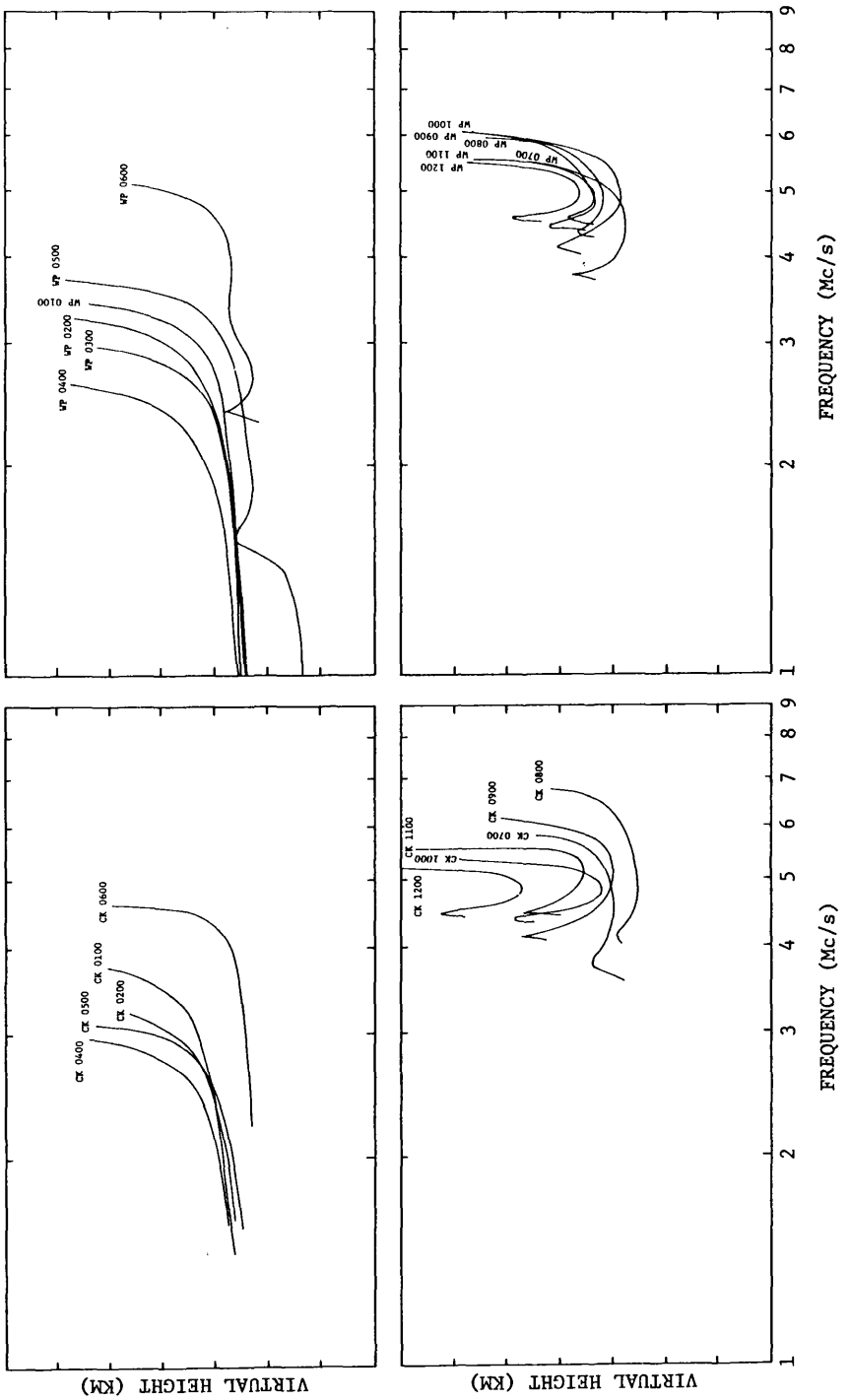

Fig. 4 - Typical hourly variations of Wallops Island (WP) and Cape Kennedy (CK) pairs of h′ vs f traces in the summer

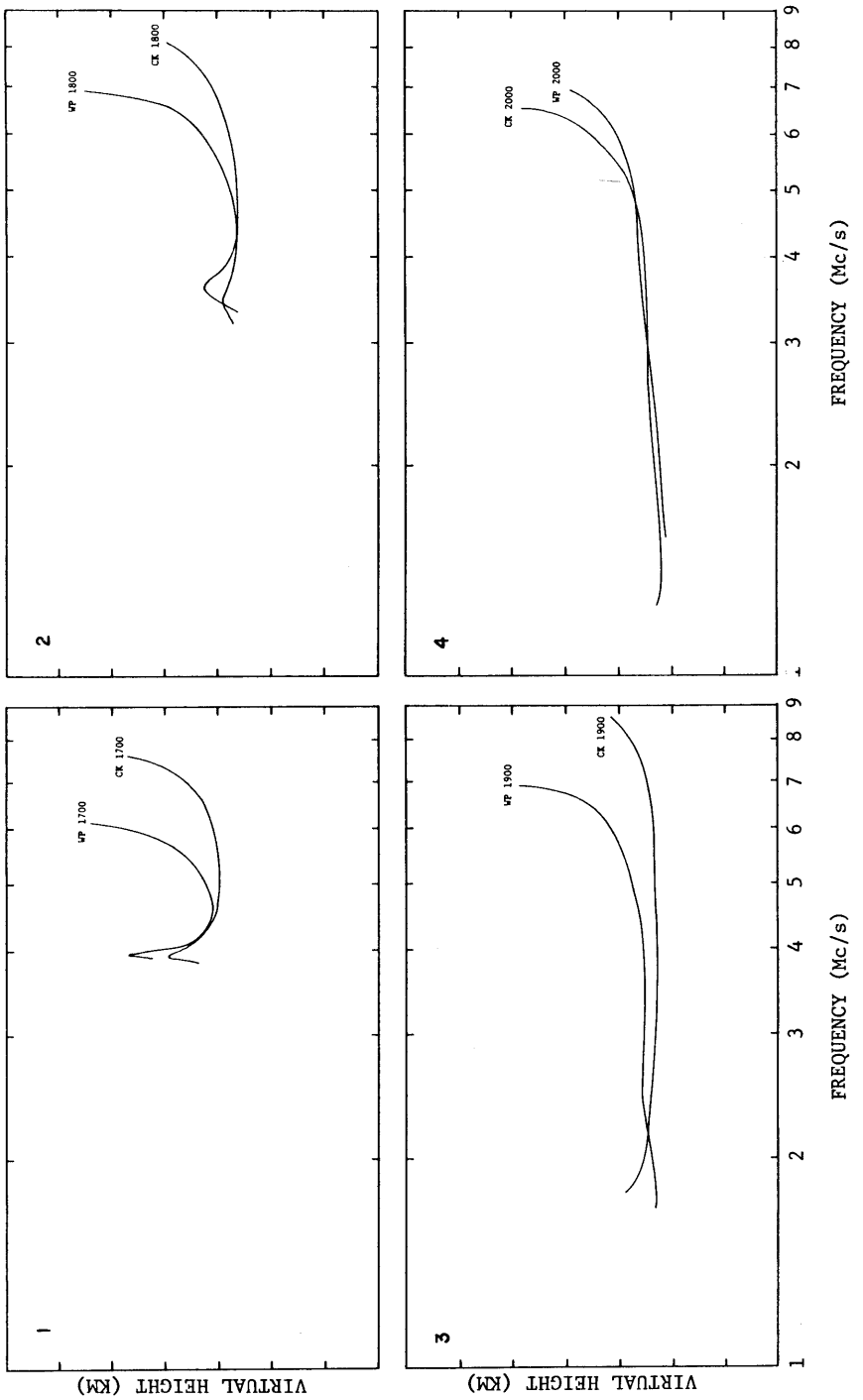

Fig. 5 - Superimposed Wallops Island and Cape Kennedy h′ vs f traces in the summer

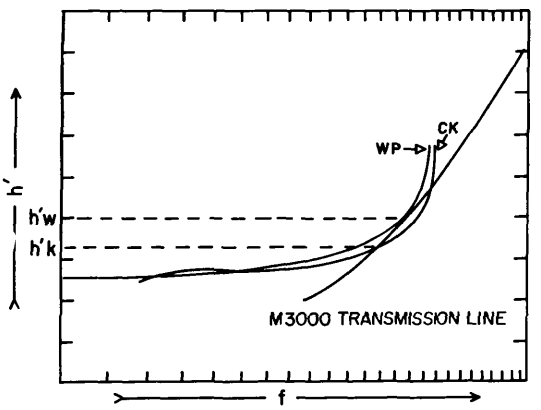

Fig. 6 - Overlaid Wallops Island and Cape Kennedy traces and the M3000 transmission curve selection of the two virtual heights

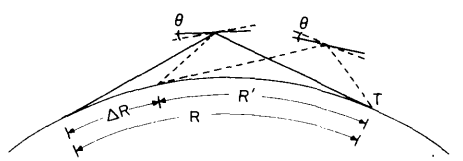

Fig. 7 - Tilt geometry

tilt is the same in both cases and must be less than R. If some limit other than zero had been set on launch angles, an upward going-away tilt could provide an R′ greater than R. Of course, this R is smaller than the distance when zero launch angles are permitted. For a down-tilt, a grazing launch angle or the smallest possible launch angle is required to maximize one-hop range, whereas for an up-tilt, a launch angle somewhat larger than the tilt angle provides maximum range. In the latter case, smaller launch angles provide rays that do not return to the earth after one reflection; but the rays may return to the earth after a second reflection.

Figures 8a and 8b give data for June 1965; tilt angle launch angle and one-reflection maximum range are shown for the days in the month for which good sounding traces were available. The treatment of the radar in this report will be the same as that in Refs. 1 and 2. The radar will be considered as placed in the south looking north. The situation at midnight is illustrated in Fig. 8a. The average tilt is up to the north at the MUF and slightly down to the north at well-below the MUF. The results of the 17-day midnight sample taken at the MUF are as follows:

1. Nine days have an up-tilt.
2. One day has no-tilt.
3. Seven days have a down-tilt.
4. On eight days a zero launch angle gives maximum coverage.
5. The largest launch angle for grazing at the other end is 34°.
6. The propagation distance is greatest on the no-tilt day.

The results of the 17-day midnight sample well below the MUF are as follows:

1. Six days have an up-tilt.
2. Three days have no-tilt.
3. Eight days have a down-tilt.
4. On ten days a zero launch angle gives maximum coverage.

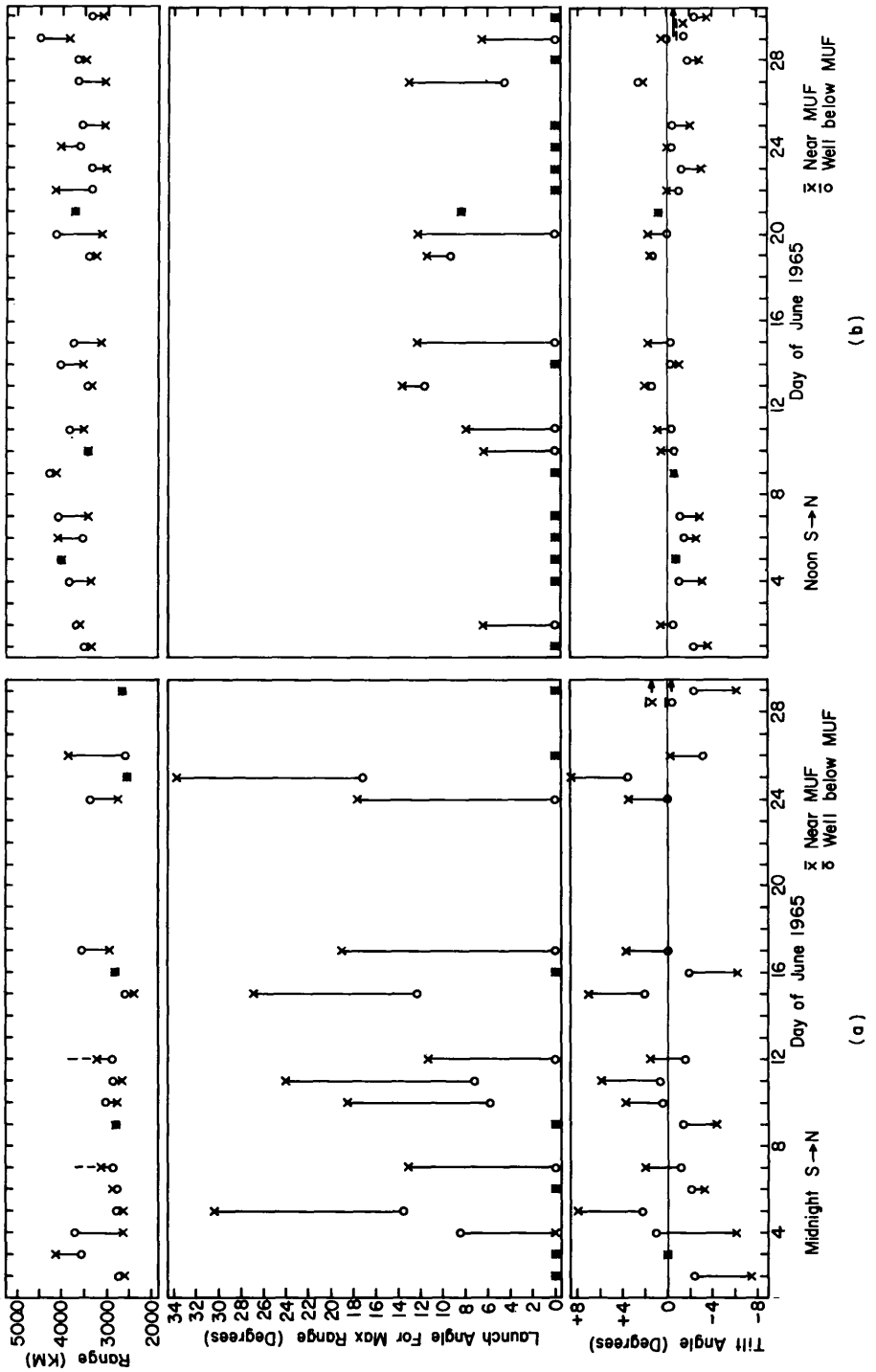

Fig. 8 - Daily (a) 17-day midnight sample (b) 23-day noon sample tilt angle, launch angle for the maximum one-hop range, and maximum one-hop range for one month

5. The largest launch angle required for grazing at maximum range is 17°.
6. Propagation distances are greatest on the small and no-tilt days and shortest on the maximum tilt day.

In general the MUF tilts are the more extreme. On at least seven days a no-tilt condition occurred at some frequency. The average tilts are not inconsistent with Fig. 2.

The situation at noon is given in Fig. 8b. The average tilt indicated for both frequencies is about a -1/2°, and when this is the case, a zero launch angle gives maximum range. The results of the 23-day noon sample near the MUF are as follows:

1. Ten days have an up-tilt.
2. Two days have no-tilt.
3. Eleven days have a down-tilt.
4. On 13 days a zero degree launch angle provides maximum one-hop range.
5. The largest launch angle for grazing incidence at the other end is 13.5°.
6. Propagation distances are the greatest on small and no-tilt days and are shorter on maximum tilt days.

The results of the 23-day noon sample well below the MUF are as follows:

1. Four days have an up-tilt.
2. Two days have no-tilt.
3. Seventeen days have a down-tilt.
4. On nineteen days a zero-degree launch angle is required to get maximum one-hop range.
5. The largest launch angle is 12°.
6. Propagation distances tend to be greater on small or no-tilt days and shorter on maximum tilt days.

On at least eight days some frequency between the frequency near the MUF and the one well below the MUF should provide no-tilt and maximum one-hop range. By inspection, it is not obvious that the average tilts derived correlate with the average contours of Fig. 2. During the day the variability of the tilt angle is not as large as at night.

By examining the data for one month at noon and midnight, the day-by-day tilt may be compared with the monthly median. The variability as exhibited was considerable and it appears useful to display typical variations for a day. Figure 9 gives the results of hourly ionograms on one day of the month. The hourly scatter in tilt and required launch angle is somewhat similar to the daily scatter for a given hour. Within the limits of the hourly sampling rate, some indications of cyclic behavior can be seen. At well below the MUF the amplitude of tilt oscillations is considerably less than at near the MUF. For about 15 hours of the day a no-tilt condition exists for some frequency between the two plotted. At either the frequency near the MUF or well below the MUF, the tilt can change within the hourly sampling period from up to down; and the vertical-plane launch angle that provides maximum one-hop range can change over 10°. The cause of the tilt is, no doubt, the same as that for azimuthal angle wander. Hayden has indicated that the normal ionosphere small scale variations are due to waves or ripples and he has given the fluctuation period as lying between a few minutes and many minutes (4). It seems likely that tilt angle variations may have similar periods. For different days the periods might be quite different from the example shown.

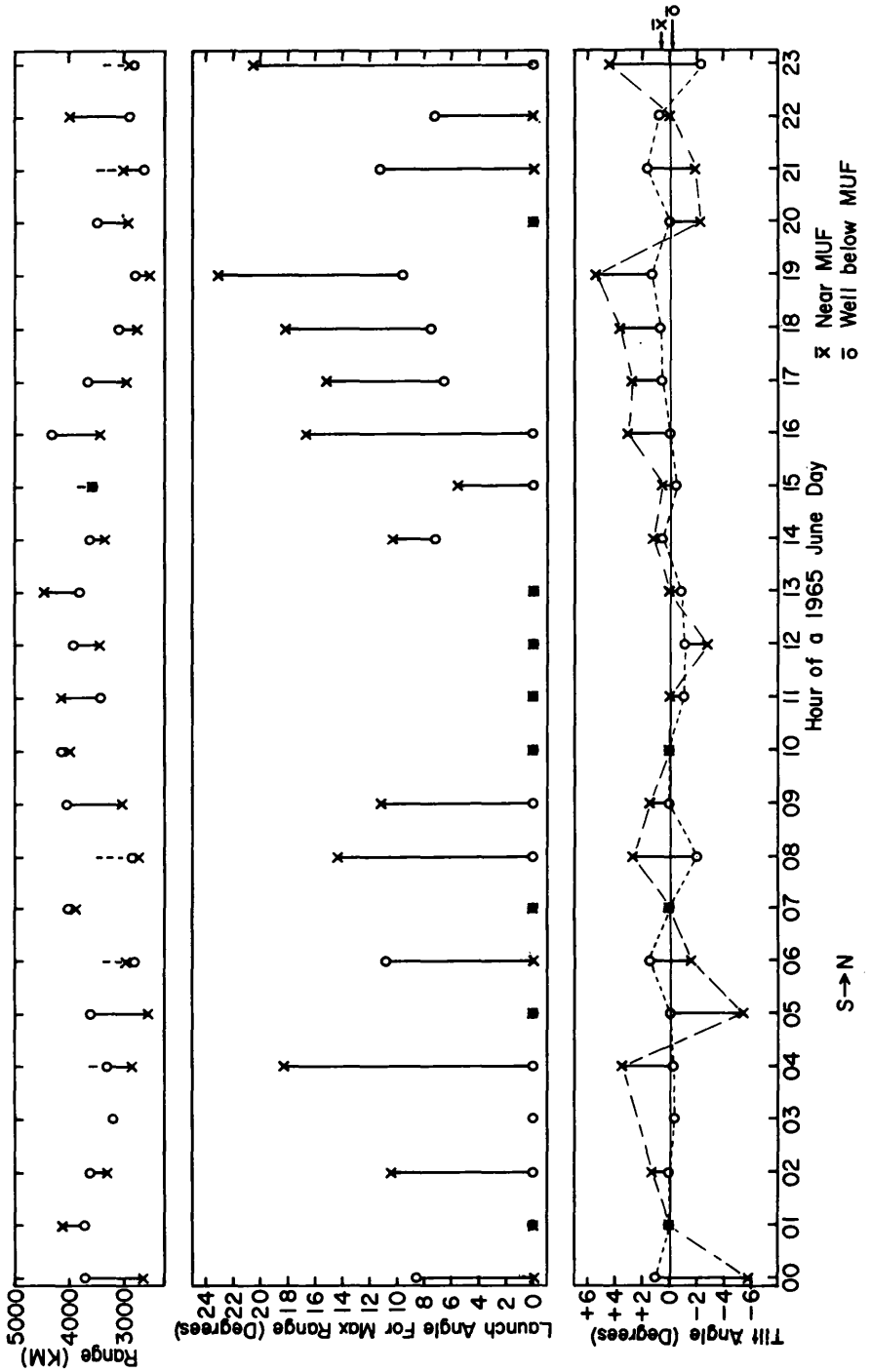

Fig. 9 - Hourly tilt angle, launch angle for the maximum one-hop range, and maximum one-hop range for one day

DISCUSSION

This rather limited set of exhibits and tilt deductions should provide some insight into tilt behavior, and definite guides to radar design can be seen. In particular, the radar with vertical antenna pattern directivity needs to be steered in a manner which can adapt to the momentary condition. This implies that the existing condition must be recognized.

Even when the monthly median tilt is up, for an appreciable part of the month the tilt can be down or zero at any time. If long-range performance is the goal, it is not reasonable to expect ionospheric tilts to offer any relief in the antenna-beam-pointing, versatility requirements in the vertical plane. The tilt behavior does indicate that more vertical-plane launch angles are required than would be predicted on a constant concentric or constant eccentric ionosphere assumption.

Whatever the tilt condition is at one time, it can be expected to change within a fairly short period. It seems evident that as distance increases from a radar site up-tilts will be followed by down-tilts and vice versa, and the condition of a continuous going-away up-tilt will be fairly rare. Maximizing the one-hop distance is desirable because of the 10 to 20 dB power loss by the two-hop mode plus the accompanying poorer measurement of target range, speed, and azimuth. For periods when the tilt is down, the smallest possible launch angle provides the maximum one-hop range; thus, the ability to launch rays at small angles improves reliability.

It is felt that tilt behavior in sense has been accurately, but not completely, portrayed. The magnitudes, however, need confirmation, and more information is needed before tilt distributions can be included in propagation predictions. It is hoped that a current ITSA experimental program can be used to extend the description of tilt behavior.

REFERENCES

1. Headrick, J.M., Lucas, D.L., and Zettle, E.N., "Predicting Performance of HF Skywave Radar," Proc. of the ARPA Meeting of 1-2 June 1966 (Secret paper, unclassified title)

2. Headrick, J.M., Lucas, D.L., and Zettle, E.N., "HF Skywave Radar Performance," NRL Report 6568 (Secret report, unclassified title), May 1967

3. Wright, J.W., et al, "Mean Electron Density Variations of the Quiet Ionosphere," NBS Technical Notes No. 40-1 through 40-12 issued in 1959-1963 (Unclassified)

4. Hayden, E.C., "The Wullenweber Antenna Array and Limitations to Passive Radiolocation Accuracy," Proc. of the ARPA Meeting of 1-2 June 1966 (Unclassified paper)

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION SECRET 2b. GROUP 4

3. REPORT TITLE (Unclassified)

TILT BEHAVIOR OF THE IONOSPHERE

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
An interim report on a continuing problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

J.M. Headrick and D.L. Lucas

6. REPORT DATE September 15, 1967	7a. TOTAL NO. OF PAGES 16	7b. NO. OF REFS 4
8a. CONTRACT OR GRANT NO. NRL Problem R02-42 b. PROJECT NO. MIPR (30-602) 64-3412 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6590 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	

10. DISTRIBUTION STATEMENT
In addition to security requirements which apply to this document and must be met, each transmittal outside the Department of Defense must have prior approval of the Director, Naval Research Laboratory, Washington, D.C. 20390.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Dept. of the Air Force (Rome Air Dev. Center) Washington, D.C. 20310

13. ABSTRACT [SECRET]

A tilted ionosphere, i.e., earth eccentric contours of electron density, affects ionospheric radar performance. Expected tilt behavior influences radar antenna design, and the existing tilt condition at any time dictates frequency and launch angle requirements. A sample of the north-south refracting region was examined for tilt effects; this region is considered to be defined by ionosonde records spaced 1100 km apart. A simple method is used to derive some virtual tilts. Noon and midnight tilt values for one month show considerable variation and deviation from the monthly median. For nearly half the time, the tilt angle can be reduced to zero by appropriate frequency selection; and in general, the no-tilt condition determines the maximum one-hop range. Hourly tilts, examined for one day of the month, were found to be variable and somewhat dependent upon frequency. In addition the hourly tilts seem to indicate a daily cyclical behavior. For optimum long-range performance the example studied indicates that radar needs to be quite flexible, that a continuous assay of the propagation path is required with appropriate adjustment to the instantaneous conditions, and that launch angles as small as possible are needed.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Tilt Behavior						
Ionosphere						
Radar Performance						
Launch Angles						
Long-Range Distances						
Radar Directivity						
Tilt Median Profiles						
Virtual Height vs Vertical Frequency Traces						
Maximum One-hop						
Maximum Usable Frequency						
Frequency						
Virtual Height						
Ionosonde						
Ionospheric Contours						
Minimum Radar Angles						