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OBLIQUE ECHOES FROM LARGE-SCALE HORIZONTAL GRADIENTS OBSERVED BY ALOUETTE-2 TOPSIDE SOUNDER

by Jayaram Ramasastry

Electronics Research Center
Cambridge, Mass.

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16. Abstract

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OBLIQUE ECHOES FROM LARGE-SCALE HORIZONTAL GRADIENTS OBSERVED BY ALOUETTE-2 TOPSIDE SOUNDER

By Jayaram Ramasastry
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SUMMARY

This paper reports and explains certain loop-shaped ionograms observed by the Alouette-2 topside sounder at Ouagadougou, Upper Volta, Africa. The occurrence of loop-shaped traces in the ionograms is due to oblique echoes received by the sounder receiver when the satellite is travelling inside a large-scale electron density depression. The oblique returns are caused by total reflection from the walls of the depression region. The minimum or nose frequency and the size of the loop trace are dependent on the structure of the depression region and the horizontal distance of the satellite from the edge of the depression. The loop-shaped traces have been observed only in the northern hemisphere in the latitude range 20°N-25°N and during midnight hours.

INTRODUCTION

Sweep-frequency topside sounder experiments on board the International Satellites for Ionospheric Studies (ISIS) satellites (Alouette-1, Alouette-2, ISIS-A) were designed primarily to obtain the electron density profiles in the topside ionosphere (refs. 1, 2). A radio pulse at a specific frequency is transmitted and the receiver records the return echoes of the transmitted pulse. The transmitter is swept through a range of closely spaced frequencies with the receiver tracking the signal and recording the return echoes of the transmitted pulses at each frequency. This information is then presented as a plot of frequency versus time delay.* Such a plot is called an ionogram. On an ionogram, echoes from consecutive pulses appear continuously, since the frequencies are so closely spaced, and are referred to as traces. Figure 1 is an example of a normal ionogram recorded by the Alouette-2 topside sounder. In a topside sounder ionogram, there are normally two echoes or traces received at any one frequency corresponding to the two magnetoionic modes (ordinary and extraordinary). These two traces are indicated in Figure 1. These normal echoes are caused by radio waves which propagate

*Time delay or group-delay of a radio wave echo is the time elapsed between the time the frequency pulse is transmitted and the time when the echo is sensed by the tuned receiver.

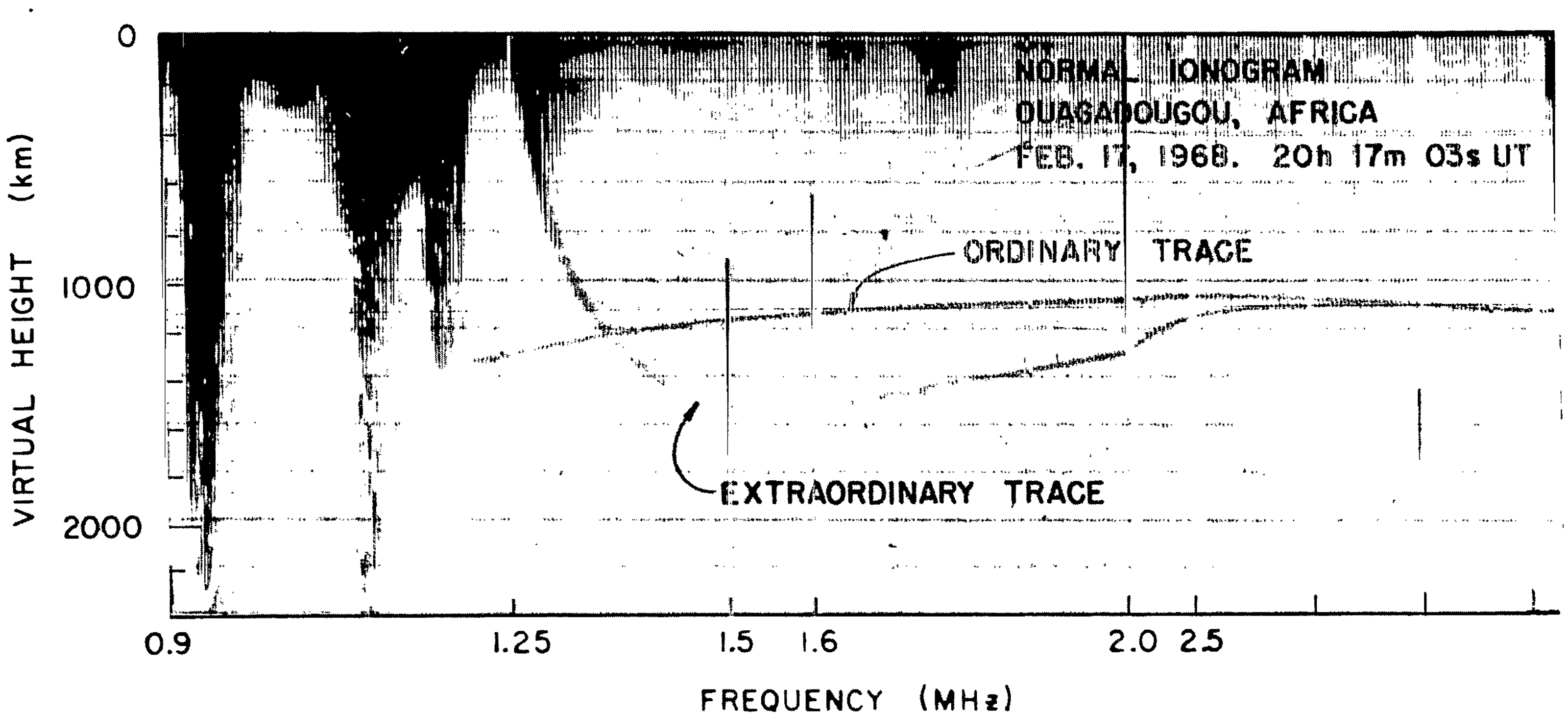


Figure 1.- Normal ionogram

vertically downward to the critical height* where they are totally reflected. The time-delay versus frequency characteristic of each of the modes could be used to obtain the electron density profile from the satellite altitude to the critical height (reflection level) using standard techniques (ref. 3).

However, quite often, additional echoes are received at the satellite over a range of frequencies or at discrete frequencies. These are caused by various mechanisms such as plasma resonances, spread-F, ducting, and scattering.

This paper reports and explains certain loop-shaped ionograms observed by the Alouette-2 topside sounder. Such ionograms have been frequently recorded at Ouagadougou, Upper Volta, Africa. Figure 2 shows a sequence of ionograms containing loop-shaped traces. Ionograms 3 and 4 of the sequence show typical examples of loop-shaped traces. They are shown in an enlarged form in Figure 3. Only the extraordinary trace will be discussed since the ordinary trace is cut off at low frequencies in which range it should exhibit the same phenomenon. In an ionogram, the frequency increases to the right and the time-delay increases downward. In the above mentioned ionograms, at a certain minimum frequency (called the nose frequency), an additional echo is received at the receiver. For frequencies higher than the nose frequency, two additional echoes are received and they form the two branches of the loop. The following are the other typical observed characteristics of such nose-shaped traces:

(1) They have been observed only in the northern hemisphere (particularly in the North to South passes of the satellite) in the geomagnetic latitude range $20^{o}N-25^{o}N$. A typical value would be $21^{o}N$.

(2) They are nighttime phenomena. The observed local time range is 2400 hours ± 0200 hours.

(3) As the satellite moves towards the equator, the nose frequency of the loop decreases and the separation between the upper and lower branches of the loop increases. In other words, the loop gets broader. This feature can be noticed in ionograms 2, 3, and 4 shown in Figure 2.

(4) The delay time for the lower branch of the loop increases with increasing frequency and approaches the delay time for the

* The critical height for the ordinary mode is the height at which the electron plasma frequency is equal to the signal frequency. The critical height for the extraordinary mode is a function of both the electron plasma frequency and the gyrofrequency.

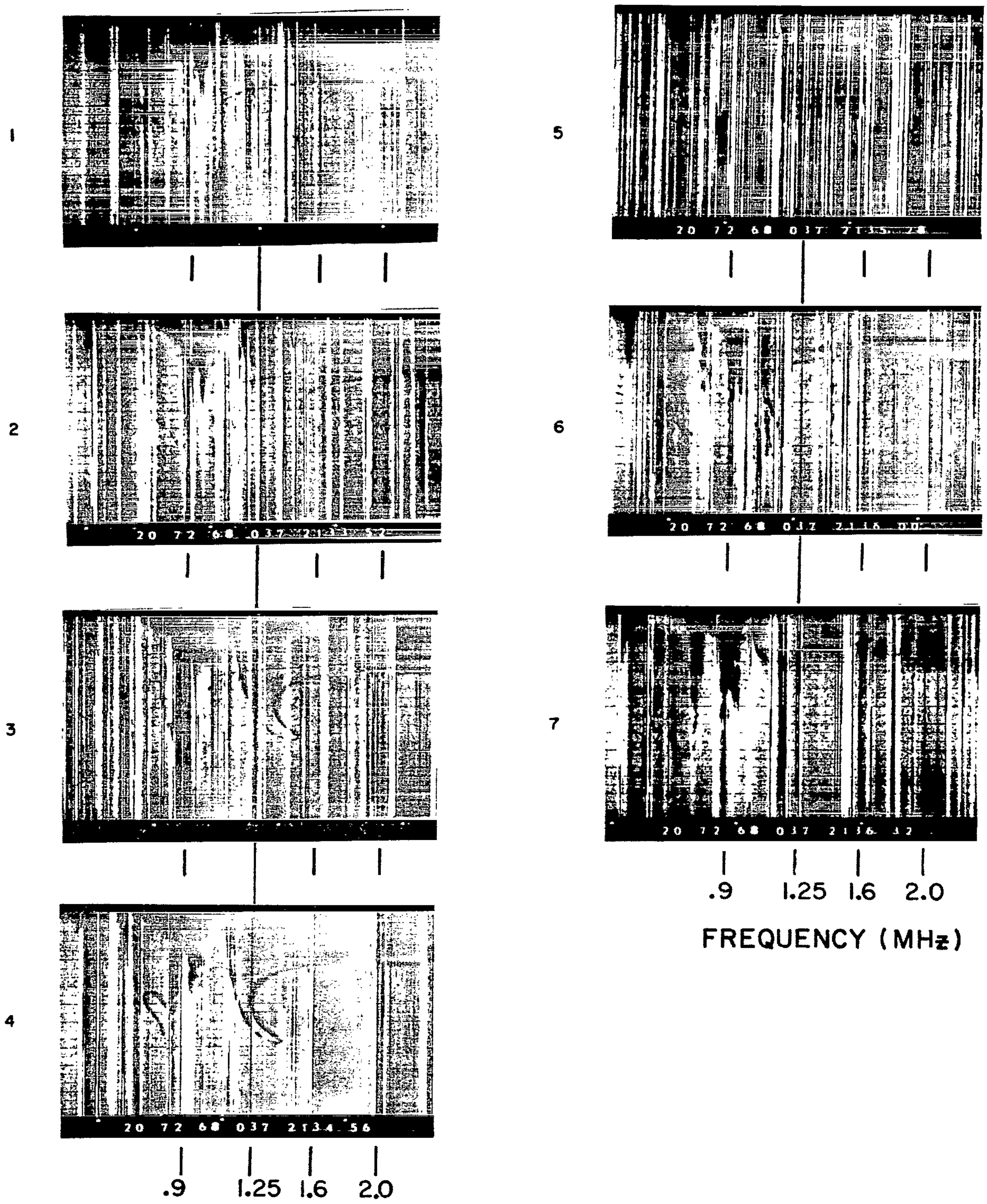


Figure 2.- February 6, 1968, sequence

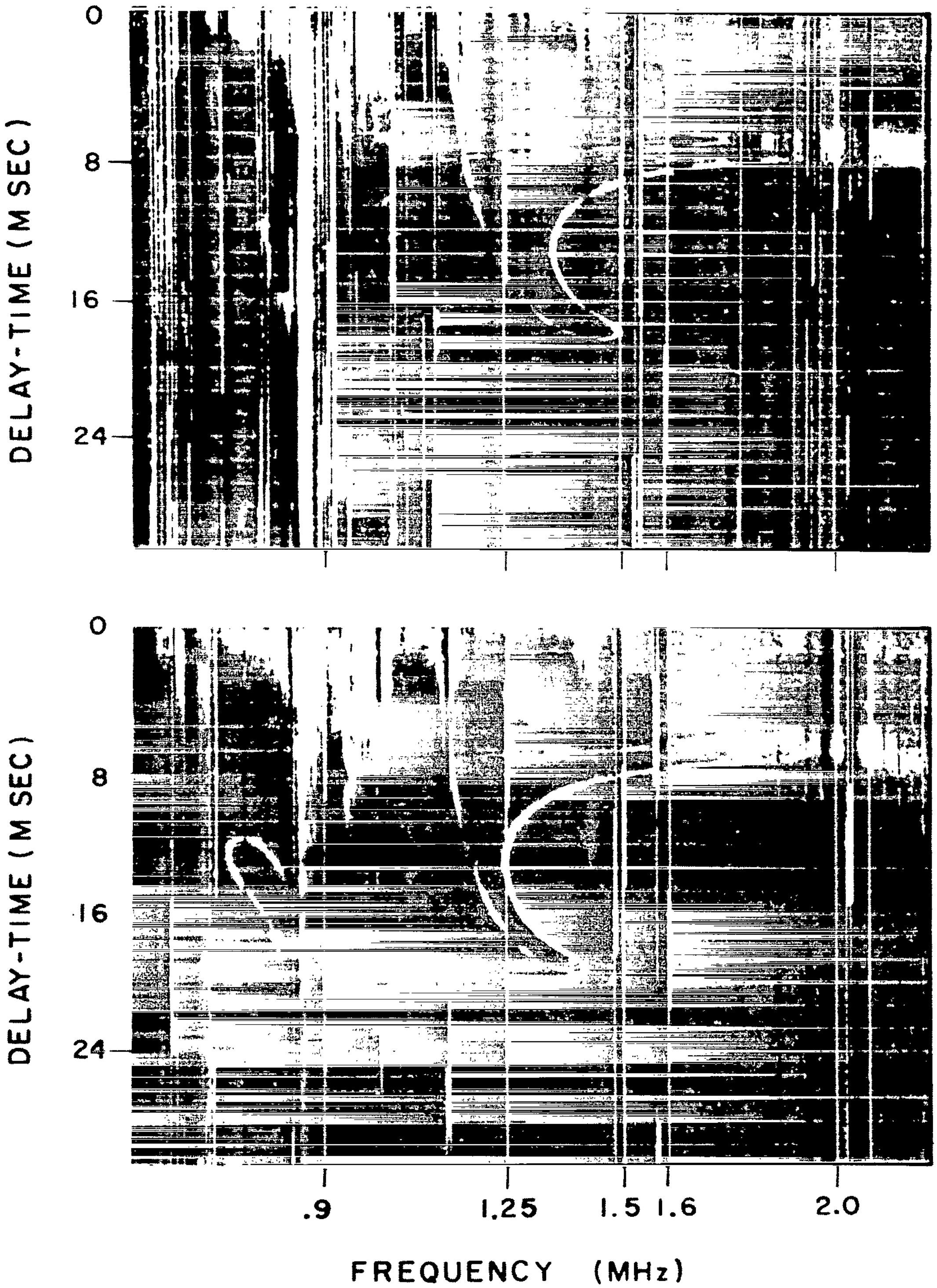


Figure 3.- Enlargements of two ionograms

normal extraordinary trace. The delay time for the upper branch, on the other hand, decreases with increasing frequency and approaches a constant value equal to the free-space propagation time. This constant value is seen to decrease as the satellite moves towards the equator.

The occurrence of nose-shaped traces can be explained as due to oblique echoes received by the sounder-receiver when the satellite is travelling inside a large electron density trough or depression region. The multiple echoes arise from oblique propagation of sounder signals to the edge or wall of the depression where the electron density is sufficiently large and the ray-path vector is normal to the wall in order to totally reflect the radio waves.

THEORY

The ray paths of signals transmitted from a satellite orbiting in the topside ionosphere will now be discussed. Assume that the signals are transmitted at all incident angles downward and that the electron density increases exponentially downward from the same altitude as that of the satellite. For any transmitted frequency, we have a locus of points where the ray-paths are horizontal. This is also called the locus of turning points since the rays do turn back at these points on the locus. As the transmitted frequency is increased, the locus of turning points gets bigger. Figure 4 shows an example of the locus of turning points. In a horizontally stratified ionosphere, rays that are normally incident on the ionosphere do not get deviated and are totally reflected at the critical height. The oblique rays turn away from the satellite at different points on the locus. The Alouette-2 topside sounder ionograms are normally representative of vertical or near-vertical propagation. This is not always the case. Large horizontal gradients or ionization depressions are often observed in the ionosphere.

By studying the variation in the local electron density at the satellite along its trajectory, it is possible to determine whether the satellite is passing through regions having large horizontal gradients. For this study, the trajectories corresponding to three sequences containing loop-shaped traces are employed. Figure 2 represents the sequence of ionograms recorded on February 7, 1968. Figure 5 shows the two other sequences recorded on January 19 and 20, 1968, respectively. The numerals within each sequence indicate the corresponding ionogram numbers from the beginning as the satellite moves towards the equator in a North to South pass. We have analyzed the local electron density variations along the trajectories corresponding to the three sequences. Figure 6 shows the results of our analysis. Shown in this figure are the local electron density and the

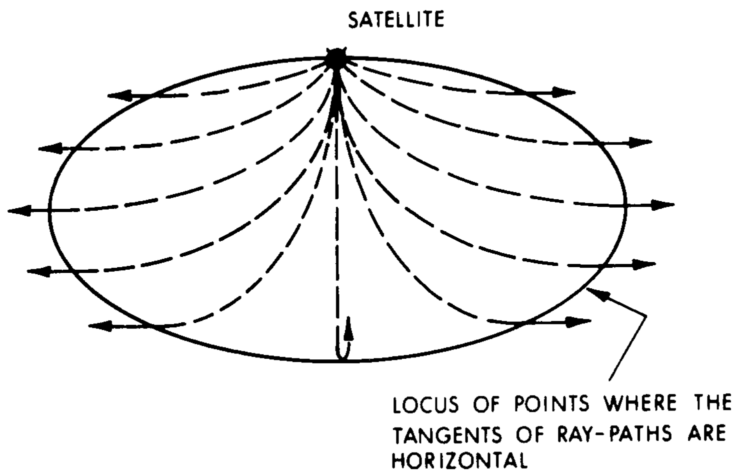


Figure 4.- Locus of turning points

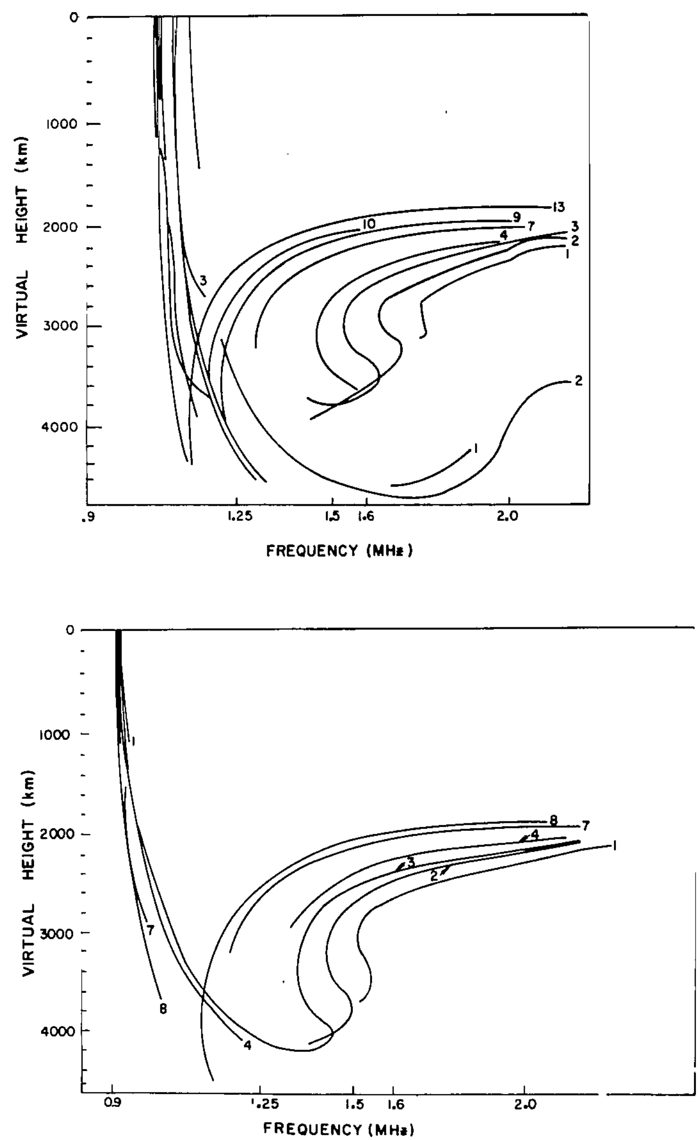


Figure 5.- Two sequences of January 19, 20, 1968

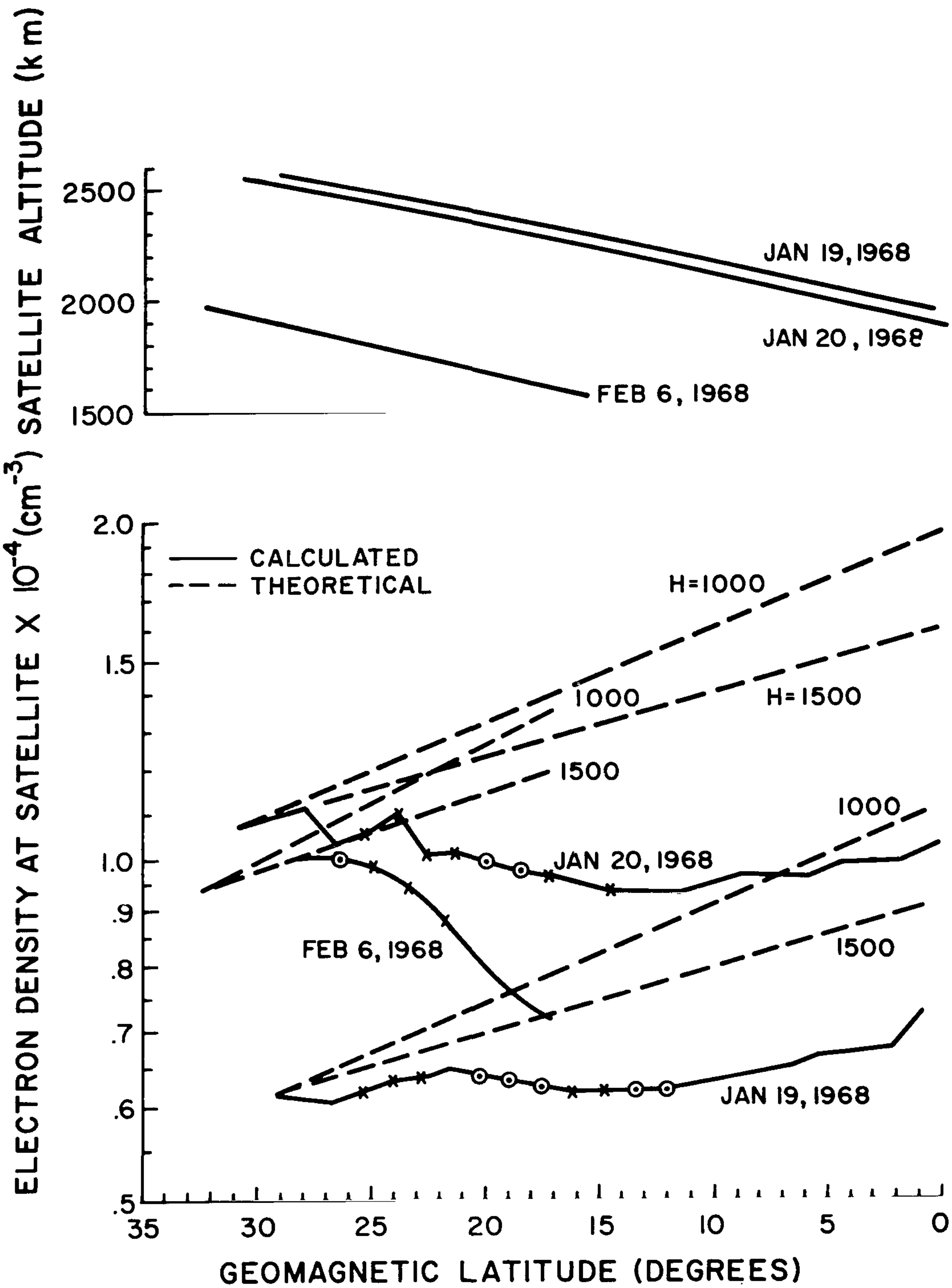


Figure 6.- Local electron density distribution

corresponding satellite altitude as a function of geomagnetic latitude for each of the three sequences. In all three cases, the satellite is moving towards the equator in a North to South pass. The satellite altitude is also decreasing along the trajectory. The local electron density at the satellite was calculated by using both F_{XS}, the extraordinary wave frequency at the satellite altitude, and F_N, the plasma resonance frequency. These frequencies are easily recognizable in Alouette ionograms. If the electron density at the satellite at the beginning of any of the three sequences is used as an initial value, then the electron density at later times should show an increase since the satellite altitude is decreasing. This is expected since the electron density is known to decrease with increasing altitude from the top of the F-region in the topside ionosphere. This assumption is valid if there are no large-scale horizontal gradients (equivalent to latitudinal variations).

We have shown two theoretical electron density profiles along the satellite trajectory corresponding to each of the three sequences. For purposes of calculation, the local electron density at the beginning of the sequence was used as an initial value. From thereon, the electron density, N(h), was assumed to increase exponentially downward from the initial satellite altitude as given by the expression:

$$N(h) = N_0 . e^{h/H} \tag{1}$$

where h is the vertical height in kilometers measured from the initial satellite position, N_0 is the initial local electron density, and H is the plasma scale height in kilometers.

Two values are assumed for H (1000 and 1500 kilometers). Hence, we have two theoretical curves. The parameters of N_0 and H are known. The term h is the difference between the initial satellite altitude at the beginning of a sequence and the altitude at any subsequent point along the trajectory. The calculated value of N from Eq. (1) gives the theoretical electron density at that point. There are two theoretical curves corresponding to H=1000 km and H=1500 km for each sequence. We can then compare the measured and calculated local electron densities along the path for each of the three sequences. One may notice that the local electron density actually keeps decreasing along the trajectory. There is an increasing trend only close to the equator. Such a reduction in density along the satellite path as against the expected increase caused by decreasing satellite altitude can be attributed to the presence of large-scale horizontal gradients of electron density along the satellite path. The horizontal extent of the depression region is approximately 2000 kilometers. Based on the analysis presented above, there is some indication that the satellite was approaching a region of decreased electron density when each of the three sequences were recorded.

An idealized model of such a depression region is shown in Figure 7. The electron density contours are horizontal and parallel to each other both inside and outside the depression region. At the edge of the depression, there is a discontinuity of contours. We have simplified the model by assuming that at the wall of the depression, the electron density contours are vertical, parallel, and much closer together than the horizontal contours. This is the region, hereafter called the "wall", where sharp horizontal gradients of electron density exist. Such a wall is capable of totally reflecting some of the oblique rays which would not otherwise return to the satellite. The approximation of a "vertical wall" is crude and serves only to illustrate the problem. Figure 8 shows some sample ray paths in a depression region. Some of the oblique rays which travel up to the wall of the depression region can return to the satellite if the ray path vector intersects the wall normally and the electron density at the point of intersection is equivalent to that at the critical height of reflection for normal incidence. For some frequencies, these conditions are satisfied and we receive oblique echoes at the satellite in addition to the normal echoes. At some minimum frequency, we receive only one additional echo since the locus of turning points intersects the wall at only one point. In other words, at a specified minimum frequency, there is only one oblique ray which can return to the satellite. As the frequency is increased further and assuming that the distance between the wall and the sounder transmitter is not changing, two oblique rays can return to the satellite instead of one since the larger loci now intersect the wall at two points. Therefore, oblique rays launched at two different angles can return to the satellite. These two echoes now form the upper and lower branches of a loop-shaped frequency versus time delay trace with the oblique return at the minimum frequency forming the nose frequency of the loop. Figure 9 is a diagram indicating the intersection of the loci of turning points at specific frequencies with a stationary wall. The horizontal distance between the transmitter and the wall is assumed to be constant and only the frequency is varying. Also, as shown in Figure 9, at frequencies greater than the nose frequency, multiple echoes are obtained.

In order to afford a comparison with observed ionograms, we have to calculate the group-delays of echoes received at various frequencies in a depression region. Once again, we assume a horizontally stratified ionosphere with no magnetic field. Also, the depression region is represented by the model discussed in Figure 7. We will study the frequency versus group

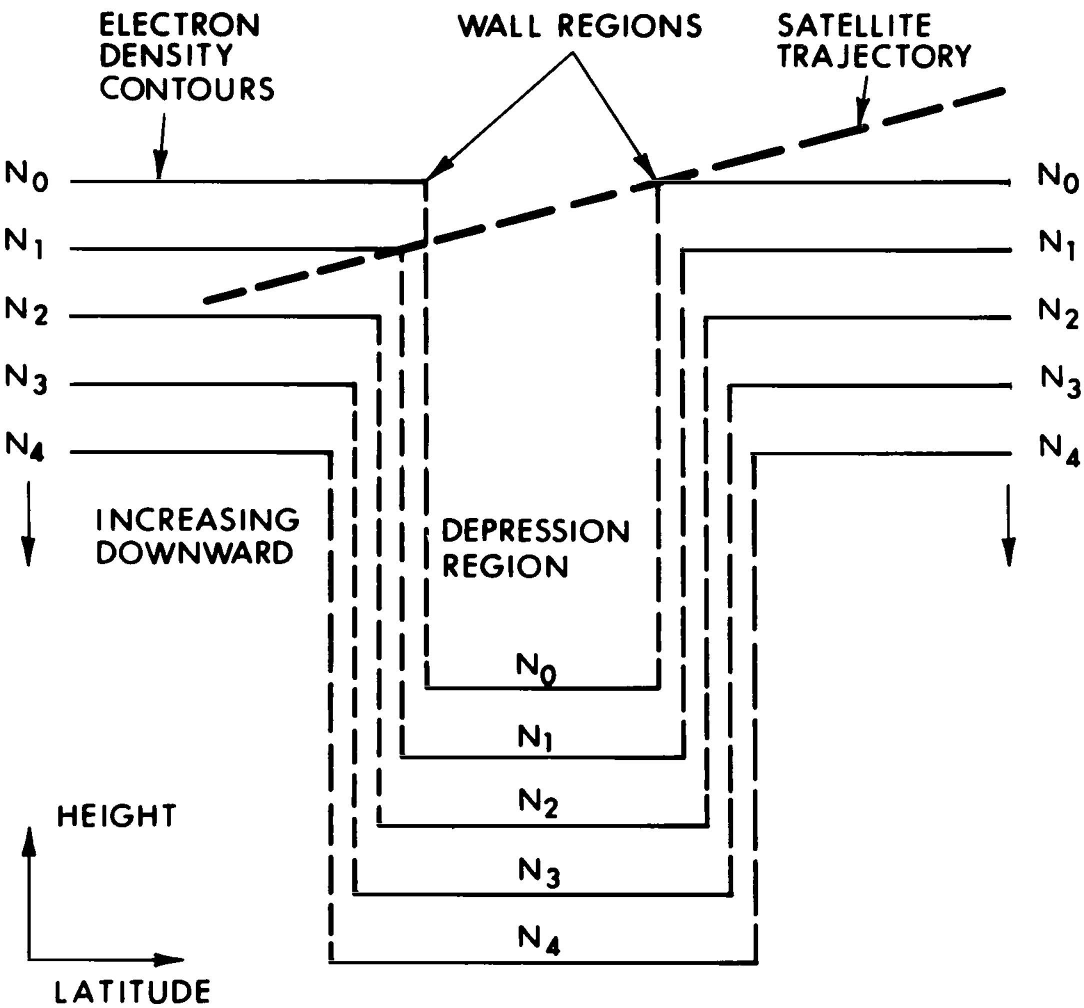


Figure 7.- Depression model

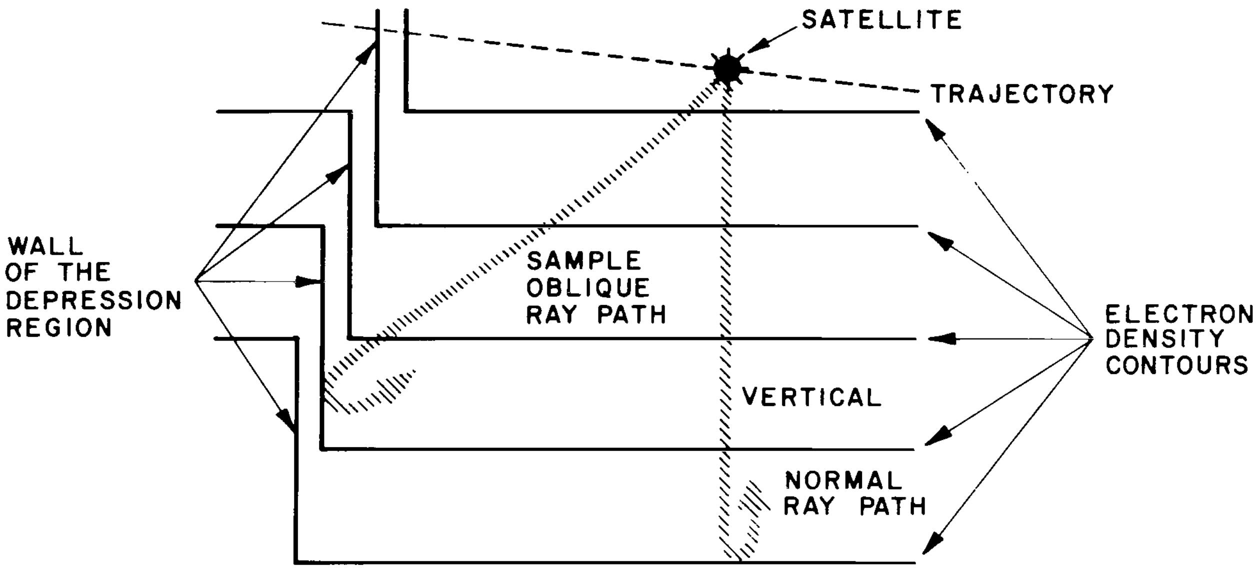


Figure 8.- Ray paths in a depression

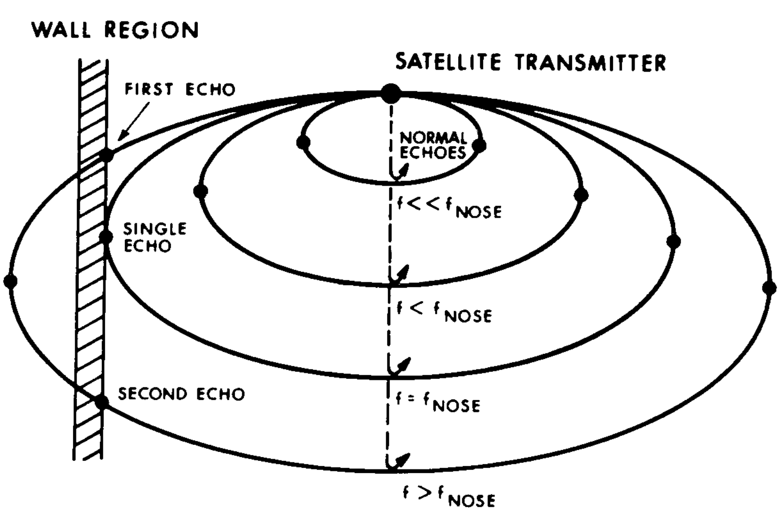


Figure 9.- Turning points of specific frequencies

delay characteristics of oblique echoes only. The equation relating the two parameters is given by (ref. 4)

$$F' = \frac{1}{\sqrt{1-1.111\times10^{-11}D^2T^{-2}}} \cdot \cosh\left[1.5\times10^{5}TH^{-1}\sqrt{1-1.111\times10^{-11}D^2T^{-2}}\right] \tag{2}$$

where D is the horizontal distance in kilometers between the wall of the depression region and the transmitter, F' is the normalized signal frequency given by F/F_N, F is the signal frequency and F_N is the plasma frequency at the satellite altitude. T is the corresponding group-delay in seconds. H is the plasma scale height in kilometers.

A value varying between 1000-1500 kilometers is assumed for H. The electron density is assumed to increase exponentially downward from the satellite altitude as given by Eq. (1).

For a constant value of D, one can obtain a F' versus T profile and this is what is recorded in an ionogram. The F' versus T equation given here does not relate to that portion of the ionogram which corresponds to vertical propagation. It corresponds only to oblique propagation with the assumption that the signals whose ray-paths intersect the wall normally at a distance D are reflected back. According to Eq. (2), for a constant value of D, we should get a loop-shaped F' versus T profile with the nose frequency (F_{min}) of the loop corresponding to the frequency at which there is only one oblique ray reflected from the wall. For frequencies below F_{min} no reflections are obtained from the wall. Hence, the nose frequency is a function of D the horizontal distance between the transmitter and the wall. As the value of D increases, one can determine that F_{min} also increases. In our case, as the satellite approaches the wall, the value of D decreases. Therefore, F_{min} should decrease.

COMPARISON WITH SATELLITE OBSERVATIONS

The sequence of ionograms shown in Figure 2 is used to compare the observed results with the theory. The normalized nose frequencies of the loops in ionograms 1, 2, 3, and 4 of the sequence are 1.365, 1.280, 1.194, and 1.112 MHz, respectively. As mentioned earlier, the normalized nose frequency is equal to the nose frequency divided by the extraordinary wave frequency at the satellite attitude (= F_{nose}/F_{xs}).

Figure 10 shows the loci of turning points for these four frequencies. Also indicated in the figure are the satellite position and the wall positions relative to the satellite. From this figure, we also can get an estimate of the horizontal

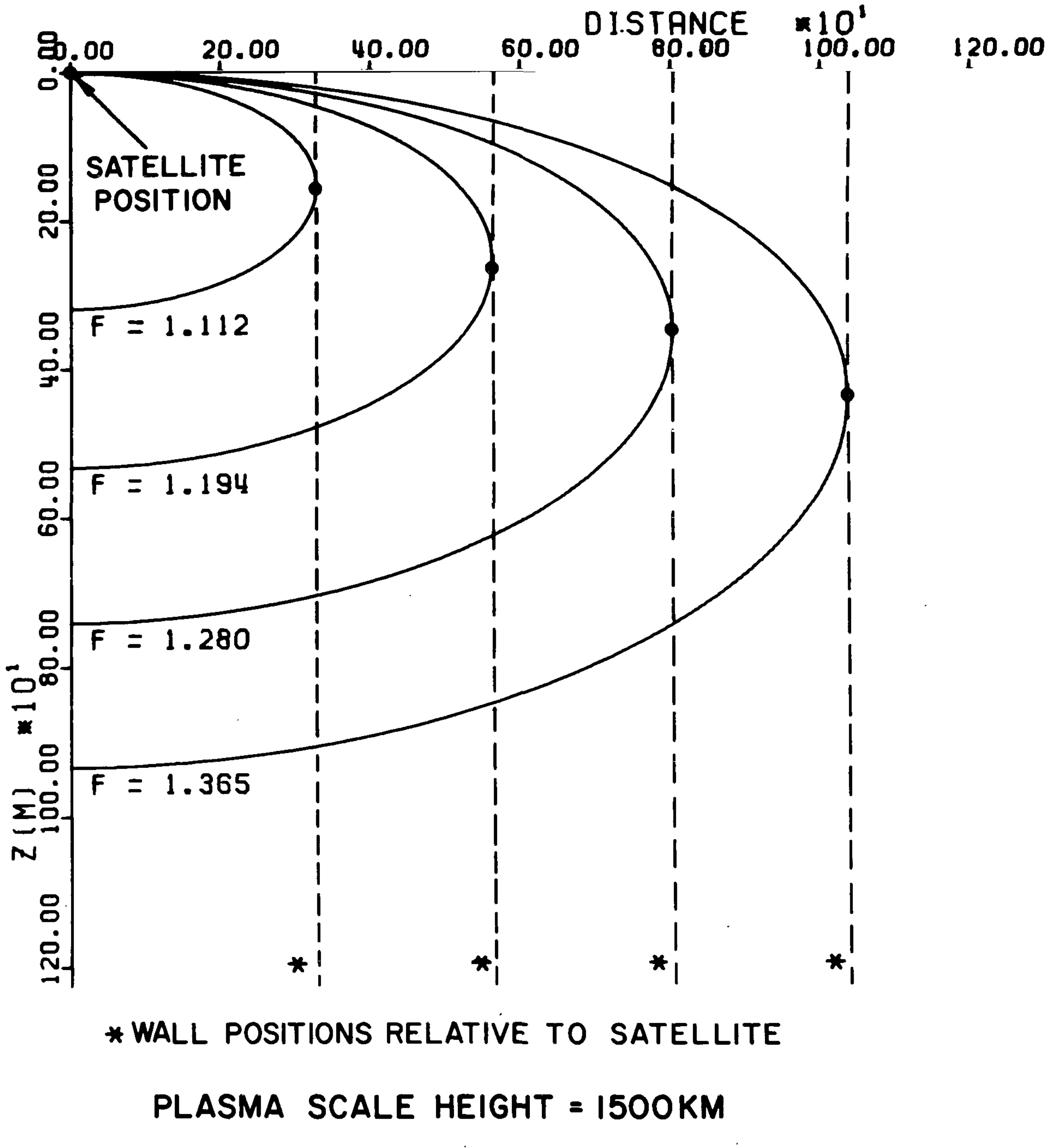


Figure 10.- Locus of turning points of four frequencies

separation distance D between the transmitter and the wall corresponding to the time each of the ionograms were recorded. Table I shows the values:

TABLE I

HORIZONTAL DISTANCES FOR VARIOUS NOSE FREQUENCIES

Ionogram	F_{nose}/F_{xs}	D calculated from Figure 10 (km)
1	1.365	1045
2	1.280	805
3	1.194	585
4	1.112	325

We have an indirect way of checking whether the values of horizontal distance between the satellite and the wall calculated above are accurate. Figure 11 shows the satellite trajectory corresponding to the sequence of ionograms shown in Figure 2. The horizontal distances indicated on the x-axis are measured with respect to the first ionogram of the sequence. The numerals marked on the trajectory correspond to the respective ionograms of the sequence. From Figure 11 we can calculate the horizontal distance traversed by the satellite relative to its position when the first ionogram was recorded. In other words, the horizontal range with respect to ionogram 1 covered by the satellite by the time it records ionograms 2, 3, and 4 should compare favorably with the relative horizontal ranges calculated in Table I. The comparison is shown in Table II.

The agreement is within acceptable limits. Hence, it can be concluded that the wall was located at a horizontal range of approximately 1050 kilometers when the first ionogram of the sequence was recorded. The satellite moved closer to the wall as the succeeding ionograms were recorded. The corresponding horizontal distances are as shown in Table I.

Figure 12 shows the normalized frequency F' versus time delay T plots for horizontal distances D calculated for ionograms 1, 2, 3 and 4. This is accomplished by using Eq. (2). One can see the loop traces. The nose frequency is seen to decrease as D decreases or as the satellite moves closer to the wall. Also, as

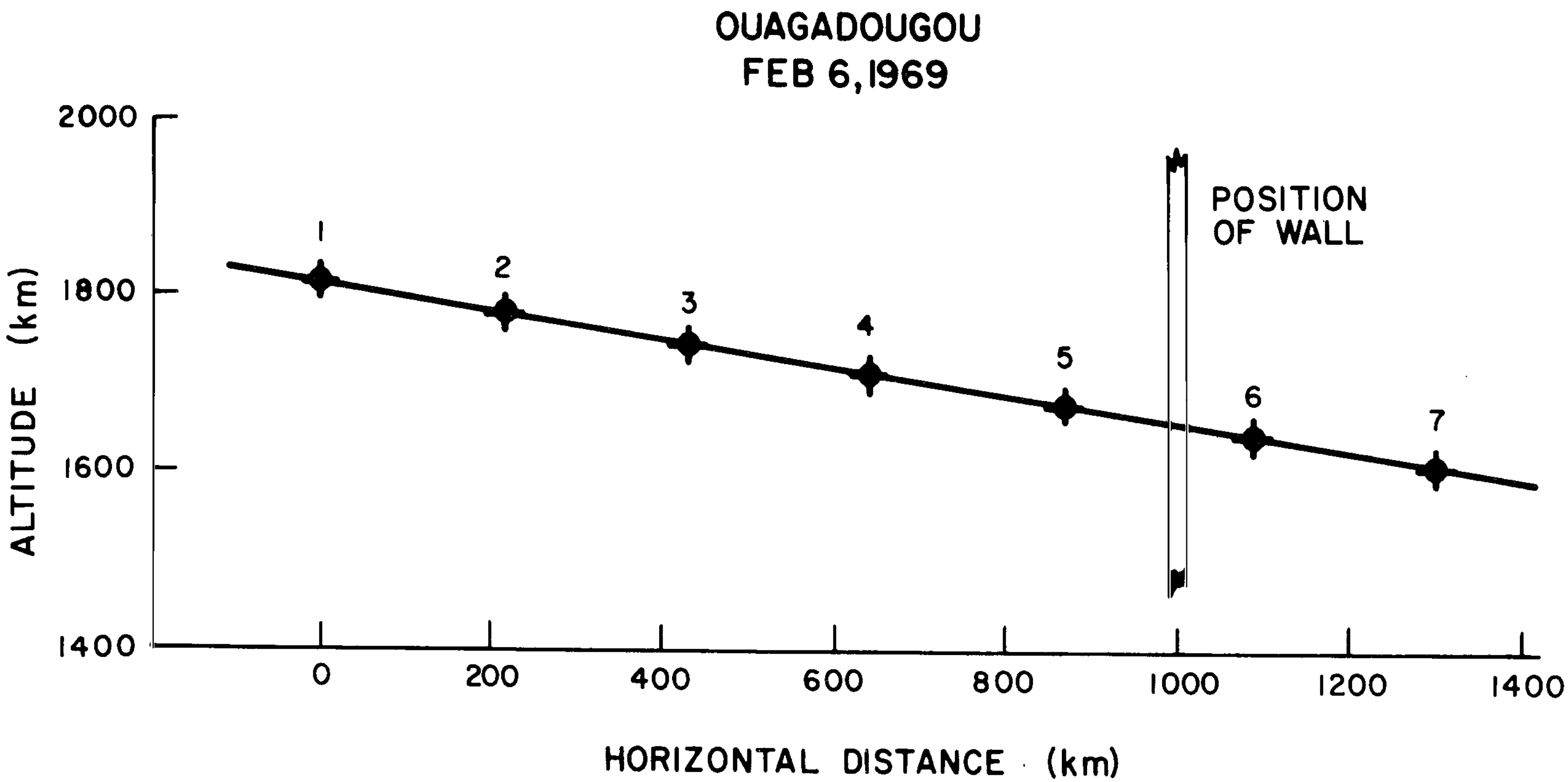
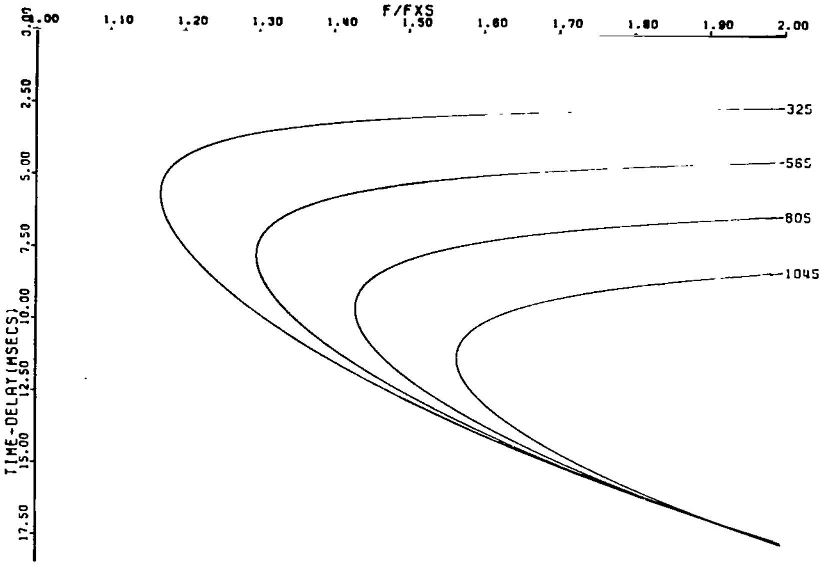
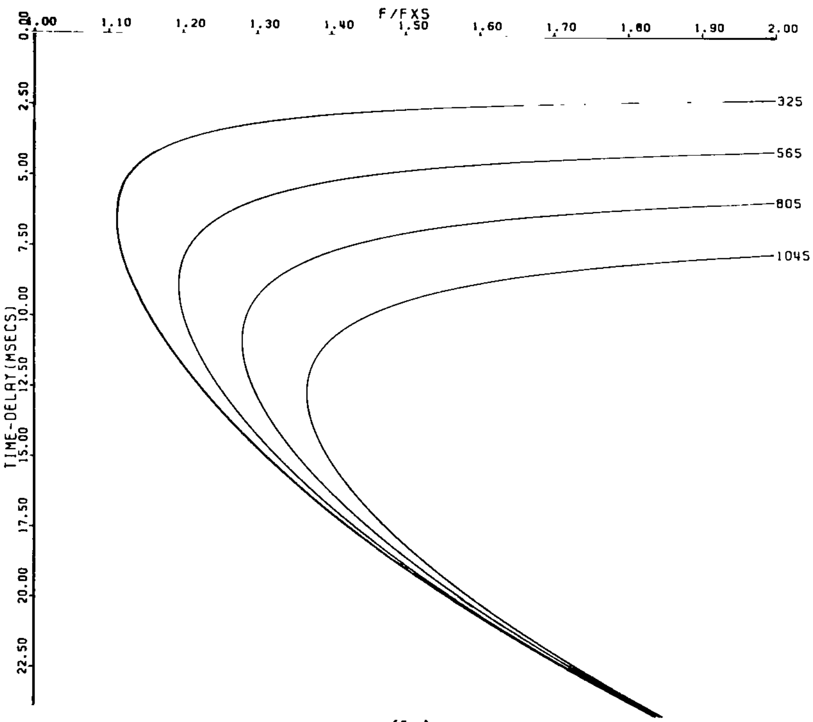


Figure 11.- Satellite frequency of Figure 2



(a)



(b)

Figure 12.- F' vs T - (a) 1000 km (b) 1500 km

TABLE II

COMPARISON OF THE HORIZONTAL DISTANCE CALCULATED FROM THE TRAJECTORY WITH THE HORIZONTAL DISTANCES LISTED IN TABLE I.

Ionogram	Relative Horizontal Range from Trajectory (km)	Relative Horizontal Range from Table I (km)
1	0	(1045-1045) = 0
2	225	(1045-805) = 240
3	450	(1045-585) = 460
4	670	(1045-325) = 720

the nose frequency decreases, the loops get broader. These features are in general agreement with what is observed in progression in ionograms 1, 2, 3, and 4 of the sequence. Therefore, most of the features characteristic of the loop-shaped traces are satisfied by the ionization depression model. There is only one discrepancy noticed in comparing the observed and calculated results. On the ionograms, the delay time corresponding to the nose frequency is seen to increase as the nose frequency decreases. However, in our calculations, the delay time decreases instead. Our model of a square well depression region with narrow vertical wall which is stationery with respect to the satellite is highly idealized. We have also neglected the magnetic field in our calculations. This leads to the assumption that there is only one propagating mode. We have used F/F_{XS} instead of F/F_N for the normalized frequency, F'. By definition, F_{XS} is the critical frequency of the extraordinary mode at the satellite altitude and F_N is the plasma frequency or the critical frequency of the ordinary mode at the satellite altitude. Of the two, only F_{XS} is dependent on the local magnetic field. Such an assumption leads to errors in calculating the absolute values of group delays. It is possible to include the magnetic field in our analysis. However, it leads to lengthy and tedious numerical computations. The purpose of this paper is only to illustrate and explain the macroscopic features of the loop-shaped traces.

CONCLUSION

It may be concluded that the loop-shaped traces observed on the Alouette-2 swept frequency ionograms are caused by total reflection of oblique radio waves at the edge of large-scale horizontal depressions of electron density. The nose frequency and size of the loop trace depends upon the distribution of electron density in the depression and the distance of the sounder transmitter from the edge of the depression region.

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