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# CHARACTERISTICS OF MAGNETOSPHERIC DUCTS OBSERVED BY THE ALOUETTE-2 TOPSIDE SOUNDER

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# CHARACTERISTICS OF MAGNETOSPHERIC DUCTS OBSERVED BY THE ALOUETTE-2 TOPSIDE SOUNDER

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## SUMMARY

The Alouette-2 topside sounder data have been used extensively to study the field-aligned propagation of HF radio waves. This technical note presents results about the physical characteristics of magnetospheric ducts with reference to their scale-sizes and peak fractional deviations of electron density. More than 400,000 Alouette-2 ionograms have been analyzed to study the conjugate ducting phenomenon. A select sample of data is used to decipher the duct characteristics. The calculated average values for the scale sizes and peak fractional deviations of electron density are in agreement with the previously published results for the Explorer-20 and Alouette-1 topside sounder data.

## INTRODUCTION

The phenomenon of field-aligned propagation of HF radio waves or "Conjugate Ducting" has been extensively studied by several authors (Loftus et al., 1966; Muldrew, 1963, 1967, 1969; Ramasastry et al., 1968a, 1968b, 1969) using the Alouette-1 and 2 and Explorer-20 topside sounder satellite observations. The investigations reported hitherto may be grouped into three categories; (1) studies of patterns of conjugate echoes observed in the topside sounder ionograms and analyses of the frequency versus time-delay characteristics of such traces, (2) studies of the percentage occurrence of conjugate echo events as a function of local time, latitude, L-value, magnetic $K_p$ index, etc., and (3) studies of the physical characteristics of magnetospheric ducts with reference to their scale-sizes and peak fractional electron density enhancements (or depletions). More than 400,000 Alouette-2 ionograms have been examined to study the conjugate ducting phenomenon. The results of our investigations on the physical characteristics of magnetospheric ducts are presented in this report.

## Conjugate Echoes in Alouette-2 Topside Sounder Ionograms

An example of a frequently observed "double-hook" pattern of conjugate echoes (Ramasastry et al., 1968a) is shown in Figure 1. Also shown in the figure, are the various traces arranged according to their actual time-delays. For the most part, only extraordinary rays exhibit conjugate echoes in the Alouette-2 data. Ordinary wave conjugate echoes are very rarely observed. Detailed descriptions of the various conjugate - echo patterns observed by the Alouette-2 sounder are provided by Muldrew (1963, 1969) and Ramasastry et al., (1968a, b).

Observation of conjugate echoes in the high L-value range is very rare. To date, only 40 ionograms containing conjugate echoes where the associated L-values are greater than 3 have been observed. It should be mentioned that near-end ducted traces are observed even at polar latitudes (Shmoys, 1968). However, conjugate echoes which consist of a pair of echoes, a near-end return, and a far-end return (from the magnetically conjugate point in the opposite hemisphere) are never observed at very large L-values. The reason for not observing high L-value conjugate echoes is two-fold: (1) the long propagation paths result in the arrival of far-end returns after the receiver of the swept-frequency sounding system has shifted to a much higher frequency than that of the far-end echo return, and (2) at high L-value, the field-lines extend so far into the magnetosphere when they cross the equatorial plane that the ambient electron densities are too low to support the electron density gradients required to keep the HF radio waves trapped along the field-aligned ducts. The rare occasions when conjugate echoes appear on the ionograms at high L-values can be attributed to unusual magnetospheric conditions.

A typical example of an ionogram exhibiting conjugate echoes and recorded at high L-value is shown in Figure 2. The satellite was at an altitude of 2830 km, 50°N magnetic latitude, and L = 3.7. The four-ducted echoes in the ionogram (bottom to top) are the near-end (N), far-end (F), round-trip (N+F) and a higher order trace (2N+F). The delay times of the F, N+F and 2N+F echoes are in the 0.3 to 0.4 sec range. The next higher order echo group (N+2F, 2N+2F, 3N+2F) would arrive with time-delays on the order of 0.7-0.9 sec and it would be very difficult for the badly detuned receiver to respond to them.

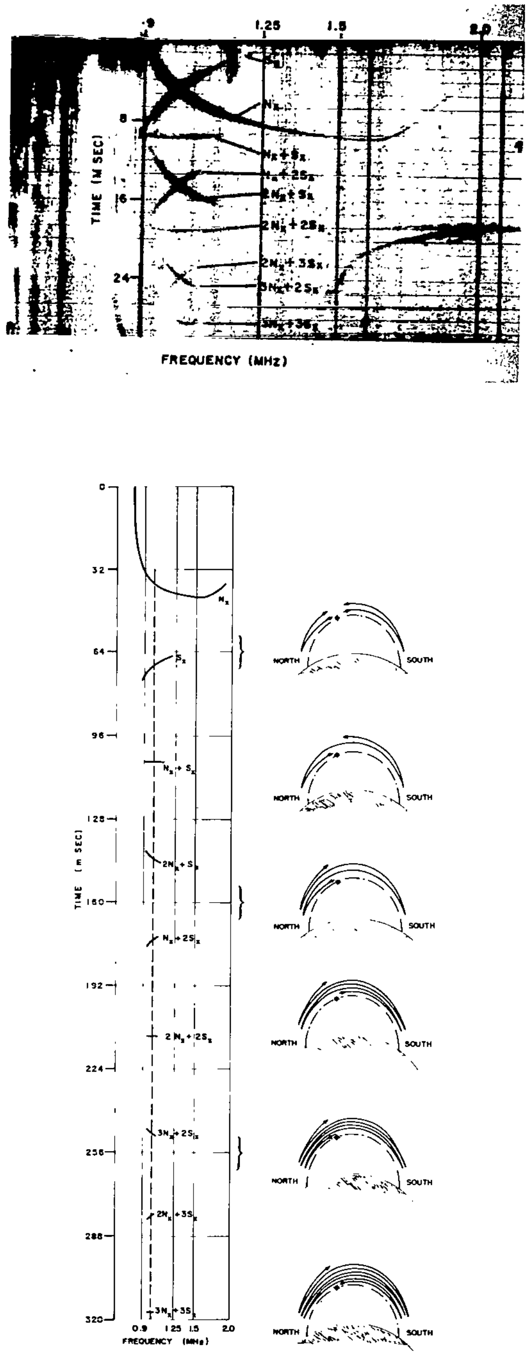


Figure 1.- The "double hook" pattern recorded at Quito, Ecuador, on August 18, 1966 at 08:00:05GMT. (Local Time = 02:07:46, Geomag. Lat. = 12.56°N, Geomag. Long. = 18.22°W, L = 1.53)

Figure 2.- Example of an ionogram with conjugate echoes recorded at a high L-value (Recording Station: Resolute Bay. L value = 3.70)

## DUCTING EVENTS AS A FUNCTION OF $K_p$ INDEX

Previous workers [Loftus et al., 1966; Muldrew, 1967; Ramasastry et al., 1969] have found no obvious correlation between the HF ducting events and the magnetic $K_p$ index. The duct occurrence versus $K_p$ analysis with all the available Alouette-2 data for the years 1965, 1966, 1967, and 1968 has recently been completed. Since the general magnetic activity is on the increase since 1965, it was hoped that some change in the duct occurrence characteristics would be noticed. However, no correlation between ducting events and $K_p$ index and no change in the distribution as the sunspot maximum approached have been observed. It may be mentioned that a ducting event in the analysis represents a sounding sequence in an orbit when at least one ionogram containing conjugate echoes is observed. The analysis was also carried out assuming that each ionogram containing conjugate echoes represents a ducting event. The conclusions did not change.

Shown in Figure 3 are the percentage occurrences of ducting events as a function of $K_p$ index for the years 1965, 1966, and 1967. The observed distributions follow the distribution of topside roundings as a function of $K_p$ index for the respective years. A similar relationship for the 1966 data (Ramasastry et al., 1969) for Singapore only was found earlier. Once again, it may be concluded that higher level of magnetic activity does not increase the occurrence rate of ducting events. Observation of a large percentage of ducting events at low $K_p$ values seems to indicate that the magnetospheric ducts are formed by source mechanisms that are not affected by the increased magnetic activity.

The percentage occurrence of ducting events as a function of $K_p$ index for the year 1966 for the four stations (Singapore, Orroral Valley, Santiago, Quito) which recorded a large percentage of ducting events is shown in Figure 4. Singapore and Orroral Valley recorded more than 50 percent of all the ducting events observed during 1966. Santiago and Quito come next in the intensity of ducting activity. The duct occurrence versus $K_p$ distribution, however, is essentially the same for each of the four stations.

## Physical Characteristics of Conjugate Ducts

The physical characteristics of field-aligned electron density irregularities or "ducts" associated with the conjugate echoes observed by the Alouette-1 topside sounder have been discussed by Muldrew (1963). For a conjugate echo event observed by Alouette-1 satellite, Muldrew found the half-thickness of the

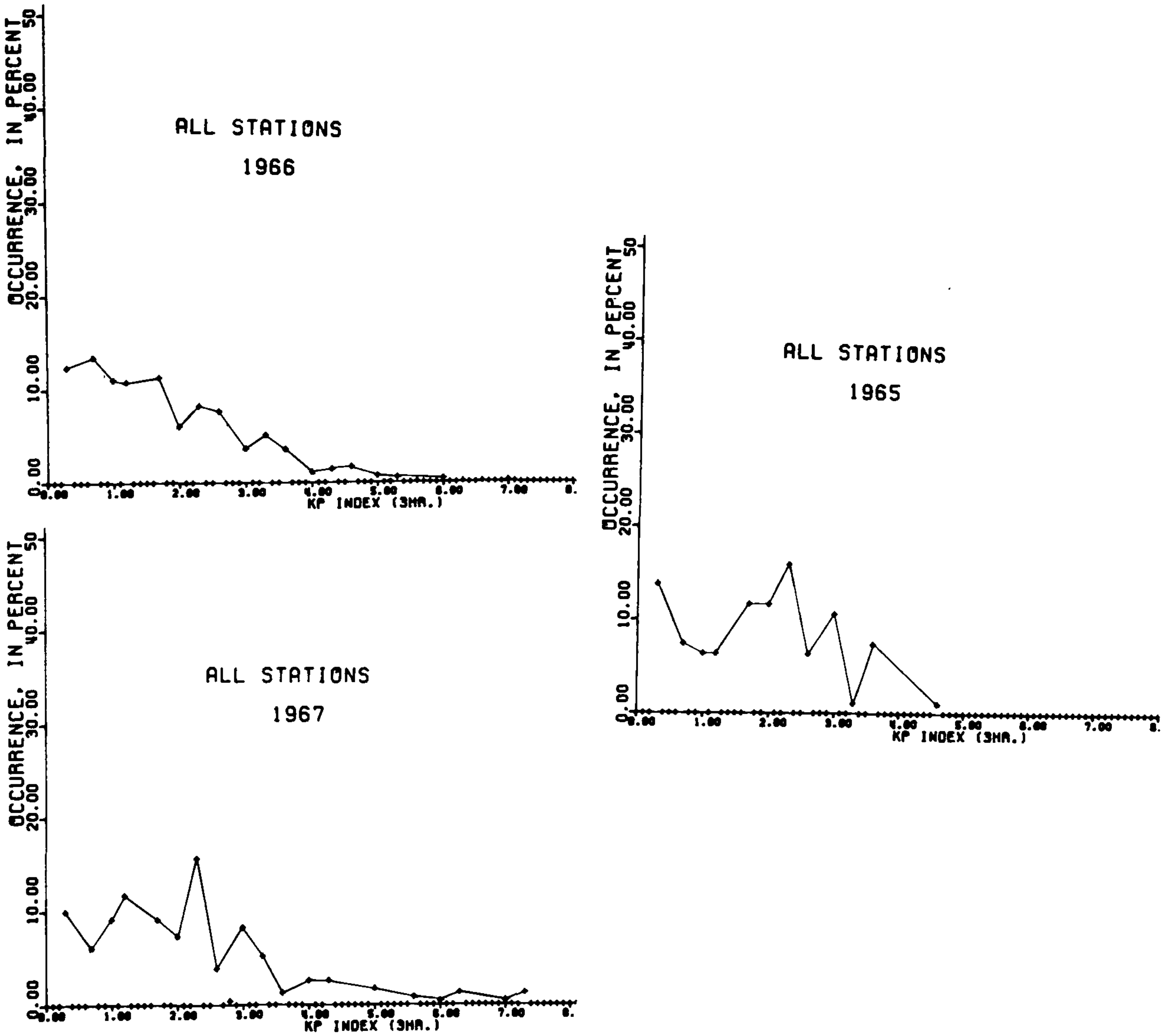


Figure 3.- Percentage occurrence of Conjugate Ducting Events as a function of $K_p$ for the years 1965, 1966 and 1967.

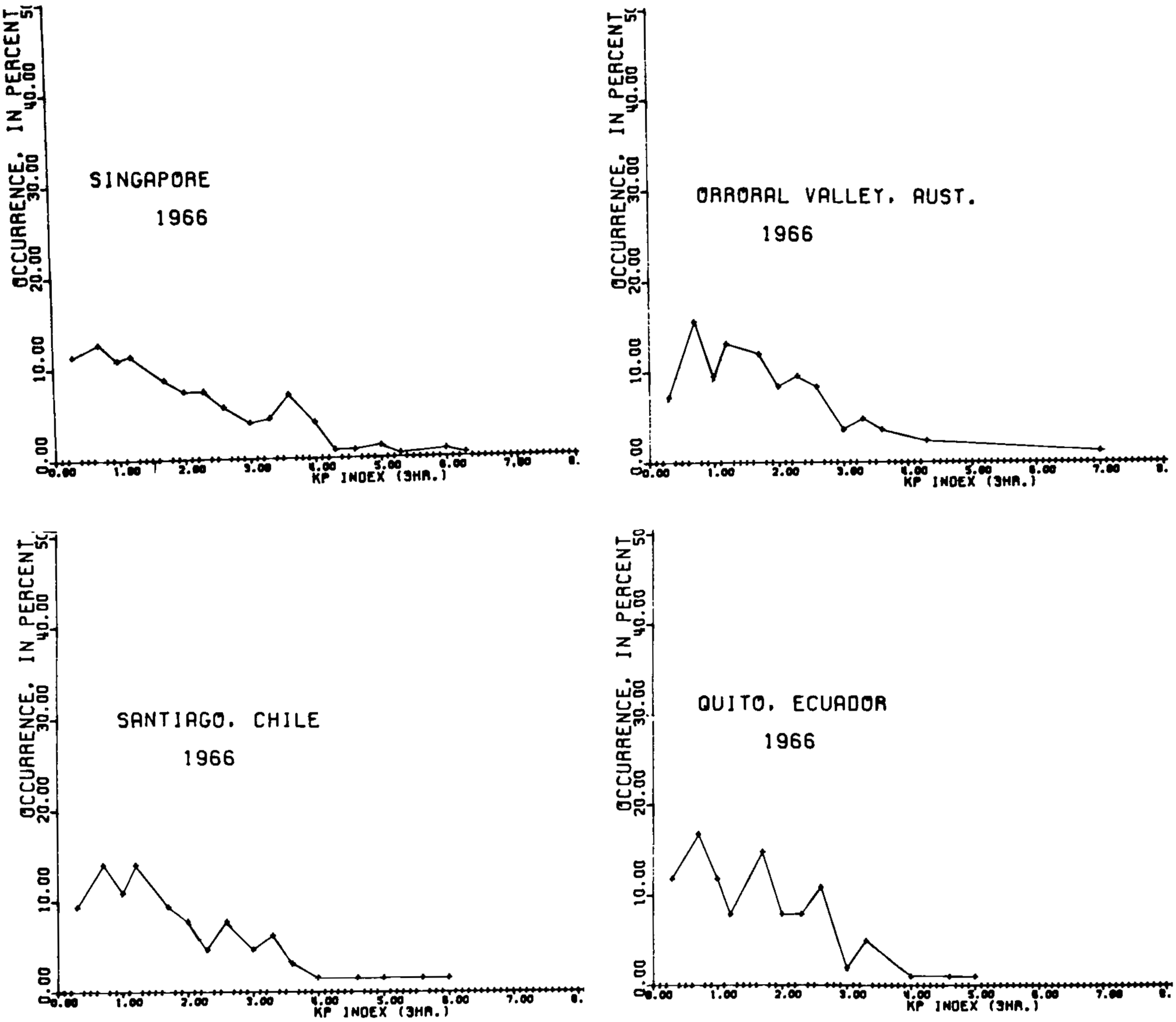


Figure 4.- Percentage Occurrence of Conjugate Ducting Events as a function of $K_p$ for four stations (Quito, Santiago, Singapore and Orroral Valley) for the year 1966.

ducting region to be 0.6 km with an electron density enhancement of about one percent. In their analysis of Explorer-20 fixed-frequency topside sounder data, Loftus, et al., (1966) obtained a logarithmic normal distribution for the horizontal duct thickness. The distribution is centered at 4.2 kilometers with a standard deviation (expressed as a factor) of 2.1. Individual values ranged from 1 to 40 kilometers. The corresponding transverse duct thicknesses are smaller than the horizontal duct thicknesses for the range of dip-angles considered in the data. Loftus, et al., also calculated the center-to-center separation of conjugate ducts along the satellite path and obtained a logarithmic normal distribution which has a mode at 42 kilometers with a standard deviation (expressed as a factor) of 4.3. Individual values ranged from 3 to 2640 kilometers. They also found that for most conjugate ducts, the variations in electron density from the background was probably less than one percent. In this section, the results obtained by analyzing the conjugate echoes observed by the Alouette-2 topside sounder are presented.

Figure 5 shows two characteristic types of conjugate echo patterns observed in the Alouette-2 data. At the bottom of each ionogram is shown the corresponding satellite trajectory with respect to the magnetic field-line distribution at the satellite altitude. The guiding ionization duct is aligned along the direction of the magnetic field. The satellite positions where the near-end (N), far-end (F), and the round-trip (N+F) traces began and ended are indicated on the trajectory. The echo patterns demonstrate the manner in which the appearance of the various conjugate echo traces is affected by the position of the satellite with respect to the field-aligned duct.

We have assumed that the radio signals are guided in a whispering gallery mode along an enhancement duct. In the ionogram on the left in Figure 5, the near-end echo begins at a much lower frequency than the other echoes which all start abruptly at a higher frequency. This behavior can be explained by postulating that the ducts are more tenuous at higher altitudes. The satellite was at a latitude of 14.0° North (geomagnetic) and moving southward. Assuming that the ducts are field-aligned, the satellite was crossing the ducts from the poleward side. When the satellite is at a slightly higher latitude than the duct position at the satellite altitude, it is possible to trap near-end echoes in a combination mode propagation (Muldrew, 1963; Dyson, 1966). Signals launched at the satellite position could penetrate through the duct and yet get refracted slowly into the duct towards the near-end and then be guided by the more effective portions of the duct at lower altitudes. Signals cannot be trapped towards the far-end of the field-line, since both the electron density gradient in the duct and the radius of curvature of the field line become smaller as one moves along the field-line

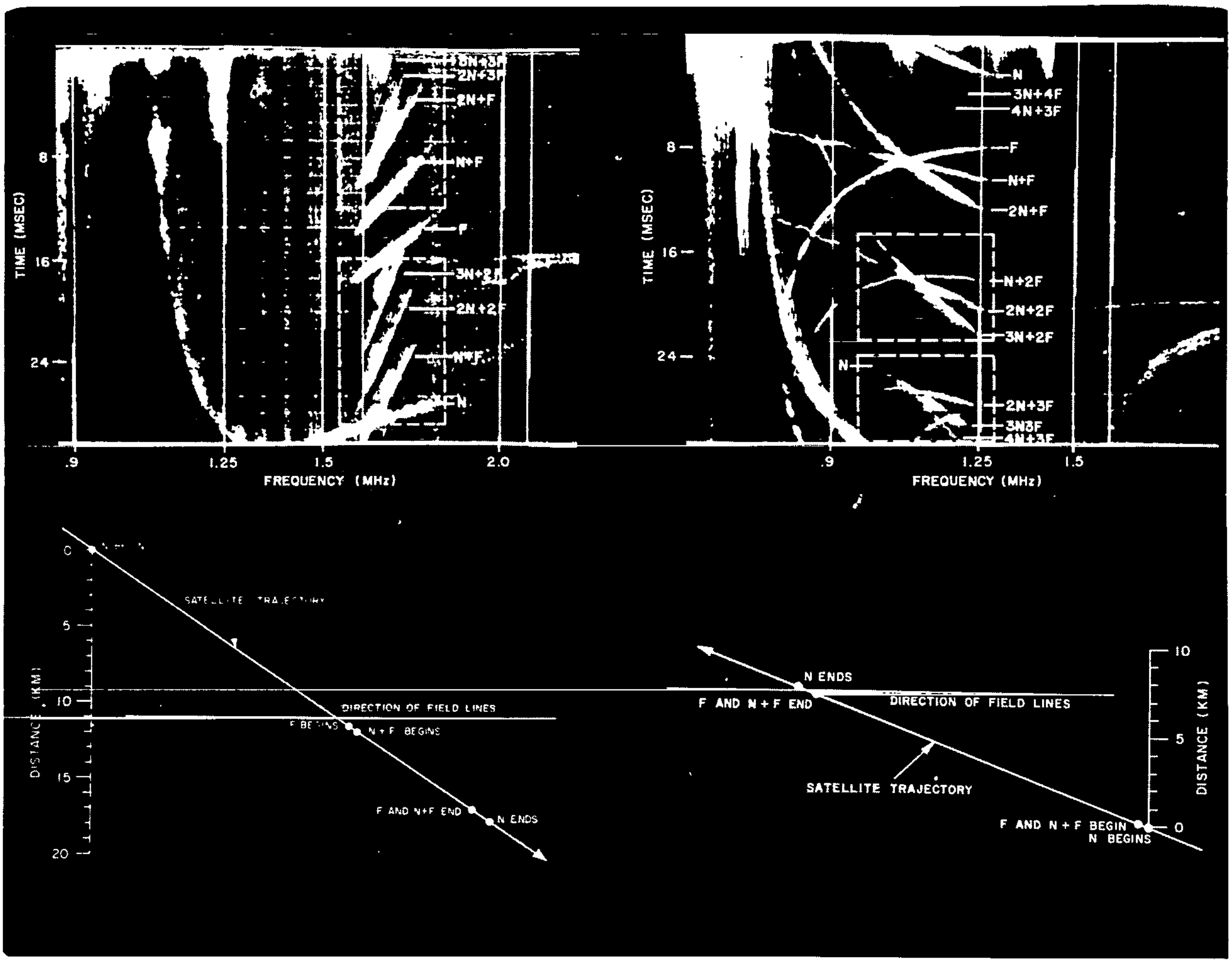


Figure 5.- Two characteristic types of ionograms with conjugate echoes. In the left ionogram the near end trace begins much earlier than other traces. In the right ionogram all the traces begin simultaneously.

towards the equatorial plane. This is the reason why the near-end trace is observed just after $f_{xs}$ (extraordinary wave-frequency at the satellite altitude) and all the other traces begin at a higher frequency. At the time (and frequency) all the other traces appear in the ionogram, the satellite presumably has crossed over to the equatorial side of the enhancement duct. Thus, when the satellite is at or just equatorward of the enhancement duct, direct-ducting in the form of whispering gallery mode of the near-end, far-end and all the other higher order modes takes place. The "positive" slope would occur on the equatorward side of the enhancement duct.

On the other hand, when the satellite is travelling poleward with respect to the field-aligned duct, both the signals travelling along the field-aligned duct toward the equatorial plane (far-end) and towards the earth (near-end) can be trapped. Therefore, all the conjugate echoes are observed to begin simultaneously as soon as $f_{xs}$ is exceeded in the sweep-frame. An example where all the conjugate echoes begin at the same frequency is shown in the ionogram on the right in Figure 5. The satellite was at a geomagnetic latitude of 11° North and travelling northwards.

In general, all the conjugate echoes would be expected to begin simultaneously as soon as $f_{xs}$ is exceeded in the sweepframe when the satellite is travelling polewards with respect to the field-aligned duct. If it is travelling equatorwards, the near-end trace begins immediately after $f_{xs}$ and all the other traces begin at a higher frequency when the satellite is on the positive gradient side of the enhancement duct. An exception would occur if the satellite happens to be on the positive gradient side at the time the sweep frequency reaches $f_{xs}$. Then, all the traces would begin simultaneously.

The shape of the delay-time versus frequency characteristic will not undergo any noticeable change over a small range of L-values. This means that the near-end echo can be continuous while the satellite passes between two closely-spaced ducts. However, the far-end and higher-order traces cannot be continuous in such transitions when the satellite is crossing the ducts. If the ducts are very closely spaced compared to the distance traveled by the satellite during the sweep-period of the ionogram (≈32 seconds), one can observe the discontinuities in the far-end and higher order traces. These discontinuities correspond to the transition from one ducting region to another. Meanwhile, the near-end trace remains continuous since it is guided in adjacent ducts by combination modes. In the Alouette-2 data, approximately five (5) percent of the conjugate echo ionograms exhibit multiple ducting regions. An example of a multiple duct ionogram is shown in Figure 6.

Figure 7 gives distributions of the duct separation distance (S) and track width of the first ducting region (D) for the ionograms which exhibit multiple ducting regions. These distances are measured normal to the field-lines. D is the distance traversed by the satellite normal to the field-line between the times the far-end and higher order traces first appear and disappear. In Figure 8 is shown the distribution of trackwidth (D) for 2070 ionograms containing conjugate echoes. The distribution is similar to the D distribution in Figure 7. This means that the ducts observed in the ionograms showing multiple ducting regions have the same general dimensions as all the other ducts. The only difference is that they are spaced more closely together.

In this context, the frequency occurrence of sequences of ionograms containing conjugate echoes observed at the equatorial stations (Ramasastry et al., 1969) may be discussed. Especially true of Singapore data is that in many of those satellite passes when conjugate echoes are observed, almost every ionogram in the sounding sequence exhibits conjugate echoes. In the ionograms, the conjugate echo traces are usually not observed above 2.0 MHz due to the much faster rate at which the receiver is detuned at frequencies > 2.0 MHz. The sweep-rate is approximately 0.15 MHz/sec from 0.2 to 2.0 MHz, and 1.0 MHz/sec in the 2.0-14.0 MHz range. The sweep-period is 32 seconds. But for 25 seconds (from 2.0 MHz sweeptime of one ionogram to the $f_{xs} \approx 0.9$ MHz sweeptime of the succeeding ionogram), there is no way of determining whether ducts exist because of the design of the experiment. During the 25 seconds, the satellite covers a horizontal distance of approximately 150 km.

In summary, the average duct separation is of the order of 50 kilometers in the equatorial regions. The duct separation could be less than 20 kilometers, as has been seen from the analysis of ionograms with multiple ducting regions. However, such ionograms comprise only 5 percent of the total.

Figure 9 shows the distributions of the track width of conjugate ducts for three different cases. Also included in the figure is the distribution of "horizontal duct thickness" obtained from Explorer-20 topside sounder data by Loftus, et al., (1966). The manner in which it was obtained indicates the "horizontal duct thickness" should more correctly be called "horizontal track width". The three distributions for the track width (D) shown in the figure are for: (1) all the Alouette-2 conjugate echo ionograms irrespective of the value of $f_{xs}$ on the ionograms, and (2) those ionograms in which $f_{xs} \leq 0.95$ MHz


Figure 6.- An example of an ionogram with conjugate echoes showing multiple ducting regions.

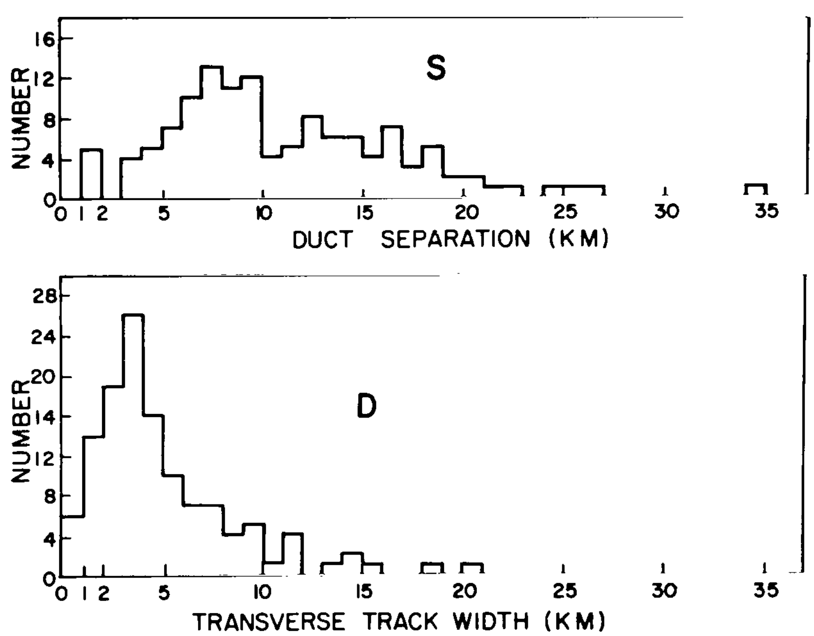


Figure 7.- Distributions of transverse duct separation distance (S) and track-width (D) deciphered from ionograms showing multiple ducting regions.

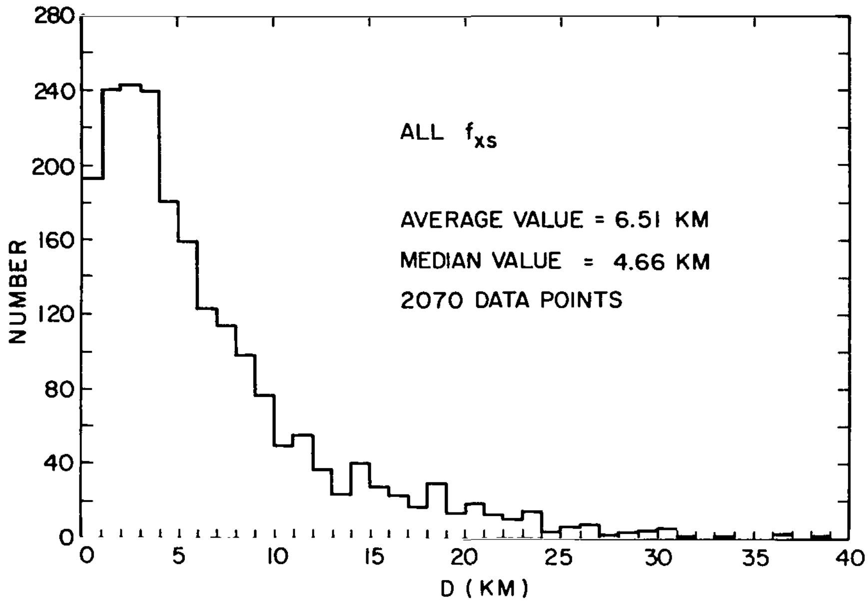


Figure 8.- Distribution of the Track width (D) of conjugate ducts observed by Alouette-2 sounder.

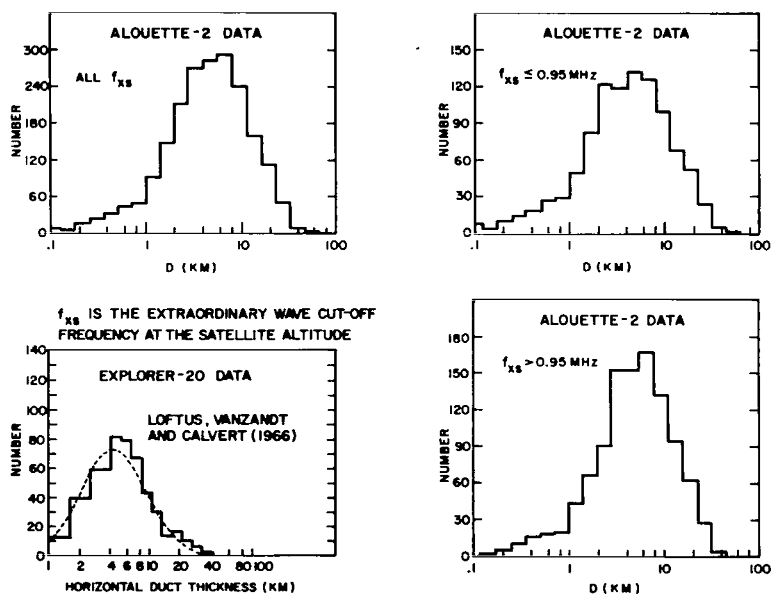


Figure 9.- Logarithmic-normal distribution of the track width (D) of conjugate ducts for various cases.

and (3) those ionograms in which $f_{xs}$ > 0.95 MHz. Low values of $f_{xs}$ indicate low electron density regions and high values of $f_{xs}$ indicate high electron density regions. Figure 10 shows the number of ducted soundings versus $f_{xs}$ (MHz). The median value is approximately 0.95 MHz. This is the reason 0.95 MHz is chosen as the frequency separating the two groups presented in Figure 9. However, there is no conspicuous difference in the track width distribution for the two $f_{xs}$ groups. Distributions for altitudes above and below the median value also show no marked differences. As for the distribution representing all the data, a median value of 4.66 kilometers is observed which is close to the 4.2 kilometer value given by Loftus, et al., (1966) for the Explorer-20 data.

In Figure 11 are plotted the average track widths (D) of conjugate ducts for various L-value ranges. The numerals within the parentheses indicate the total number of data points in each L-value range. Values of D within each L-value range vary by an order of magnitude but there is a tendency in evidence for the average value of the track width to increase with L-value.

Let $h_o$ be the perpendicular distance at the surface of the earth between two adjacent L-shells, L and L + ΔL. Then, the perpendicular distance between them at any other latitude, θ, is given by

$$h = h_o \frac{\cos^3\theta}{\cos^3\lambda} \left\{\frac{4 - 3\cos^2\lambda}{4 - 3\cos^2\theta}\right\}^{1/2} \tag{1}$$

where λ is the latitude of the L field-line.

$$L = \frac{1}{\cos^2\lambda} \tag{2}$$

Assume that the duct width is proportional to the separation distance between the two adjacent L shells (L and L + ΔL). If it is postulated that all the ducts have the same transverse dimensions at the surface of the earth, the ratio of the duct sizes at any given latitude θ for two ducts associated with the L shells $L_1$ and $L_2$ is given by

$$\left.\frac{h_1}{h_2}\right|_\theta = \left(\frac{L_1}{L_2}\right)\left(\frac{4L_1 - 3}{4L_2 - 3}\right)^{1/2} \tag{3}$$

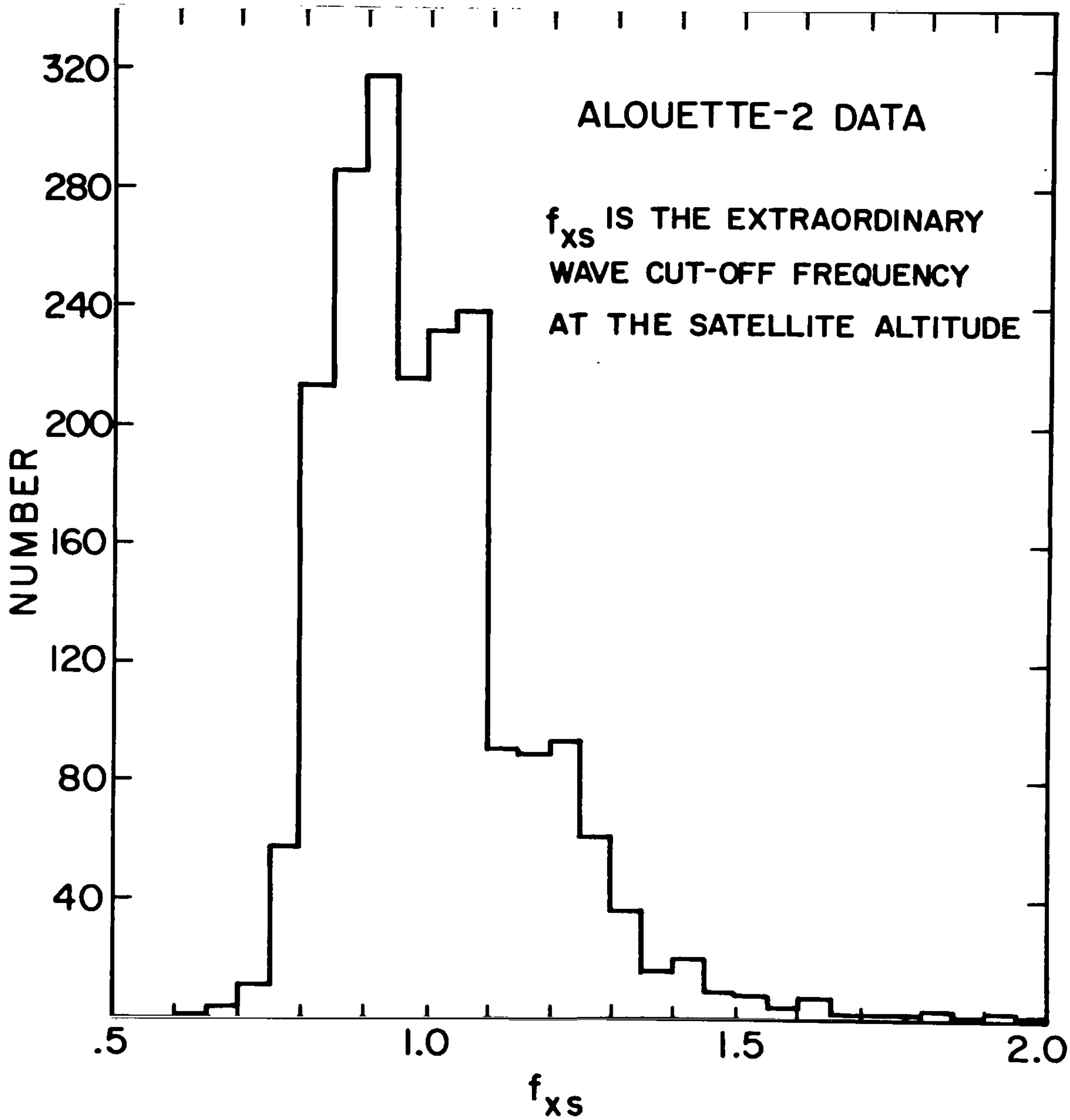


Figure 10.- Distribution of $f_{xs}$ (extraordinary wave frequency at the satellite altitude) for the ionograms with conjugate echoes.

The solid line shown in Figure 11 is a plot of Eq. (3) with an arbitrary multiplicative constant used to make the curve fall in the data range. As mentioned before, the average values of track-width (D) are indicated in the figure for various L-value ranges. It is interesting to note that in the L-value range 1.1-2.0, the data points lie close to the solid-line which represents Eq. (3). At high L-values, the data are not representative because of the small number of data points.

Finally, Figure 12 shows a distribution of the peak fractional enhancement of electron density in the duct. The median value is approximately one percent which is in general agreement with previously published results (Loftus, 1966; Muldrew, 1963). The peak fractional enhancement is calculated by assuming that at the exit frequency of the conjugate echoes, the ray-curvature is equal to the field-line curvature (Muldrew, 1963). From this, one can calculate the maximum electron density gradient in the enhancement duct. From the measured value of the duct width [duct width is estimated using the value of the track width and following the procedure outlined by Muldrew (1963)] corresponding to the ionogram, it is then possible to calculate $\Delta N$, the peak enhancement of electron density in the duct. Since the values of $f_{xs}$ and $f_h$ (gyrofrequency at the satellite altitude) corresponding to the ionogram are known, the background electron density, N, at the satellite altitude is calculated. Hence, one can compute $\Delta N/N$ which represents the peak fractional enhancement of electron density.

## DISCUSSION

There is general agreement among investigators about the average sizes and fractional deviations of electron density of the HF magnetospheric ducts. But a more detailed description of their morphology, life-times, and absolute physical characteristics is still lacking. All the results published hitherto on the ducting phenomenon are strongly affected by limitations in the sounding techniques. The east-west extent of the ducts and the relationship between the whistler ducts, HF ducts, and the thin-type irregularities which are responsible for aspect-sensitive scattering are still open questions. Some of the whistler investigators (for example, Somayajulu and Tantri, 1968) have reported an increase in diffuseness and track width of whistler ducts with magnetic activity in addition to the formation of new ducts. However, the Alouette-1 and 2 and Explorer-20 topside sounder data have not revealed any increase in ducting activity in the presence of magnetic storms or at high $K_p$ values. Recently, Muldrew and Hagg (1969) described that the high-latitude field-aligned ducts are tubular in shape

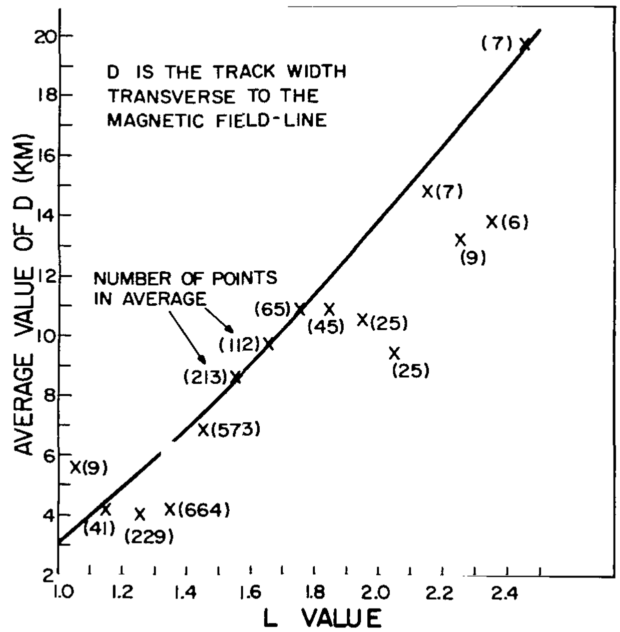


Figure 11.- Track width (D) for conjugate ducts versus L-value. The solid line is a theoretical curve. The numerals indicate the total number of data points.

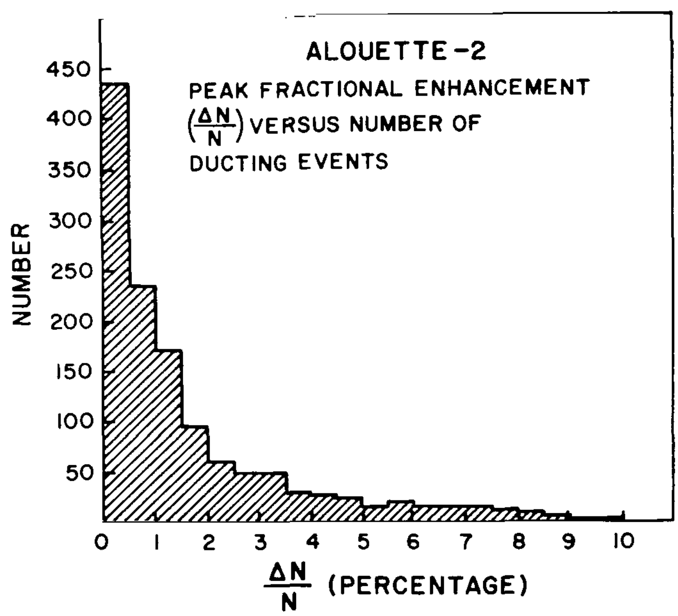


Figure 12.- Distribution of the peak fractional enhancement of electron density ($\Delta N/N$) within the conjugate ducts.

with a characteristic duct-width of about 0.3 to 0.4 kilometers. They also postulated depletion ducts at high latitudes to account for the observed propagation characteristics while not ruling out the existence of enhancement ducts. Using an electron density probe that has a resolution of 50 meters, Brace (1965) found electron density deviations with a characteristic thickness of roughly 0.3 km at high latitudes. Muldrew (1963, 1969) postulated field-aligned sheets of ionization in equatorial and mid-latitudes to account for the characteristics of conjugate echoes in the Alouette-1 data. Much is known about the irregularities causing spread-F, (both bottom-side and topside) (Herman, 1966, 1969), but the relation between the spread-F causing irregularities at various latitudes and the conjugate ducts is not clear at present. A precise knowledge of the physical characteristics and morphology would be of great value in understanding the formation mechanism of field-aligned ducts. However, such exact information cannot be obtained with the present sounding techniques adopted in the topside sounder satellites.

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