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THE VERTICAL ANGLE OF ARRIVAL OF HIGH-FREQUENCY SIGNALS PROPAGATING FROM THULE TO GOOSE BAY

For brief periods in 1985 and 1986, the high-frequency radar system installed at Goose Bay, Labrador, was used to receive a signal transmitted from Thule, Greenland. With the dual antenna arrays of the radar serving as an interferometer, it was possible to determine the vertical angle of arrival of the received signal. Two different experiments were performed. In one, the signal was swept in frequency from 8 to 20 MHz. In the other, eight discrete frequencies were used, with multiple samples taken for each frequency. From these data a Doppler power spectrum and a cross spectrum were formed, and the vertical angle of arrival was determined from the cross spectrum. Results often showed higher angles of arrival than would be expected, suggesting that the high-latitude ionosphere may exhibit unstratified structures (ionospheric tilts) that could significantly modify the nature of high-frequency communications channels.

INTRODUCTION

The high-latitude region is important in high-frequency communications for several reasons. High-frequency communications are particularly useful at high latitudes, simply because of the difficulties of producing other reliable communications systems. Also, the high-latitude ionosphere is a highly dynamic and structured environment that can be used as a natural system to determine how the ionosphere can be structured, how such structures evolve, and how communications systems are affected by such dynamic structuring. In this context, the high-latitude ionosphere can be seen as a test bed for communications systems that would be expected to function in a nuclear explosion environment.

We know from both theoretical methods and direct observation that ionospheric density irregularities exist at scales from hundreds of kilometers to meters. Except at the very largest sizes, these density structures are strongly aligned with the magnetic field. At all scales they contribute to the path a signal will take; motion of the structures produces variations in the signal path. Basler et al.[1] and Price[2] have recently studied the theory of how those variations affect the communications channel, assuming that the mean path can be described by tracing a ray path through a horizontally stratified ionosphere. Their work was done in conjunction with observations made by SRI International's high-frequency channel probe, detailed in Ref. 1. Results showed that the mean ray path is modified primarily by magnetic field-aligned striations, which can be treated as perturbations on the horizontally stratified ionosphere. It is not clear, however, how those results might be modified when the ionosphere cannot be adequately described by a horizontally stratified model. Similar work has been done by Wagner et al.[3] and Wagner and Goldstein [4] at the Naval Research Laboratory.

The Goose Bay high-frequency radar was constructed by APL in October 1983. (A complete description of the radar can be found in Ref. 5.) Although the primary purpose of the radar was to observe small-scale (decameter) ionospheric irregularities at very high magnetic latitudes, the antenna and receiver system can also be used strictly to receive other transmitted signals.

In 1985, a project was set up in conjunction with the Rome Air Development Center at Hanscom Air Force Base to study the nature of high-frequency communications channels at very high latitudes. The original radar configuration was a single array of 16 log-periodic antennas. A second array of 16 identical antennas was added to, and positioned 100 m in front of, the original array. This configuration made it possible to determine both the azimuthal angle of arrival and the elevation angle of arrival of the incoming signal at Goose Bay. The angle-of-arrival measurements, coupled with the signal's time of arrival, yielded for the first time three-dimensional information about high-frequency propagation at very high latitudes. Details of the experiment are given below, along with a description of the method used to determine the elevation angle, some experimental results, and a discussion of those results in terms of ionospheric models.

EQUIPMENT

The Goose Bay radar consists of two parallel arrays of 16 log-periodic antennas (Fig. 1) operating in the frequency band from 8 to 20 MHz. A block diagram of the experimental setup is shown in Fig. 2. The antennas from each array are connected into a switching matrix that is used to select the antennas from one array to feed into a 16-element phasing array. The phasing array steers the antenna beam in one of 16 directions, covering an azimuthal sector of 52° centered on 5° east of geographic

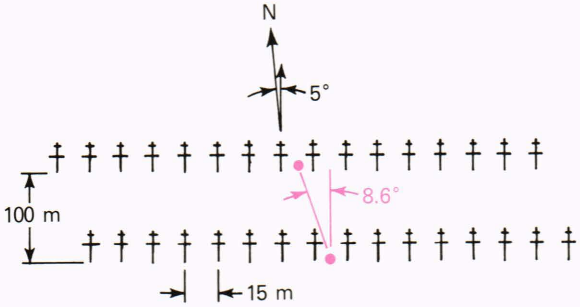


Figure 1—Schematic diagram of the Goose Bay high-frequency radar antenna system. There are two parallel arrays of 16 antennas each. All antennas are log periodic, with a frequency response from 8 to 20 MHz. The centers of the two arrays are offset by approximately 15 m.

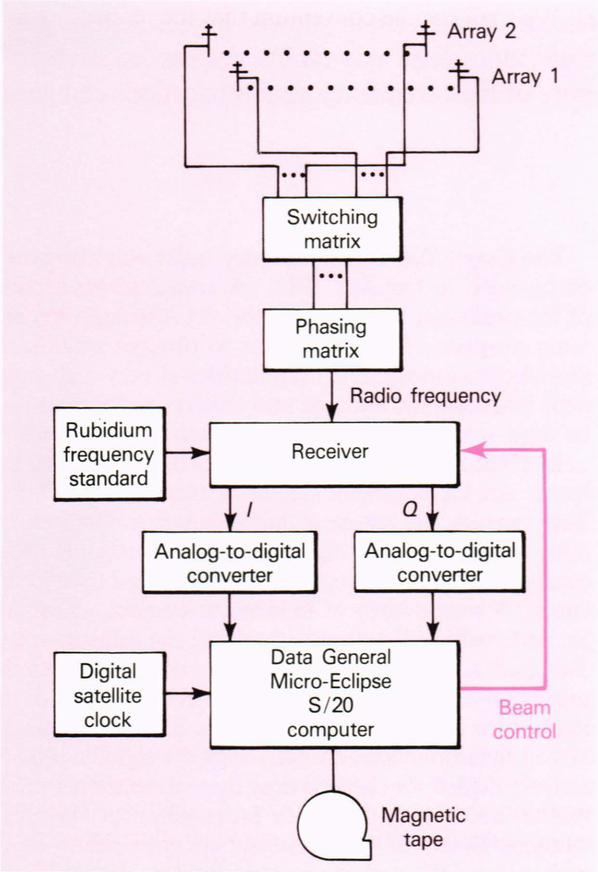


Figure 2—Block diagram of the experimental setup at Goose Bay.

north. The output of the phasing matrix is then fed into a phase-locked quadrature receiver. The frequency of the receiver is digitally controlled by computer and locked to a rubidium frequency standard. A digital satellite clock that receives the time signals from the GOES-East geosynchronous satellite provides accurate timing. The experiment is controlled by a Data General Micro-Eclipse S/20 computer. Raw data from the receiver are digitized and stored on magnetic tape for later off-line processing.

EXPERIMENTAL METHOD

The transmitter at Thule sends a phase-encoded signal. The code sequence consists of 31 chips, each lasting 200 μs, for a total code length of 6.2 ms. The code sequence is repeated for 25 ms and then reset to the beginning of the sequence. The code is made up of 180° phase shifts, which therefore can be viewed as simple sign reversals. It is an optimal pseudorandom code, yielding an approximately 30-dB improvement in the signal-to-noise ratio while simultaneously determining the group path delay. The off-line processing procedure is the digital equivalent of a matched filter, and, at the delay for which the received sequence matches the known code, the summed output of the filter is 31 times larger than at the other delays. The power is proportional to the square of the amplitude, which produces a 30-dB signal at that delay.

Since the receiver is a quadrature receiver, there are actually two outputs from the matched filter: one from the I output and one from the Q output. The received phase of the signal is given by

$$\chi_1 = \tan^{-1}(Q_1/I_1) \ , \tag{1}$$

where the subscript 1 indicates the rear antenna array. Similarly, the signal from the front array will also produce a maximum at the same delay, with a different phase χ_2. The difference between the phases can then be used to find the elevation angle of the arriving signal.

Two experiments were performed. In the first, hereafter referred to as the sounder mode, the frequency was changed in 10-kHz steps every 50 ms, starting at 8 MHz and ending at 20 MHz. This experiment was used to determine what frequencies were propagating between Goose Bay and Thule and how the group path delay and the elevation angle depended on frequency.

The second experiment, hereafter referred to as the spectrum mode, operated for a more extended time on a selection of eight frequencies. A single frequency was sampled nearly continuously for 10 s, and a series of eight 32-point sequences was formed for the data from both arrays. The eight frequencies were used in succession, and the procedure was repeated four times. The 32-point sequences were then used to form Fourier spectra for each sequence. In the original conception of the experiment, the transmitter would be on for the entire 10-s period for each frequency; changes to the operating software at Thule were never made, however, and the transmitter was always shut off in the middle of the seventh sequence. The serendipitous result was that the moment of transmitter shutoff could be used to ensure that the Goose Bay system was properly synchronized with the Thule transmitter. Also, there would be a period when no signal was transmitted, so that a true noise level could be determined.

ANGLE DETERMINATION

We now discuss briefly the method for determining the azimuthal and elevation angles, including the effects of the separation of the two antenna arrays, the offset of the array centers, and the influence of Doppler shifts on determining the angles.

The phasing matrix is the primary determinant of the azimuthal angle. It provides fixed time delays for the signal being received at each antenna in the array. Because it provides time delays rather than phase shifts, the angle determined by the phasing matrix is independent of the frequency (details of the phasing matrix can be found in Ref. 5). For perfect isotropic radiators, the phasing-matrix angle defines a cone around the axis of the array (Fig. 3a). The relative phase of the signals received on the two antenna arrays can be used to define another cone angle, this one around the axis connecting the centers of the two arrays (Fig. 3b). This axis is not perpendicular to the axis of the array, because the centers of the two arrays are offset (see Fig. 1). The intersection of the two cones determines the location in the sky from which the signal is received. The mathematics used to find this intersection is straightforward but tedious, and we present only the final result here. Let ψ be the angle in the horizontal plane (with respect to the array normal) set by the phasing matrix, and let α be the cone angle determined by the phase difference at the two arrays. Then the true azimuth (ϕ) and elevation angle (ϵ) are given by

$$\tan \phi = \sin \psi \cos \xi / (\cos \alpha + \sin \psi \sin \xi) \ , \tag{2}$$

$$\sin^2 \epsilon \cos^2 \xi = \sin^2 \alpha - \sin^2 \psi - \sin^2 \xi - 2 \cos \alpha \sin \psi \sin \xi \ , \tag{3}$$

where ξ is the angle between the normal to the array and the axis joining the centers of the two arrays (see Fig. 1).

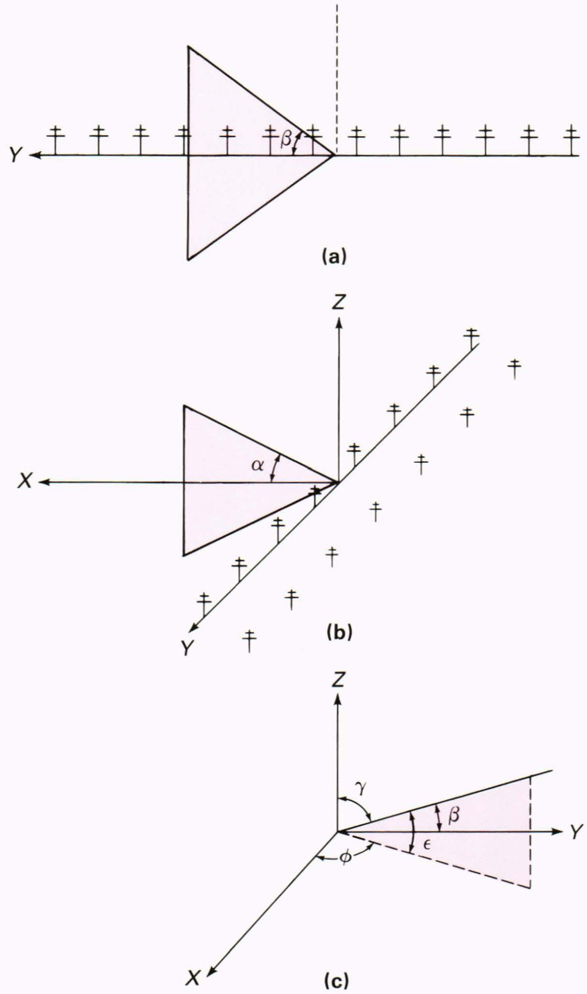


Figure 3—(a) The cone angle (β) with respect to the line passing through all the antennas of a single array. This angle is determined by the phasing matrix ($\beta = 90° - \psi$). (b) The cone angle (α) with respect to the axis perpendicular to the arrays. (c) The relations between cone angles γ and β and the elevation (ϵ) and azimuthal (ϕ) angles.

We now turn to the question of how the angle α, the primary determinant of the elevation angle, is computed. We shall use the convention that the received signal is propagating in the negative x direction. The difference in phase of a ray propagating at angle α with respect to the x axis (caused by the 100-m separation of the arrays) is then given by

$$\Delta\chi_{\text{sep}} = kd \cos \alpha \ , \tag{4}$$

where k is the wave number and d is the separation between the centers of the two arrays (101.15 m). There is also a constant phase difference because of the different cable lengths connecting the two arrays to the phasing matrix.

The Goose Bay receiver is a phase-coherent quadrature. If the received signal has no Doppler shift, the quadrature outputs will be constant, and the received phase will also be fixed. If, however, there is a frequency shift between receiver and transmitter, the output phase will vary with time. Since the signals are received at a later time on the forward array, there will be an additional shift, resulting from any frequency difference $\Delta\omega$ (i.e., Doppler shift), given by

$$\Delta\chi_{\text{Dop}} = \Delta\omega \ \Delta\tau \ , \tag{5}$$

where $\Delta\tau$ is the time separating a sample pair (6.2 ms).

There is one final complication. The receiver can measure only the phase modulo 2π. At the high-frequency range under discussion here, the separation between the antennas is several wavelengths. We therefore need to determine how many multiples of 2π must be added to the measured phase difference to find the total phase difference. The maximum phase difference in Eq. 4 clearly occurs at the minimum value of α, which is at the 0° elevation angle. We then assume that in the propagation experiment the angle of the incoming signal must lie between 0° elevation and the elevation angle that produces an additional 2π phase shift from the maximum. Figure 4a shows the contribution of each phase-shift term at a fixed elevation angle of 30° (assuming no Doppler shift) as a function of beam number of the phasing matrix (i.e., as a function of the angle ψ). Figure 4b shows the residual phase as a function of α for

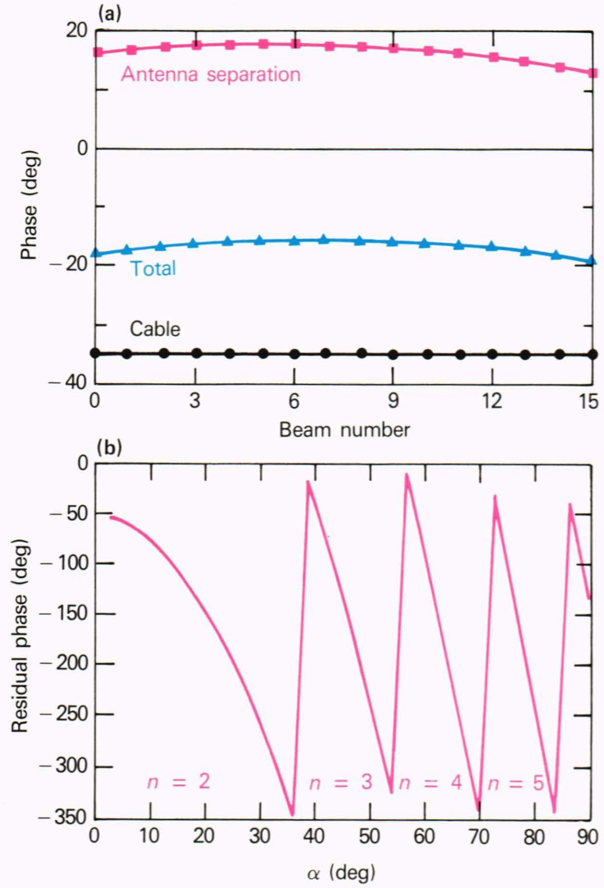


Figure 4—The phase difference between the signals received by the two arrays for a frequency of 12.3 MHz. (a) The contributions, as a function of beam number, resulting from the separation of the two arrays and from the difference in cable lengths. Also shown is the total phase difference. (b) The residual phase (total phase modulo 360°) on beam 5 as a function of the cone angle α. The value of n gives the multiple of 2π.

a fixed value of ψ (beam 5) and a fixed frequency of 12.3 MHz.

RESULTS

In the sounder mode, one sample pair was taken at each frequency, with the frequencies separated by 50 ms. Because only a single sample was taken on each antenna array, it was not possible to determine the Doppler shift in the frequency; it was therefore not possible to include the effect of the phase shift, because of the difference in the time at which each array was sampled. Usually, however, the Doppler shift was relatively small, and the correction to the phase shift caused by the Doppler shift could be neglected.

An example of the received power for the sounder mode is shown in Fig. 5. The signal was received at ranges 20, 21, and 22. Since we were not able to determine an absolute synchronization between the clocks at Thule and Goose Bay, we cannot use the range (i.e., the delay from the starting point in the chip samples) to find an absolute group path. The relative timing, however, is very accurate (of the order of 10 μs), and shifts in the range as the frequency is changed do indicate real differences in the group path.

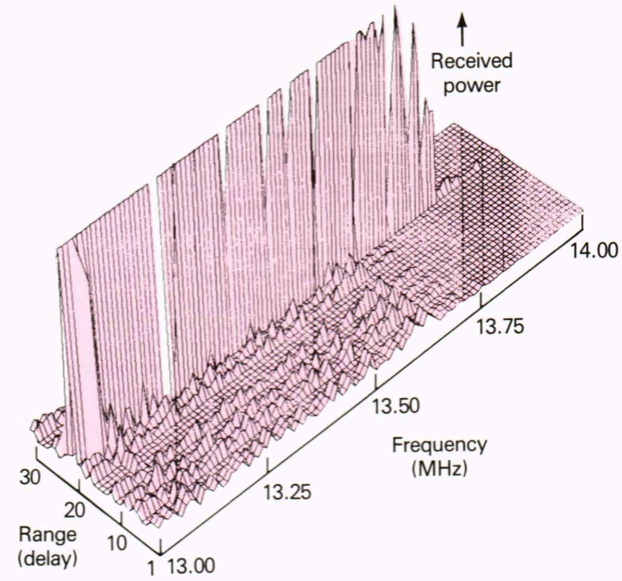


Figure 5—Power received in the sounder mode on 1 October 1985 at 2102 UT. The maximum usable frequency in this example was approximately 13.8 MHz.

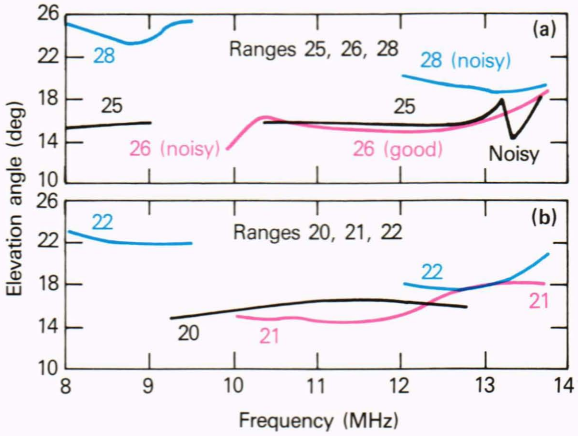


Figure 6—Elevation angle as a function of frequency at the ranges with the strongest signal on 1 October 1985 at (a) 1816 UT and (b) 2102 UT .

In Fig. 6 we plot the elevation angle for the strongest ranges at 1816 and 2102 UT. Note the difference in the ranges at which the signal is coming in on Fig. 6a compared with those on Fig. 6b. There is a clear difference of five ranges, corresponding to a 300-km decrease in the group path length. This would also tend to indicate a decrease in the effective height of the reflection point by approximately one-half that value, or 150 km.

In discussing the results from the spectrum mode, we will concentrate on a 24-h period (from 0000 to 2400 UT) in July 1986. Although at various times there were communications channels between Goose Bay and Thule from below 8.4 MHz up to about 17.0 MHz, there was nearly always a channel for 12.3 MHz, and we will concentrate on the changes seen in the propagation at that frequency.

Figure 7 shows the range, power, and elevation angle of arrival for the strongest channel at 12.3 MHz. During this 24-h period, the signal often was present at several ranges, indicating the presence of multiple channels. The strength of the dominant channel varied widely, from a maximum of slightly over 40 dB to a minimum of about 8 dB. Throughout the course of the day there was a fairly steady change in the range at which the dominant signal appeared, starting at range 13 and ending at ranges 15 and 16. There is also a trend toward a greater elevation angle, but this is not precisely in step with the change in the range. Thus, from 0000 to 1200 UT, the range of the dominant signal changed from 13 to 15, whereas the elevation angle remained between 14 and 18°. From 1500 to 2100 UT, the dominant signal tended to be at range 15 or 16, while the elevation angle changed from about 18 to nearly 25°.

Figures 8 and 9 show the profiles of power versus range and time for 0003 and 2103 UT, respectively. In Fig. 9 two distinct propagation channels are present, one at range 13 ("low ray") and the other at range 15 or 16 ("high ray"). Figure 10 shows the power and angle for ranges 13 and 15 for the entire 24-h period. The low ray was initially the dominant signal, with a signal-to-noise ratio between 20 and 40 dB. The elevation angle of this propagation path (when present) was always about 15°. At approximately 0900 and 1200 UT, the high ray was present and was usually the dominant signal. At first the elevation angle was basically the same as for the low ray, although there was a 120-km difference in the group path length. By about 1500 UT, however, the elevation angle of the high ray had increased to about 18°. At about 1800 UT, both the high and low ray were present, and there was a clear difference not only in the group path length, but also in the elevation angle (about 15° for the low ray and 18° for the high ray). By about 2100 UT, the dominant path was often at range 16, and the elevation angle for the high ray had continued to increase to nearly 25°.

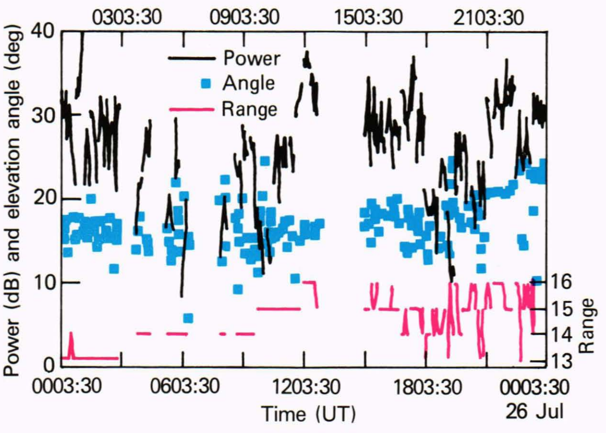


Figure 7—Range, power, and elevation angle for the strongest signal in the spectrum mode at 12.3 MHz during the 24-h period of 25 July 1986.

Figure 11 shows the power and elevation angle for ranges 13 and 16 at about 2100 UT. The high ray was the dominant propagation mode, with a signal-to-noise ratio approximately 10 dB above that of the low ray. The elevation angle was very steady, staying around 21° from about 2103 to 2108 UT, and increased to around 24° from about 2117 to 2122 UT. The elevation angle

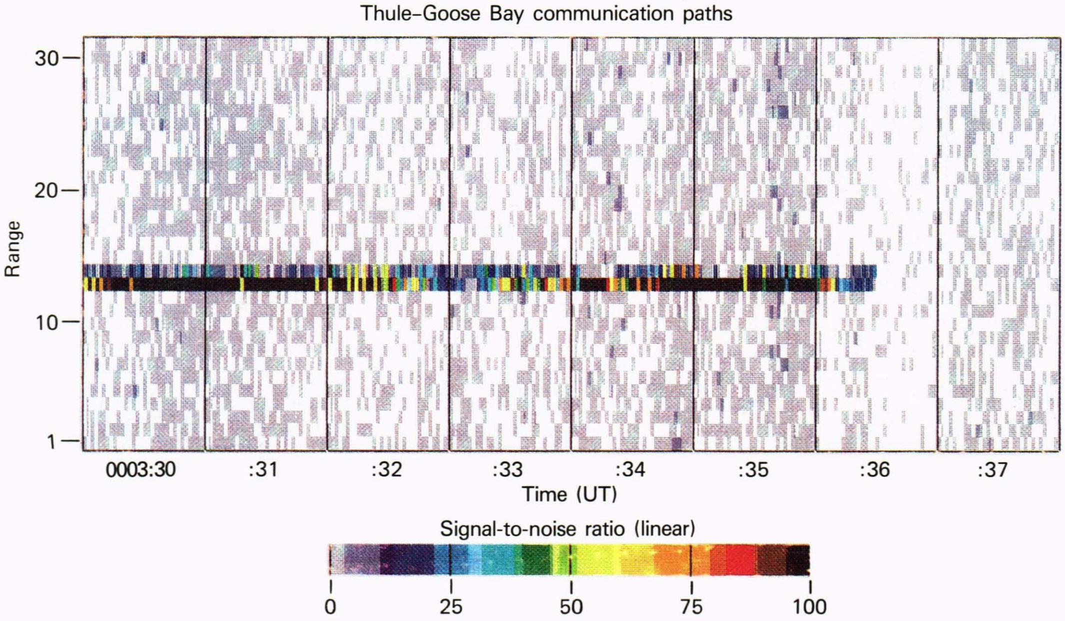


Figure 8—Power versus range and time for the spectrum mode at 0003 UT on 25 July 1986, for a frequency of 12.3 MHz. Each panel represents a single decoded sample sequence (32 samples), and the power is indicated at each range by the color.

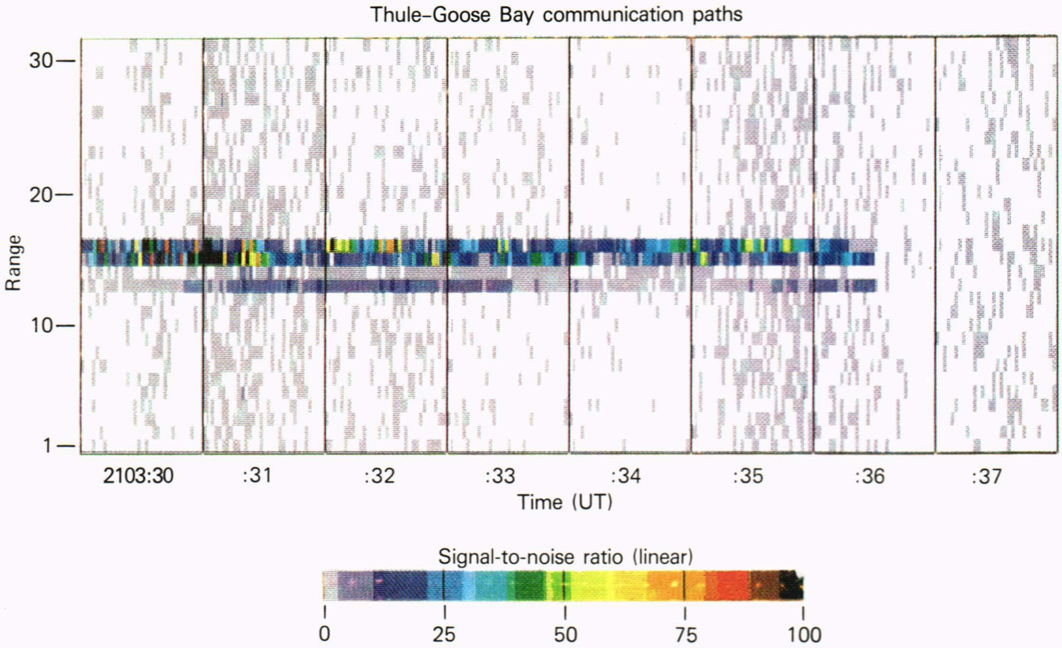


Figure 9—Power versus range and time for the spectrum mode at 2103 UT on 25 July 1986, for a frequency of 12.3 MHz. See Fig. 8 caption for explanation. Note the presence of two distinct propagation modes.

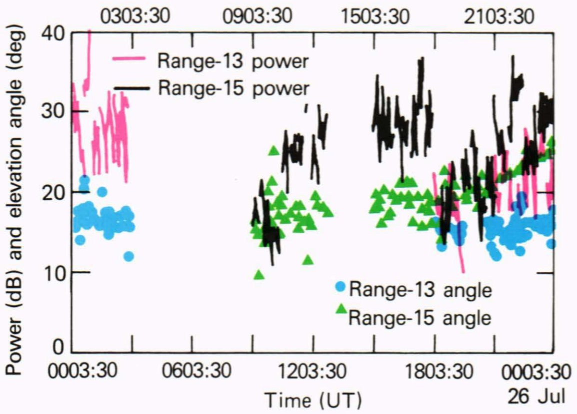


Figure 10—Power and elevation angle for ranges 13 and 15 during the period from 0000 to 2100 UT on 25 July 1986, at 12.3 MHz.

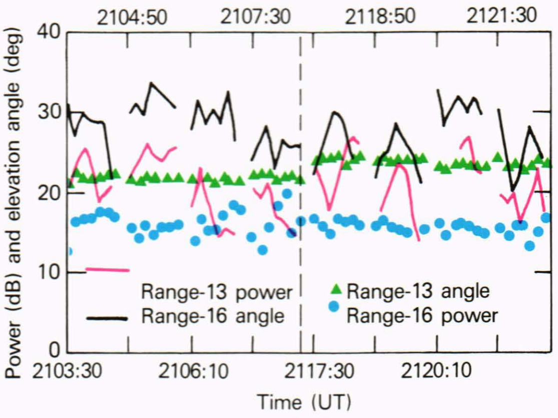
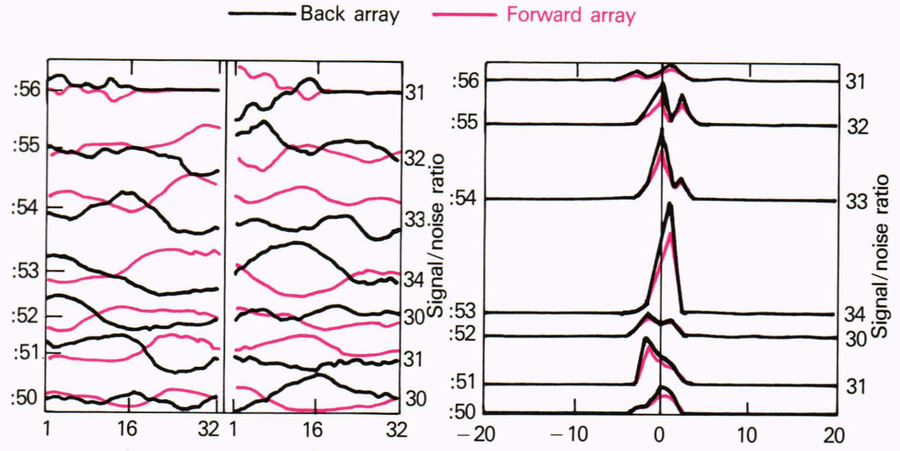


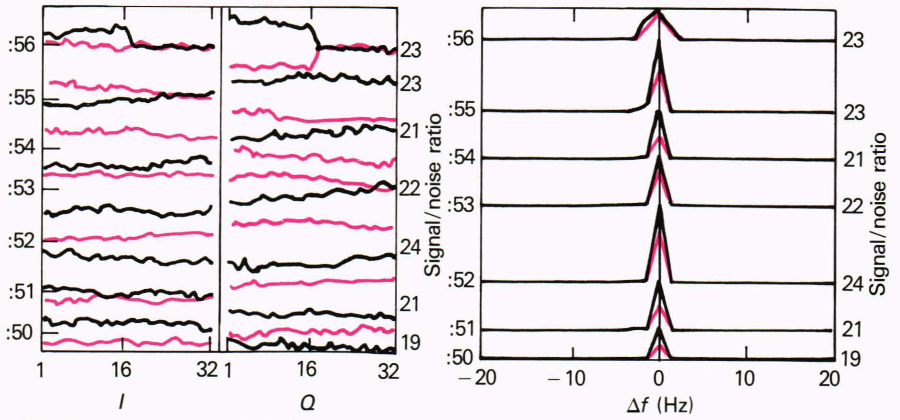
Figure 11—Power and elevation angle for ranges 13 and 16 during the period 2103:30 to 2122 UT on 25 July 1986, at 12.3 MHz. Note that there is a gap in the data from about 2108 to 2117, when other experiments were being run.

for the low ray showed more variation, but this may have been caused, at least in part, by the greater influence of noise. We note, however, that at 2104:50 UT and again at 2120:10 UT, the signal-to-noise ratio for the low ray was greater than 20 dB, and in each case the elevation angle showed variations of 2° or more. In fact, the data for the low ray suggest periodic or quasiperiodic variations in the elevation angle.

To examine these data further, we turn to the actual decoded sample sequence and the Fourier transform of the sequence. Figure 12 shows the data for both ranges starting at 2104:50 UT, and Fig. 13 shows the data starting at 2120:10 UT. The Doppler shift in the frequency is very low, and the Doppler power spectrum is virtually identical for both antenna arrays. The data for range 16 show a distinct nonzero Doppler component. At 2104 UT, the spectra show multiple components, with a tendency toward positive Doppler shifts of 1 to 2 Hz; at 2120 UT, however, the spectra show only a single component, which has a negative Doppler shift of 1 to 2 Hz. This may indicate a long-period oscillation of the height of the F-region density maximum, since the elevation angle also changed from a lower value to a higher one. The changes in the elevation angle of the low ray may indicate that it is reflecting off structures on the bottom side of the F region. As the structures move, the angle can change substantially, even though the path length changes very little and the group delay of the received signal is virtually unchanged (certainly less than a 60-km difference, which is the range resolution of this experiment).



(a) Output of the matched filter, range 16 (b) Doppler power spectra, range 16



(c) Output of the matched filter, range 13 (d) Doppler power spectra, range 13

Figure 12—Decoded sample sequences and resulting Doppler power spectra at ranges 13 (c and d) and 16 (a and b), starting at 2104:50 UT on 25 July 1986; frequency was 12.3 MHz. Note that the seventh sample sequence (at 2104:56 UT) in (a) and (c) is terminated halfway through the sequence, resulting in a distorted Doppler spectrum for the seventh sequence in (b) and (d).

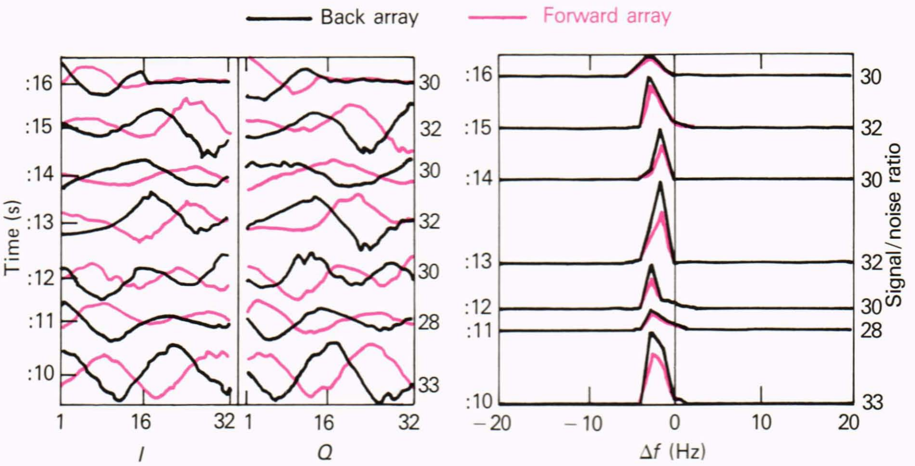
DISCUSSION

The elevation angles we have observed have often been significantly higher than originally expected. The ground distance between Goose Bay and Thule is approximately 2640 km. Figure 14 is a schematic of a ray path where the ionosphere is assumed to be horizontally stratified. The distance between transmitter and receiver is too great for a 1-hop mode reflecting off the E layer to exist. If we assume that the simplest mode is, therefore, a 1-hop mode off the F layer, we can assume an effective height of the reflection point of about 330 km. This results in a total path length of 2782 km, which implies a delay of 9.3 ms between transmission at Thule and reception at Goose Bay. The elevation angle for this simple 1-hop mode would be approximately 8°. As noted above, we commonly find an elevation angle of 15° for the low ray and over 20° for the high ray at Goose Bay. An elevation angle of 15° would require the height of the reflecting layer to be about 530 km. Although this is an effective rather than a true height, the true height would still have to be over 400 km, which is improbable. An elevation angle of 25° (the maximum value we have seen in this study) would require an effective reflection height of about 850 km.

We can also ask whether the difference between the arrival time of the high ray at 25° and range 16 and that of the low ray at 15° and range 13 is consistent with the geometry in Fig. 15. If we use an effective height of 530 km for the range-13 signal and an effective height of 850 km for the range-16 signal, we find that the difference between the total path lengths is 340 km, corresponding to a difference in range of about 5.5 range gates. Clearly, this is not consistent with the observed difference of three range gates.

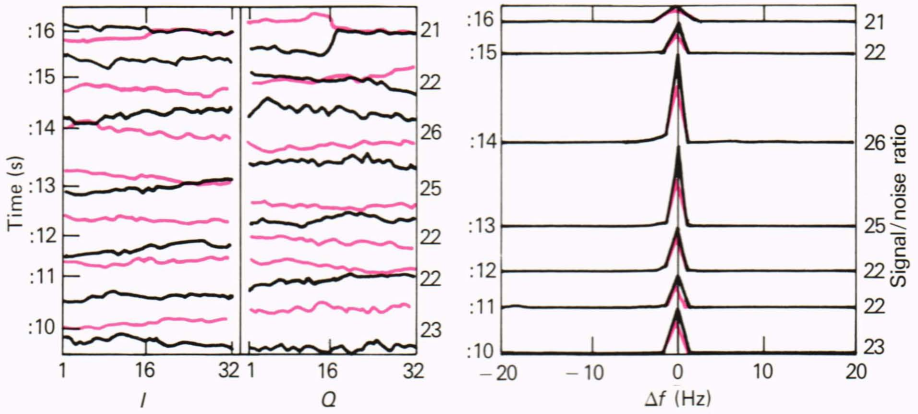
To compare the measured angles and the angles expected from a model ionosphere, we have used the Jones and Stephenson ray-tracing program[6] to follow ray paths through a realistic ionosphere. In the first example (Fig. 15a), we show the results for a high and a low ray traced through a quasiparabolic ionosphere, with a density maximum at 350 km and a half-width of 100 km. The critical frequency in this model was 5.1 MHz. Here the elevation angle of the low ray was 10°, and the angle of the high ray was 15.6°. The difference in path length between the two rays is 80 km, which would correspond to two range gates. Although this model does lessen the discrepancy between the time delays of the two rays, it does not achieve the necessary elevation angle at Goose Bay.

Figure 13—Decoded sample sequences and resulting Doppler spectra at ranges 13 (c and d) and 16 (a and b), starting at 2120:10 UT on 25 July 1986, frequency of 12.3 MHz.



(a) Output of the matched filter, range 16

(b) Doppler power spectra, range 16



(c) Output of the matched filter, range 13

(d) Doppler power spectra, range 13

In the second example (Fig. 15b), we have used an ionosphere with tilted surfaces of constant electron density. The height of maximum density is constant (350 km), but the maximum density is a function of latitude. For this model we find a high ray with a take-off angle at Thule of 12° that reaches Goose Bay with an elevation angle of 18°, and a low ray with a take-off angle at Thule of 9° that reaches Goose Bay with an elevation angle of 13°. The group path-length difference is 70 km, corresponding to a 1 or 2 range-gate difference. The angle resulting from this model is in much better agreement with actual observations at Goose Bay. Neither model gives the observed difference in group path length, but both predict a smaller difference than one would estimate from a simple reflection model. Clearly, additional modeling would improve the agreement between the measured results and the model. It is questionable, however, whether there would be any scientific validity to such an effort. A more realistic model would add an E region and perhaps divide the F region into separate F1 and F2 layers. There would then be a large number of free parameters and only three input values, the two observed angles and the group path separation. The important result would not be changed. Ionospheric tilts are necessary to explain the elevation-angle data.

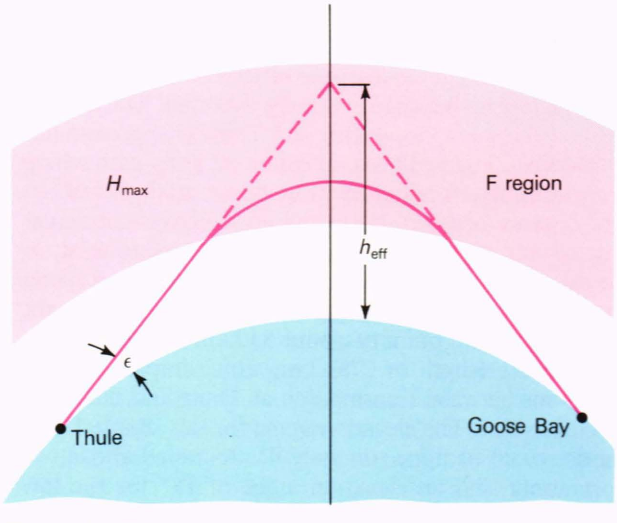


Figure 14—Schematic showing the relationship between the true ray path and the effective height (h_{eff}) for a 1-hop mode off the F region ($H_{\max}$ = height of maximum density).

SUMMARY

We have analyzed the variations in HF communications channels for time scales ranging from days to mil-

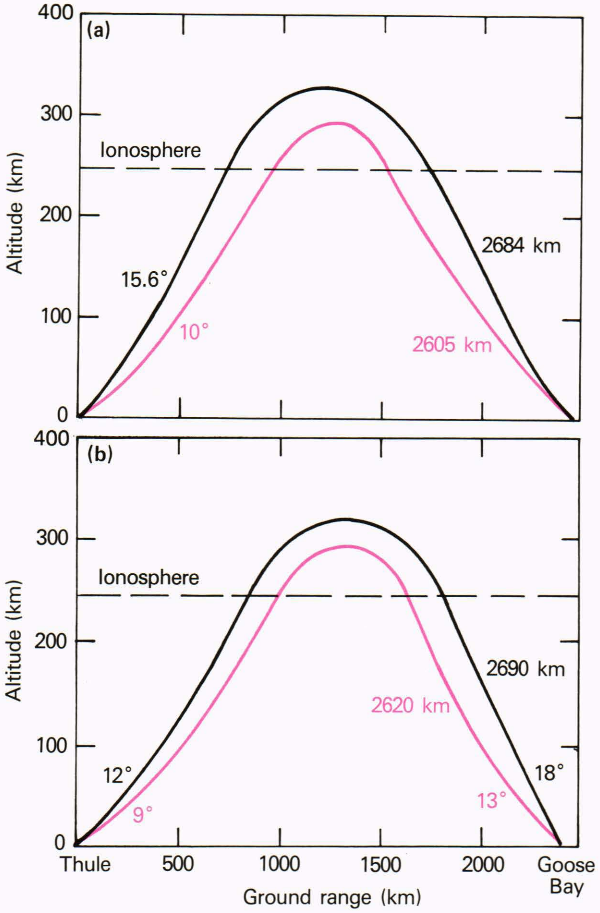


Figure 15—A realistic ray tracing of two 12.3-MHz rays launched from Thule and received at Goose Bay. (a) A horizontally stratified quasiparabolic ionosphere with H_{max} at 350 km and a half-width of 100 km. The critical frequency was 5.1 MHz. (b) An ionospheric model with tilted surfaces of constant electron density. At any given latitude the layer is parabolic, but the critical frequency varies with latitude from 3.0 MHz at Thule to 5.5 MHz at Goose Bay. The H_{max} is constant at 350 km.

liseconds. During the experimental period, solar activity was very low, and the observed effects might be expected to be larger under more active solar conditions. Although our purpose was primarily to examine variations in the vertical angle of arrival of the signal propagating from Thule to Goose Bay, variations in other parameters also were observed. There were, in fact, four parameters that characterized the high-frequency channels: (1) the maximum usable frequency, (2) the propagation delay, (3) the vertical angle of arrival, and (4) the Doppler shift of the received signal. In all of these parameters, variations were observed on all time scales. Variations in one parameter were sometimes accompanied by variations in one or more of the others. Significantly, marked variations in the vertical angle of arrival were not always accompanied by variations in the propagation delay. Presumably, with high enough resolution in the propagation delay, some variation would have been observed. It remains significant, however, that changes in the elevation angle that would suggest variations of over 120 km in the effective reflection height often showed no variation in the delay, indicating a difference of less than 60 km in the group path length. In addition to variations in the vertical angle, we commonly observed the angle to be larger than would be expected from a horizontally stratified ionosphere. By comparing the observed results with theoretical ray paths using the Jones and Stephenson ray-tracing program, we conclude that significant ionospheric tilts must be invoked to explain the observed data. The implications of this result are important not only to high-frequency communications at high latitudes, but also to over-the-horizon radar surveillance systems, where an accurate knowledge of the ray path is critical in determining the location of an echo. This strongly suggests that future efforts at modeling the high-latitude ionosphere should include the presence of ionospheric tilts. Finally, we note that if the high-latitude ionosphere is being used as a laboratory for investigating the ionosphere in a nuclear environment, tilts must be included, since they will definitely be a feature of such an environment.

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