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IN-HOUSE REPORT
NOVEMBER 1976

Computational Study of Long-Range High-Frequency Ionospheric Ducting

KURT TOMAN
DAVID C. MILLER

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The propagation of high-frequency (HF) signals over long distances by way of ionospheric channels is studied by computing ray trajectories in numerically specified ionospheres without magnetic field. Horizontal ionization gradients are introduced to provide favorable conditions for the injection of rays from the ground into elevated ionospheric ducts. Electron density height distributions with and without ionization valleys are considered. The ducting efficiency, expressed in terms of the product of frequency- and launch elevation-angle interval for trapped rays, is controlled by negative horizontal ionization

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gradients for successful injection of rays and by the shape of the electron density height profile and its change with distance. Long-range ionospheric ducting of HF rays does not require but is facilitated by the continued presence of an ionization valley in the plane of the ray trajectory.

Contents

Illustrations

Computational Study of Long-Range High-Frequency Ionospheric Ducting

1. INTRODUCTION

Ray calculations for HF propagation studies using an empirical, three-dimensional global model for the polar ionosphere, have shown that the efficiency of long-range ducting in ionospheric channels of rays originating from the surface of the earth appears to vary with time of day. In particular, for rays originating from a source at 45°N with initial azimuths of about 35° east- and west-of-north and for a set of frequencies and elevation angles, long-range ducting exceeding 6000 km in ground range was most prevalent near noon at the transmitting site. Although ranges achieved with ducted rays for both azimuths were larger for the eastern path, a comparable set of rays, characterized in terms of frequency and take-off angle could be injected into elevated ionospheric ducts in both cases. This possibility of ray injections was found to be associated with the rate of weakening of the F1 layer with increasing latitude giving rise to strong horizontal gradients (~ 9 el/cc/m) between 130 and 190 km altitude about 1000 km northward from the source (transmitter).

Figure 1 illustrates several ducted as well as unducted ordinary-wave rays computed for a collision-free ionosphere predicted by the three-dimensional RADC polar model for a winter day (1800 UT) and Kp = 3. Also shown is the spatial variation of iso-ionic contours ($Ne(el/cc) \times 10^{-5}$) within a narrow azimuthal segment

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containing the ray trajectories. All rays originate at h = D = 0. The large negative horizontal ionization gradients above D = 1000 km from the 'transmitter' appear to play a role in facilitating long-range ducting of two rays (f = 15 MHz, EL = 10° and f = 20 MHz, EL = 12°) while the other pair of rays (f = 21, 22 MHz, EL = 12°) fails to be ducted. It is seen that an extended confinement of the former rays with range appears to be associated with an ionization-valley condition and the mean-height of the meandering rays follows with range the height change of the ionization minimum which, for example for D = 4000 km, is located at h = 200 km.

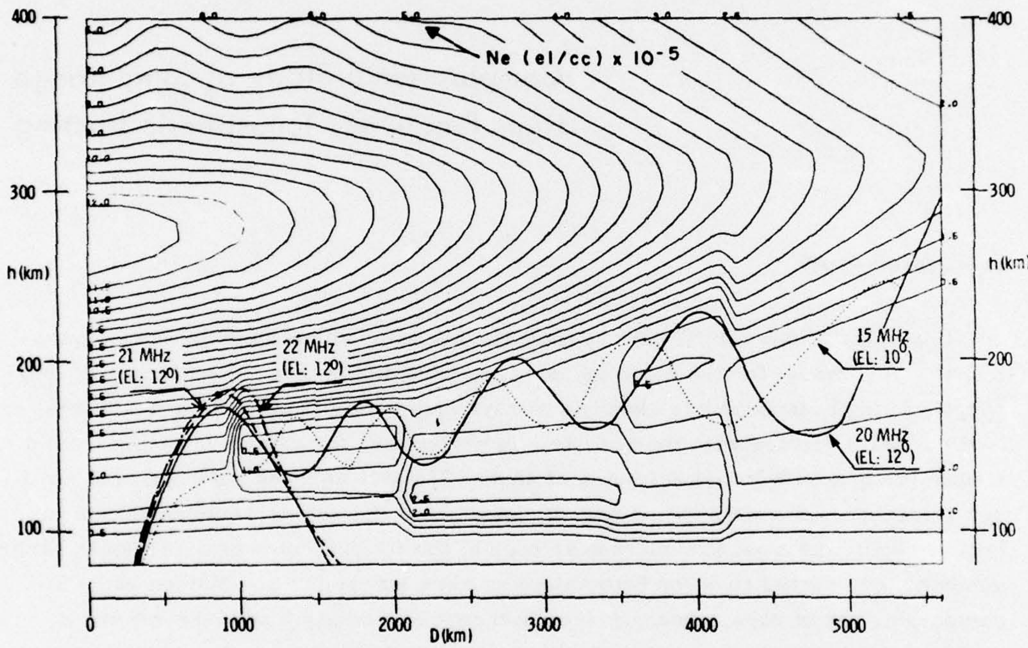


Figure 1. Ducted Rays in Polar-Model Ionosphere

In trying to learn more about the intricate details of these ducting effects it was quickly realized that the three-dimensional polar-ionosphere model, together with the use of a three-dimensional ray-tracing program in which rays are allowed lateral deviations, offered insights into ducting phenomenology only. It did not offer expedient flexibility for manipulating ionospheric profiles directly since the polar-model ionosphere was designed to be indirectly specifiable by the choice of date, time and geophysical as well as solar indices. Therefore, the following study uses a two-dimensional model ionosphere in conjunction with a two-dimensional ray-tracing program. Moreover, for the assessment of the effects of ionization gradients on ray injection and ducting it was deemed permissible to neglect the influence of the earth's magnetic field. Thus, the following discussion deals with rays in a two-dimensional, collision-free, ionic rather than magneto-ionic medium. Because of the two-dimensional model used no statements can be made about lateral deviations of rays.

2. TWO-DIMENSIONAL IONOSPHERE

For mathematical and numerical convenience and without implying any unusually superior relationship to physical reality, electron-density height profiles are formed using three segments of sine-square functions of the type

$$N = N_1 + (N_2 - N_1) \sin^2 \left\{ \frac{\pi}{2} \left(\frac{h - h_1}{h_2 - h_1} \right) \right\} \tag{1}$$

specifying the relationship between electron density (N) and height (h). These profiles are changeable through the choice of critical-frequency parameters without causing discontinuities in vertical ionization gradients. The ionospheric E layer starts at h = 90 km and has a maximum ionization at h = 110 km. An ionization valley is located at h = 160 km and the F-layer maximum is nominally located at h = 300 km but heights may also be varied spatially. Ionospheric profiles are parametrically specified in selected increments of distance along the surface of a curved earth while intermediate values of electron density are obtained by interpolation using second-order polynomials. With the choice of these parameters, vertical and horizontal ionization gradients may be introduced into an ionospheric cross-section to which radio rays, specified by 'operating' frequency and initial elevation angle, are confined.

3. RAY EQUATIONS

The six canonical equations in spherical coordinates for a ray propagating in an ionosphere without magnetic field[1] can be reduced to two equations if the medium is confined to vary only in two dimensions. The propagation geometry corresponds then to a spherical system where the ray is confined to a plane. These two differential equations have the form[2]

1. Budden, K. G. (1961) Radio Waves in the Ionosphere, Cambridge University Press, p. 282.
2. Friedman, M., Miller, D. C., and Reinhold, A. (1972) Mathematical and Statistical Analysis for the Reduction of Ionospheric Data, Sc. Rep. No. 1, Contract No. F19628-71-C-0034, ARCON Corporation, Lakeside Office Park, Wakefield, Massachusetts 01880.

$$\frac{dr}{dx} = \frac{r}{a} \tan \alpha \tag{2}$$

$$\frac{d\alpha}{dx} = \frac{r}{a} \frac{1}{\mu} \frac{\partial \mu}{\partial h} + \frac{1}{a} - \frac{\tan \alpha}{\mu} \frac{\partial \mu}{\partial x} \tag{3}$$

where a is the radius of the earth, h is the height, r is the distance of a point on the ray from the center of the earth, x is the angular distance measured from the starting point of the ray at the earth's surface, α is the angle between the ray direction and the tangent to the earth. For the ionosphere without magnetic field the refractive index μ is related to the plasma frequency f_N and the propagation frequency f by

$$\mu^2(x, h) = 1 - \frac{f_N^2(x, h)}{f^2} . \tag{4}$$

Equations, resulting from Eqs. (2) and (3) after a change of variables, are integrated analytically for $\mu = 1$. For $\mu < 1$ they are integrated numerically using a standard fourth-order Runge-Kutta technique for two simultaneous differential equations.[2] For ray computations, a 10-km stepping interval in group path is used. Thus, the ray advances in steps of variable angular-distance (Δx) and height (Δh) increments of which the latter can become very small if the ray direction is perpendicular to the radius vector of r.

4. IONOSPHERE WITHOUT IONIZATION VALLEY

Since long-range ducting of rays in the ionosphere was expected to be less efficient for ionospheric profiles without ionization valley, ionospheric cross-sections were generated for which the electron density of all ionization profiles increases monotonically with height. These profiles were synthesized by means of two sine-square segments representing an E and F layer of nominal critical frequency values. These segments were joined by a 1-km thick spherical layer whose uniform electron density matched that of the E layer at the height h = 110 km of its maximum ionization with the electron density at the bottom of the F layer at h = 111 km. The electron density profiles were made to vary with distance extending to 10,000 km along the surface of the earth. For the first 5000 km the horizontal ionization gradients $\frac{dN}{dx}$ were made to be negative and thereafter positive.

In the domain of propagation frequency (6 to 21 MHz) and initial elevation angle (0 to 11°), an array of rays was launched at h = 0 in 0.5-increments of these units.

For foE = 3.5 MHz and an initial value at x = 0 of foF2 = 9 MHz at h = 300 km, with an average negative gradient $\frac{dN}{dx}$ = - 0.0978 el/cc/m at h = 230 km between $0 \leq x < 2000$ km, (model 3D'), 22 rays were found to be trapped as they reached distances of more than 8000 km without touching the earth. The behavior with distance and height of some of these rays is illustrated in Figure 2, together with the iso-ionic contours of the chosen ionosphere. The contours are identified by number of (el/cc) $\times 10^{-5}$. Two groups of rays for 0° and 10° elevation angle are shown. The motion of rays ends as they touch the earth or as the ray direction in the non-ionized portion of the path coincides with the direction of the tangent to the earth. For an initial elevation angle of 10°, for example, rays computed for 13.5 and 14.5 MHz return to the ground at relatively short distances, while a ray for 14.0 MHz appears trapped in an ionospheric channel. For zero-elevation angle, two rays at 19.5 and 20.0 MHz reach large distances, while rays of 19 and 20.5 MHz reach a short and moderate distance respectively.

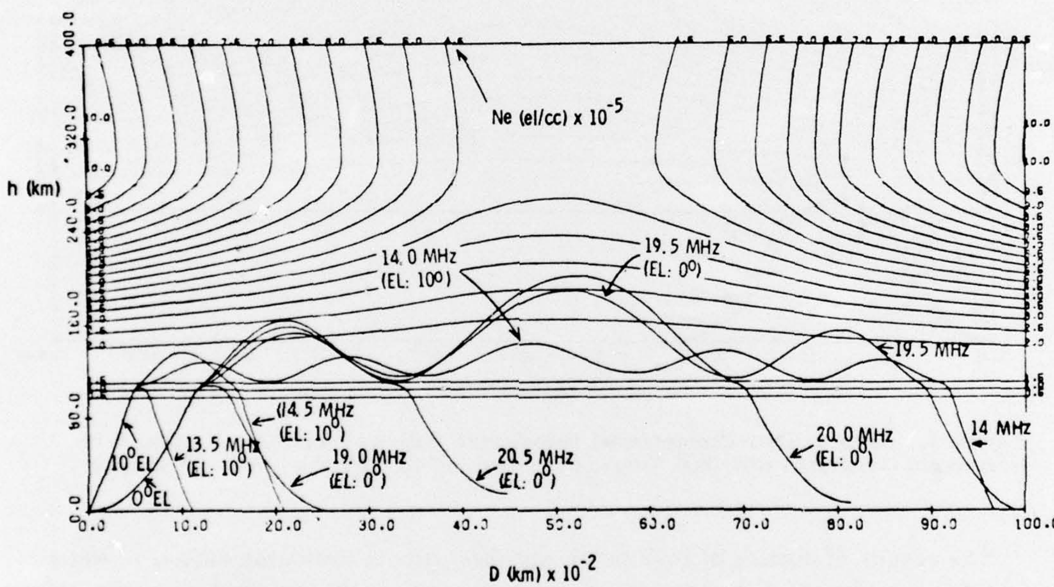


Figure 2. Rays in Two-Dimensional Ionosphere Without Ionization Valley, With Horizontal Gradients, Two-Layer Sine-Square Profiles, foE = 3.5 MHz

That negative horizontal ionization gradients represent a necessary but not sufficient condition for useful ducting becomes apparent from the ray-tracing results illustrated in Figure 3. Here, the ionosphere is similar to the one shown in

Figure 2, except the critical frequency of the E layer was reduced to foE = 2.0 MHz, while maintaining profile continuity with the F layer. Initially, the same array of rays was launched as in the previous case without achieving long-range ducting. Although a comparison of the effectiveness of radio ducting for different ionospheric cross-sections is only meaningful for identical arrays of rays launched, reducing the frequency steps from 0.5 to 0.1 MHz in the vicinity of E-layer penetration does not reveal long-range ducting. For the rays illustrated, optimum ground ranges are achieved at 11.1 MHz for 0° elevation and 8.1 MHz for 10° elevation angle, indicating a reduction in ground range for higher frequencies in either case.

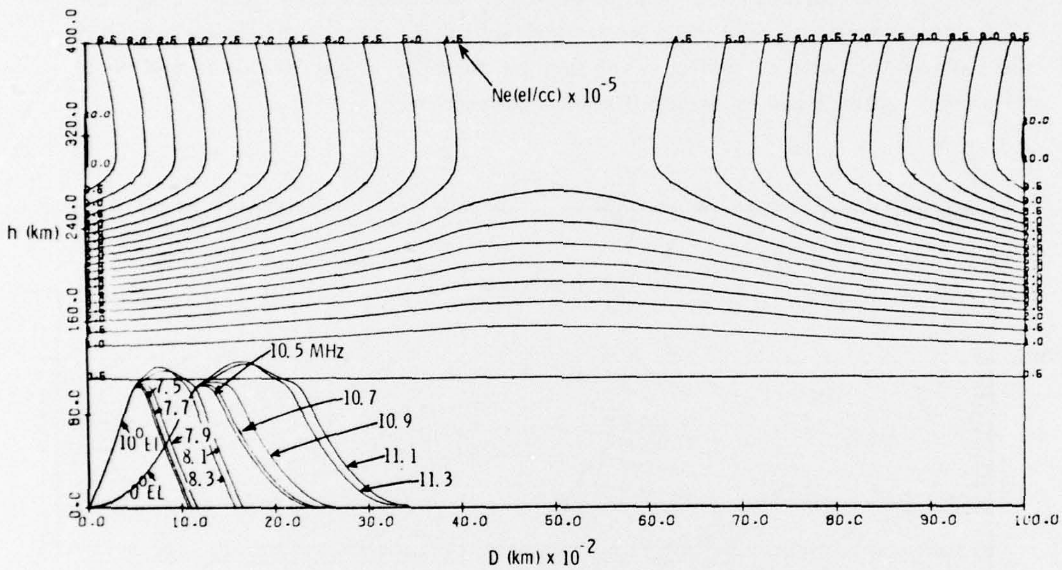
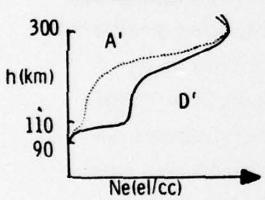


Figure 3. Rays in Two-Dimensional Ionosphere Without Ionization Valley, With Horizontal Gradients (dN/dx), Two-Layer Sine-Square Profile, foE = 2.0 MHz

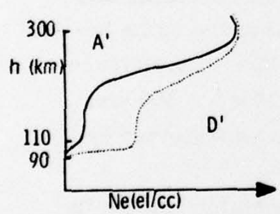
The results of ducting of rays in ionospheres without ionization valley, of which examples were illustrated in Figures 2 and 3, are summarized in Figure 4. The tables to the right of the diagrams refer respectively to those sketched ionospheric profiles that are depicted by a solid line. The dotted profiles are shown for purposes of comparison. The same array of rays in the frequency and elevation-angle domain (31 × 23 = 713 rays) was used for six profile cross-sections that distinguish themselves by magnitude of horizontal gradients (cases 1, 2, 3) and by foE = 2.0 and 3.5 MHz for type A', D', respectively. As shown on the right of the tables, these horizontal gradients were introduced through the appropriate choices of critical frequencies foF2 in 2000 km-increments of distance x. The values listed under the column $\frac{dN}{dx}$ were estimated for the first distance-increment $0 \le x \le 2000$ km, at a height of 230 km. A horizontal gradient of -0.0348 el/cc/m (1D') yielded four rays out of 713 rays launched. As the magnitude of $\frac{dN}{dx}$ was increased the number of trapped rays increased. No rays were trapped for the three cases of type A'. Although a finer grid in elevation angle and frequency could still reveal the existence of trapped rays, for the given grid none were observed. It may be concluded that for certain ionization profiles negative horizontal ionization gradients may represent a necessary but not sufficient condition for efficient ducting of rays. The effectiveness of ducting of rays in two-layer ionospheres without ionization valley appears to be influenced also by the ionization density of the underlying layer. This underlying layer may hinder long-range ducting of rays either if it is too weak (cases A') or if it is conceivably too strong resulting in rays returning to the ground without being ducted.

model type (D')
(foE = 3.5 MHz at h = 110 km)



CASES	dN/dx (h=230 km) (0<x<2000km) el/cc/m	Number of trapped rays: 6-21MHz (Step: 0.5) 0-11°ELEV(Step:0.5)	foF2 (MHz) at x (km); h = 300km					
			x					
			0	2000	4000	6000	8000	10000
1D'	-0.0348	4	8.5	8	7.5	7	7.5	8
2D'	-0.0695	9	9	8	7	6	7	8
3D'	-0.0978	22	9	7.5	6	6	7.5	9

model type (A')
(foE = 2.0 MHz at h = 110 km)



CASES	dN/dx (h=230 km) (0<x<2000km) el/cc/m	Number of trapped rays: 6-21MHz (Step: 0.5) 0-11°ELEV(Step:0.5)	foF2 (MHz) at x (km); h = 300km					
			x					
			0	2000	4000	6000	8000	10000
1A'	-0.0348	0	8.5	8	7.5	7	7.5	8
2A'	-0.0695	0	9	8	7	6	7	8
3A'	-0.0978	0	9	7.5	6	6	7.5	9

Figure 4. HF Ducting in Two-Dimensional Ionosphere With Two Sine-Square Ne(h)-Profile Segments, With Horizontal Gradients (dN/dx) Without Ionization Valley

5. IONOSPHERE WITH IONIZATION VALLEY

Since long-range ducting of rays in the ionosphere was expected to be more efficient for ionospheric profiles with ionization valley, several ionospheric cross-sections were generated from the two-dimensional ionospheric model, allowing for different variations for ionization valley and horizontal gradients with distance including a case with unusually large horizontal gradients.

The lower portion of Figure 5 illustrates three cases of ionospheric cross-sections. The upper portion shows the corresponding regimes for long-range ducting in the frequency vs initial elevation-angle domain. Although this domain was discretely sampled, continuous curves were drawn for easier delineation of the behavior of the boundaries between nominal and anomalous ranges achieved by rays. Since the rays are specified only by frequency and initial elevation angle at the point of departure on the ground ($h = D = 0$), no homing scheme was involved. The termination of rays occurs when the ray touches the ground, when the direction of the ray in the non-ionized portion of the path coincides with that of the tangent to the earth at the distance reached by the ray, when an escaping ray reaches a height $h = 400$ km, or when a ducted ray nears the limits in range ($D \sim 10,000$ km) over which the ionosphere is specified.

The small cross-hatched area delineates long-range ducting of rays that propagate through the ionospheric cross-section for which horizontal ionization gradients are restricted to $160 < h \leq 300$ km and are zero below $h = 160$ km. This is expressed by the constant values for the plasma frequency at the valley, $fv = 2$ MHz at $h = 160$ km, and for $foE = 3.5$ MHz at $h = 110$ km, with increasing distance as shown in the f(D)-diagram (a) at the lower left of Figure 5. For $h > 160$ km, horizontal gradients are present as manifested by the variation of foF2 with distance. The cross-hatched area, narrowing in bandwidth with increasing elevation angle, is believed to extend beyond EL = 15°. The location of the lower-frequency boundary is determined by E-layer penetration. It appears to be common for case (a), (b) and partially for case (c). f(D)-diagram (b) of Figure 5 displays the same behavior of foF2 as in (a) but the valley frequency fv was made to vary with distance introducing horizontal ionization gradients over a height range $110 < h \leq 300$ km. This change resulted in an increase of the number of ducted rays as indicated by the larger horizontally-hatched area.

The effect of a further and more drastic steepening of horizontal gradients in the ionospheric cross-section is illustrated by case (c) of Figure 5. The shape of the ducting area appears considerably changed as rays computed for all frequencies at elevation angles below 13° do not encounter conditions favorable for ducting, whereas before, the lower elevation angles seemed more effective for injecting rays into a ducting channel. The reason for this seems to be related to a shift of the

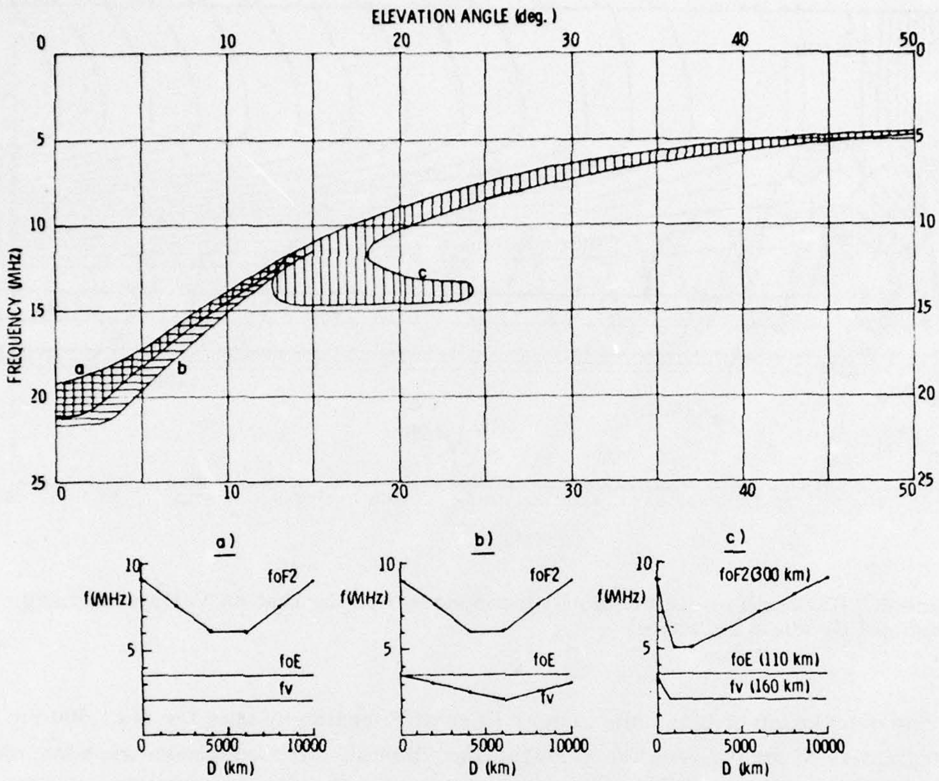


Figure 5. Effects of Horizontal Gradients on Ducting of Rays in Two-Dimensional Ionosphere With Three Sine-Square Ne(h)-Profile Segments, With Horizontal Gradients and Ionization Valley

large-gradient segment of the ionospheric cross-section toward the origin of all rays at D = 0, such that low-angle rays tend to miss the high-gradient region since they enter the ionosphere at distances where $-\frac{dN}{dx}$ is small or equal to zero. Thus, what may be called a boomerang effect in the frequency vs elevation-angle domain is a consequence of the relative position between the source of rays and the negative-gradient regime. To illustrate case (c) even further, a family of rays with an initial elevation angle of 24° and with frequencies ranging from 7 to 15 MHz was computed. As can be seen from Figure 5, rays launched at 24° elevation angle are expected to be ducted in two separated frequency bands. Such ray patterns superimposed on the ionospheric cross-section corresponding to case (c) are illustrated in Figure 6.

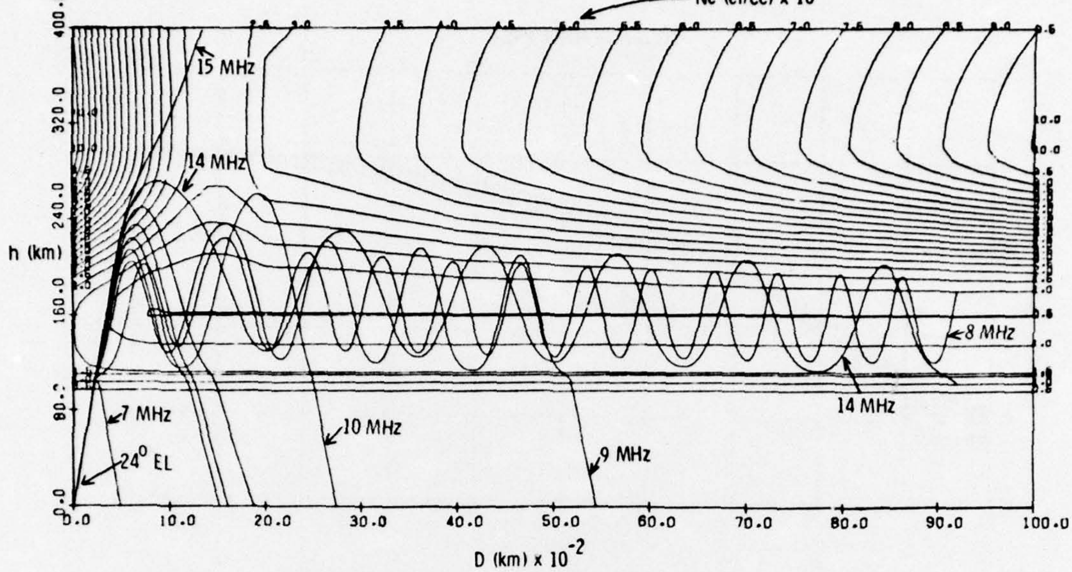


Figure 6. Rays in Two-Dimensional Ionosphere With Ionization Valley and Large Horizontal Gradients (Case c)

The orientation of iso-ionic contour lines at F-region heights for $D < 1000$ km are indicative of strong negative horizontal gradients. All rays shown were launched at an elevation angle $EL = 24°$. Although all rays between 8 and 15 MHz encounter regimes of strong negative horizontal gradients, not all rays are effectively ducted. Most-effective ducting occurs for 8 and 14 MHz. Rays for frequencies of 11, 12, and 13 MHz (to be found by interpolation) are seen to return to $h = 0$ between $1500 < D < 2000$ km. For $D > 1600$ km, horizontal gradients are positive. Although the valley condition centered at $h = 160$ km extends over the entire range, the 9 MHz-ray escapes from the duct at about $D = 5000$ km, the 14 MHz-ray begins its escape at $D > 9000$ km while the 8 MHz-ray continues to remain in the duct. Of interest is also the comparison between the 7 MHz- and 8MHz-ray. The former returns quickly to the ground while the latter becomes ducted. Negative horizontal gradients, whose presence makes ducting of rays more likely, represent a necessary but not sufficient condition for long-range ducting.

A ray pattern for an ionospheric cross-section with ionization valley and moderate horizontal gradients (case b of Figure 5) is illustrated in Figure 7. For two elevation angles of 5° and 10°, rays were computed for frequencies on either side of and including the ducting bands. Examining the conditions encountered for $EL = 10°$, it is seen that both the 13 MHz- and 16 MHz-ray satisfy a one-hop *reflection condition,* returning to the ground at about D = 1050 and 2400 km respectively. Both the 14 MHz- and 15 MHz-ray encounter favorable injection condition when entering into the ionization valley and remain there, apparently tracking the expansion and subsequent contraction of the ionization valley with distance with an undulation-height to undulation-wavelength ratio of about 0.0275 for both the 14 MHz-ray (for example, Δh = 32.88 km and λ = 1191 km) and the 15 MHz-ray (for example, Δh = 42.66 km and λ = 1555 km), indicating the possibility that this ratio may be invariant over the ducted frequency band.

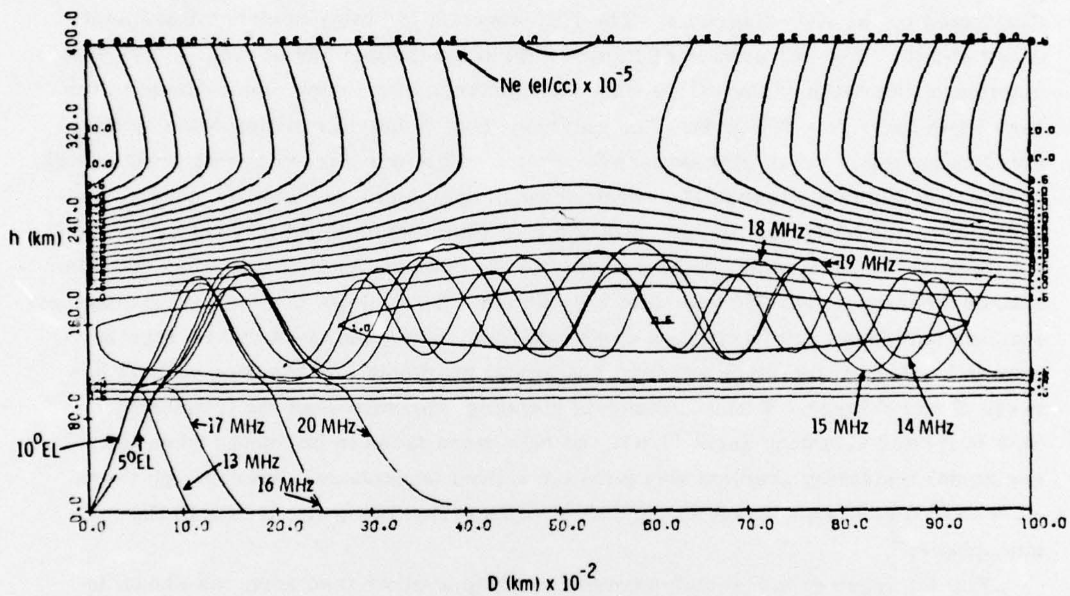


Figure 7. Rays in Two-Dimensional Ionosphere With Ionization Valley and Moderate Horizontal Ionization Gradients (Case b)

6. DISCUSSION

In the light of the foregoing results, it is now necessary to attempt separating the combined effects of negative horizontal gradients and of ionization valley conditions, as incorporated in various ionospheric cross-sections, on the efficiency of ducting of rays. This efficiency can be expressed in terms of the number of ducted rays for a fixed frequency-elevation angle array. Ionospheric cross-sections were generated with four negative horizontal-gradient conditions. Each of these gradient conditions could be paired with four ionization-valley conditions yielding a total of 16 ionospheric cross-sections. The negative horizontal-gradient conditions were specified by the rate of decrease of foF2 with distance between D = 0 and D = 2000 km at hF2 = 300 km. This yielded four negative-gradient conditions: 0, -0.5, -1.0, and -1.5 MHz/2000 km. The critical frequency of the E layer at h = 110 km was constant and equal to 3.5 MHz. Four plasma frequencies were selected to specify the valley frequency at h = 160 km as fv = 2.0, 2.5, 3.0, and 3.5 MHz. In Figure 8, the ionospheric cross-sections depicting three gradient conditions for foF2 are illustrated by the f(D)-diagrams. The f(D)-diagram for zero-horizontal gradient is not shown. The left portion of Figure 8 displays the number of ducted rays as a function of the depth of the valley where the absence of a valley corresponds to the case when foE = fv = 3.5 MHz. The electron-density height profiles were synthesized using segments of sine-square functions. The four curves are parameterized in terms of the magnitude of the negative mean horizontal gradient (el/cc/m), conveniently determined for the height of the F-region maximum at h = 300 km. The values of these horizontal gradients apply to the peak of the F region; they diminish with decreasing height and vanish at h = 160 km. Thus, rays at $h < 300$ km encounter smaller horizontal gradients than those labelled. The number of ducted rays is seen to be largest for large negative horizontal gradients and for deep valleys between E and F layer. With the discrete stepping intervals used for frequency (0.5 MHz) and elevation angle (0.5°), no rays were found to be ducted when the horizontal ionization gradient was zero (stratified ionosphere), even though there exist in this case conditions for perpetual propagation along two levels in the ionosphere.[3]

For all negative horizontal-gradient conditions other than zero, as shown in Figure 8, the number of ducted rays does not go to zero as the ionization valley is removed (foE = fv). The trend of these parameterized curves tends to show that rays may be ducted even if fv > foE indicating that a variety of monotonically increasing electron density height profiles may facilitate some ducting particularly if large negative horizontal gradients are present.

Although the global presence of ionospheric ducting channels was previously proposed,[4,5] their prediction was deduced from mean ionospheric models which in

3. Chvojkova, E. (1959) The refraction of radio waves by a spherical ionized layer, J. Atm. Terr. Phys., 16(1/2):124-135.

4. Tushentsova, A., Fishchuk, D.I., and Tsedilina, Ye. Ye. (1975) Investigations of the global properties of ionospheric wave ducts II, Geom. & Aeronomy, 15(1):62-66.

5. Tsedilina, Ye. Ye. (1975) Round-the-world radio wave propagation in ionospheric wave ducts, Geom. & Aeronomy, 15(3):371-374.

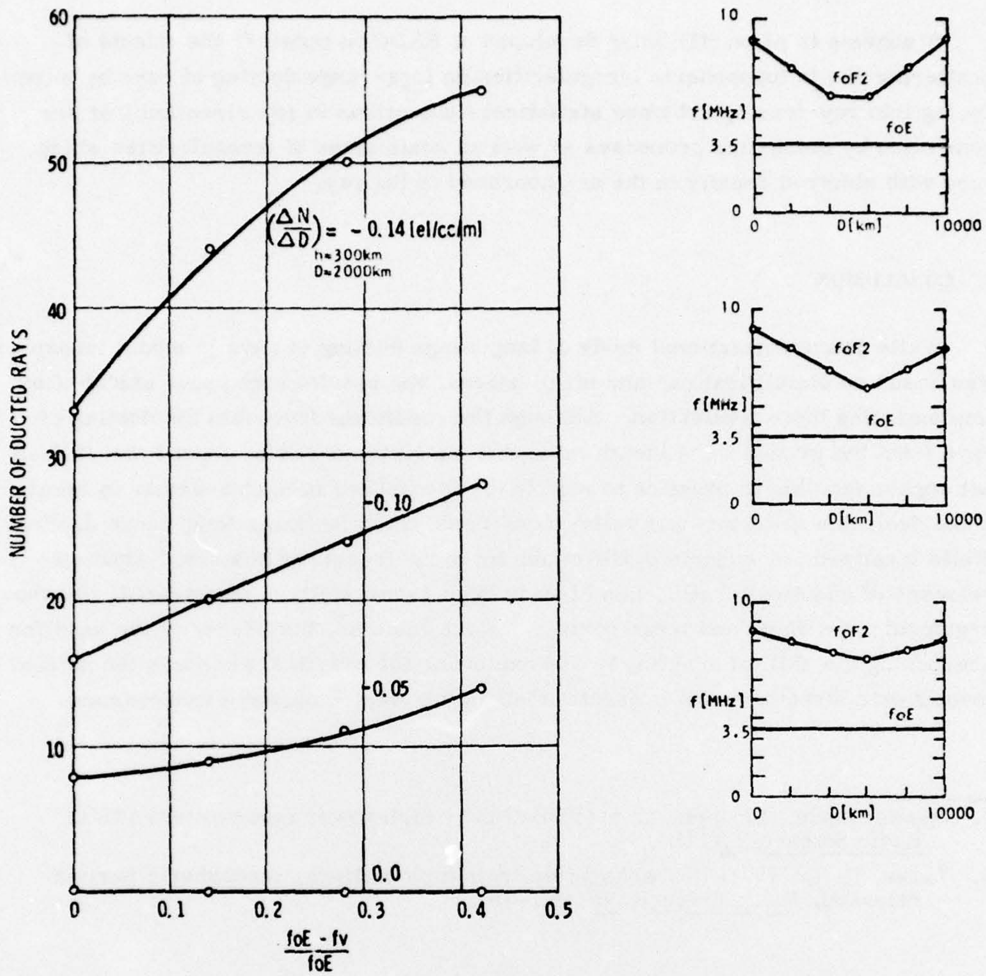


Figure 8. Effect of Ionization Valley and Negative, Horizontal Ionization Gradient on Ducting of Rays in Two-Layer Sine-Square Profile

themselves may lack sufficient correspondence with reality. Elsewhere,[6] it was suggested that the global presence of ionization valleys, as a prerequisite for efficient long-range ducting, is unrealistic, although such valleys may occur over localized regions, and scattering by ionospheric irregularities may bring electromagnetic energy from one valley regime to another. The results of this study suggest that electromagnetic energy may still be ducted through regions without ionization valley provided favorable horizontal ionization gradients are present.

6. Whale, H.A. (1969) Effects of Ionospheric Scattering on Very-Long-Distance Radio Communications, Plenum Press, New York, p. 171.

A scheme is presently being developed at RADC to consider the effects of scattering due to ionospheric irregularities on long-range ducting of rays by introducing into ray-tracing schemes statistical fluctuations in ray direction that are controlled by noise-like processes as well as scale sizes of irregularities which vary with electron density in the neighborhood of the ray.

7. *CONCLUSION*

While this computational study of long-range ducting of rays in model ionospheres was based on simplifications and idealizations, the results may prove useful when implementing their application. Although the conditions favorable for ducting of rays from the ground were identified in this analysis, it can be argued that it does not appear feasible in practice to modify the ionosphere in such a way as to create those desirable gradient- and valley-conditions which facilitate long-range ducting. While localized ionospheric modification by radio-frequency heaters,[7] artificial releases of chemical,[8] etc., has already been successfully demonstrated, the above argument appears by and large correct. What remains, therefore, is the need for sharpening the skill of adapting to and exploiting for practical purposes the natural ionospheric structure as it presents itself in the electromagnetic environment.

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7. Special Issue: Ionospheric modification by high power transmitters (1974) Radio Science, **9**(11).
8. Bates, H.F. (1971) HF backscatter from high-latitude, ionospheric barium releases, Radio Science, **6**(1):21-33.

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