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HF PROPAGATION THROUGH ACTIVELY MODIFIED IONOSPHERES

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ABSTRACT

We have developed a computer modelling capability to predict the effect of localized electron density perturbations created by chemical releases or high-power radio frequency heating upon oblique, one-hop hf propagation paths. We have included 3-d deterministic descriptions of the depleted or enhanced ionization, including formation, evolution, and drift. We have developed a homing ray trace code to calculate the path of energy propagation through the modified ionosphere in order to predict multipath effects. We also consider the effect of random index of refraction variations using a formalism to calculate the mutual coherence functions for spatial and frequency separations based upon a path integral solution of the parabolic wave equation for a single refracted path through an ionosphere which contains random electron density fluctuations.

A three-dimensional Hamiltonian Raytracing program for Ionospheric Radio Propagation

This computer program tracks (hence is named TRACKER) the three-dimensional paths of radio waves through model ionospheres by numerically integrating Hamilton's equations, which are a differential expression of Fermat's principle. The Hamiltonian method, by using continuous models, avoids false caustics and discontinuous raypath properties often encountered in conventional raytracing methods. In addition to computing the ray path, TRACKER also calculates the group path (or pulse travel time), the phase path, geometrical (or "real") path length, and Doppler shift (if the time variation of the ionosphere is explicitly included). Computational speed can be traded for accuracy by specifying the maximum allowable integration error per step in the integration.

This program is an extension of a three-dimensional Hamiltonian integration code developed in the late '1960s' by R. Michael Jones and J. M. Stevenson, commonly called the "Jones code." We have substituted a modern linear differential equation solving routine (Hindmarsh, 1980) for the Runge-Kutta solver in the Jones code. This not only allows the program to integrate accurately with larger step sizes, but also enables the program to integrate through spatially steeper electron density gradients with smaller integration errors.

This program, TRACKER, has followed the "Jones' code" concept of modularity. The program can be extended to integrate any geophysical form of raytracing by simply replacing the subroutine defining the Hamiltonian. The models of the background index of refraction, and perturbations thereon, are also in a few replaceable subroutines.

TRACKER operates implicitly in several coordinate systems. The interface to the user is done in the usual geographic coordinates, but internally the actual raypath is calculated in the more physical geomagnetic coordinates (note here that we use a tilted dipole, rather than the more complex and accurate "corrected" geomagnetic coordinates). Because we are specifically interested in the effects of perturbations on the raypaths we also include coordinate systems relevant to each perturbation, making those calculations more tractible. TRACKER calculates gradients in the index of refraction explicitly, thus allowing nonanalytic forms of ionospheres and perturbations.

Raytracing codes cannot in general compute the raypath that connects a specified source and receiver. This "homing" capability is usually included by launching a fan of rays at small increments of azimuth and elevation, and linearly interpolating to find the ray that reaches the receiver location. In many cases raypaths must be found that approach to within fractions of a wavelength of the receiver. TRACKER includes a formalism to treat this "homing" problem as a differential equation of its own. In this case the one dimensional zero crossings of the rayfans are calculated (azimuth and elevation are treated independently). These are solved sequentially and iteratively until a "homed" ray of sufficient accuracy is found.

Unlike the original "Jones' code," this program is not batch oriented, but rather is interactive. When the program is started, the user specifies what form of graphics terminal is being used. This allows to program to most efficiently display the outputs. The user then has approximately seventy five (75) commands with which to tailor his operating session. These commands cover an extensive range including controlling plot outputs (from none to directing it to special metafiles), modifying the physical raytrace parameters (such as frequency, receiver or transmitter locations, ray type, etc.), the numerical integration parameters (step size, error tolerances, etc.), and complex operations such as homing, finding multipath situations, etc.

Even in situations where ray theory does not apply, a picture of the radio raypaths often provide a "quick look" at the radio energy goes in the ionosphere. Such a picture may give the operator or scientist some insight into the specific problem, and may suggest a way to solve the individual problems encountered.

What is Raytracing?

Raytracing is a method of simulating the propagation of waves through a continuously varying refractive index structure. It uses the WKB, or high-frequency, approximation to find solutions to elliptic or hyperbolic equations that describe the flow of energy in the medium.. It is closely related to the "method of characteristics," because the calculated raypaths are the characteristics of the source differential equation. Without higher order corrections, ray theory accounts only for refraction by large-scale gradients in the background medium. In these cases raytracing will give accurate information about the geometrical raypath followed by the radio wave, about shadow boundaries (skip zones) and reflections from surfaces, phase path lengths and pulse travel times and focusing effects. In cases where multiple rays reach the receiver, additional theory will be required to combine the field information from the multiple rays. In the worst cases, where the actual applicability of the ray theory is in question, the ray path picture can help determine which regions must be treated by more complete means.

The Hamiltonian raytracing technique involves numerically integrating Hamilton's equations, given varying sets of initial conditions. In general, the Hamiltonian equations are constructed from an expression of Fermat's principle of least action. In this case, the variation principle is expressed as an integral of a Lagrangian along some as yet unspecified path, in terms of a set of generalized coordinates, q_i. As in the generalized Hamiltonian formulation, the generalized moments p_i are also defined; in this case they are directional components of the wave number vector k. Then a Hamiltonian $H(q_i, p_i)$ is constructed from the Lagrangian. Integrating the equation $H(q,p) = 0$ then gives a path that satisfied Fermat's principle.

In Cartesian coordinates, the raytracing form of Hamilton's equations are

$$\frac{dx_i}{d\tau} = \frac{\partial H}{d\tau}; \quad \frac{dk_i}{d\tau} = -\frac{\partial H}{\partial x_i}, \quad i = 1 \text{ to } 3$$

where τ is a parameter usually proportional to time, k_i are the wave number components, and x_i are the raypath physical coordinates. In a full spherical coordinate frame, the equations become significantly more complicated. This program uses the set of equations due to Haselgrove (1954) and Jones (1982).

Most Hamiltonian raytracing programs use group path $P' = ct$ as the independent variable because partial derivatives of the Hamiltonian with respect to P' are independent of the form of the Hamiltonian. This choice not only allows the program to change Hamiltonians in the middle of a raypath, it also automatically forces the integration to take smaller "real" path length steps when the ray is near the reflection region.

In order to solve these equations for the raypath, initial values for the six quantities x_i and k_i are selected (i.e. start location and initial direction of propagation), and a numerical integration of the system of six differential equations is performed.

In this form of raytracing, the user can trade accuracy for speed by changing the maximum allowable integration error per step. The numerical integrators automatically adjust the integration step length along the raypath to keep the integration error below the specified bounds. In regions where the index of refraction is rapidly varying, small steps are necessary, while in slowly varying regions the step sized may be quite large.

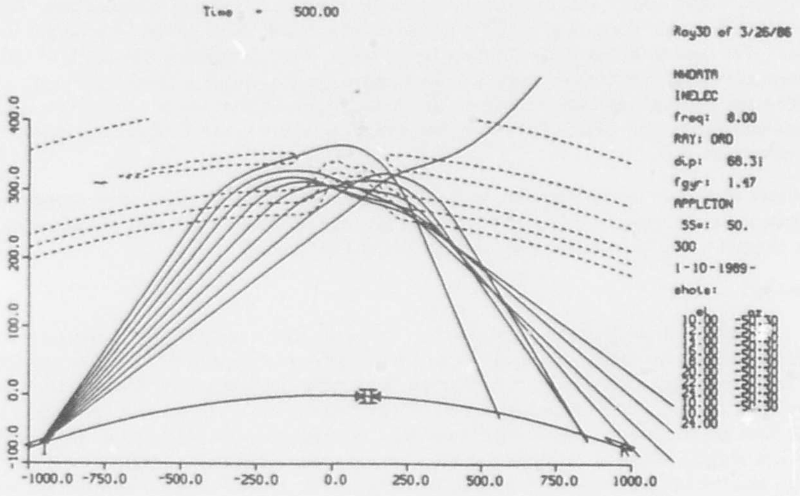

Figure 1. Rayfan through a pair of chemical releases, seen in the plasma density contours.

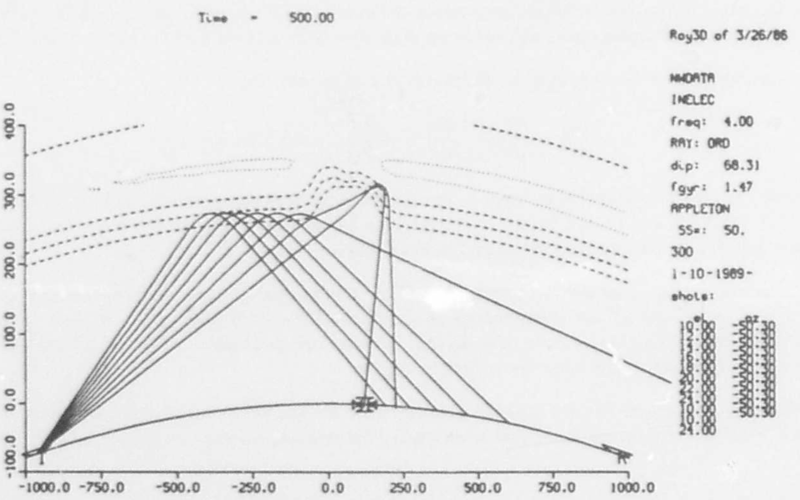

Figure 2. Similar to Figure 1, but at a higher frequency (8 MHz). Note that the depletions appear to act as a "focusing" lens.

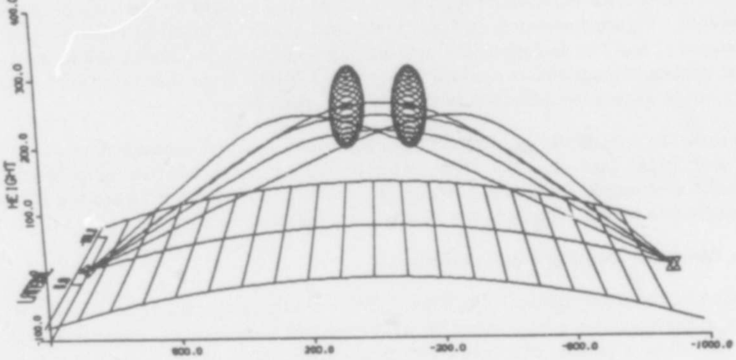

Figure 3. Chemical depletions can cause the formation of new propagation paths, above and beyond the "high" and "low" rays.

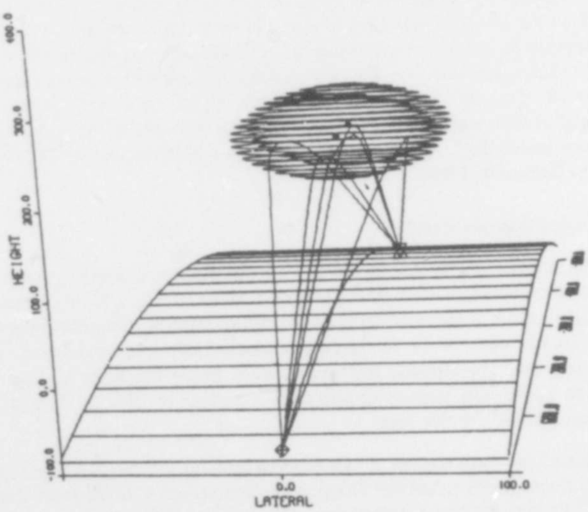

Figure 4. These new propagation paths are usually non-great circle, and are due to the focussing lens effects of the ionospheric depletions.

Examples of raypaths through chemical depletions

The outputs of the TRACKER raytracing program are varied, and tailored to studying propagation through various ionospheric perturbations. Figure 1 shows a rayfan, "shot" into a pair of chemical releases. The ionospheric plasma density contours are shown, and the depletions are evident. The effects on the rayfan are marked. Figure 2 shows the same ionosphere, but models propagation at a higher frequency (8 MHz). Note that there are still marked effects on the rayfan. These effects can in general be described as those of a focusing lens.

Figures 3 and 4 show the multiplicity of paths that can be formed by a pair of chemical releases. Two of the five paths are disturbed "low" and "high" rays, the other three are new modes generated by the focusing effects of the depletions. The time delays and signal strengths from each mode can be added to provide an estimate the multipath fading, and the stochastic model described in the next sections can be applied to each of the paths.

Effect of Random Electron Density Fluctuations

A complete prediction of hf propagation with TRACKER will ultimately be limited by the fact that the ionosphere is subject to random distortions over a wide range of scale sizes and time regimes. Such distortions arise from electron density fluctuations caused by a number of physical processes depending on location and time; the net result is that the hf communication path deteriorates due to fading, multipath, pulse spreading, etc. To predict the statistics of hf paths which reflect from an ionosphere which contains random macroscopic fluctuations in electron density we employ a method developed to describe acoustic propagation in the oceanic sound channel [*Flatté*, 1983]. In this method the scalar wave equation is approximated for long distance propagation with only small deflections by the parabolic wave equation which can be cast in the form of Schrödinger's equation and thus has a path integral solution [*Flatté*, 1986]. The statistics of the received amplitude may be calculated from the formal path integral solution without calculating a realization of the path integral solution.

This formalism allows us to calculate the statistics of single-mode hf transmissions over oblique one-hop paths. The background electron density may have an arbitrary spatial dependence although our assumption of small angular deflection precludes steep gradients in the refractive index. The random spatial structure of the electron density is assumed to be characterized statistically by a power law spectrum with outer and inner scales [Shkarofsky, 1968]. The spectral index, outer scale, inner scale, and the total variance may be a function of spatial location and altitude. The time variation of the random electron density is assumed to arise from the transport of fluctuations at a constant velocity and thus is controlled by the spatial statistics and the transport velocity. The lowest order statistics that are of interest are the second moments of the wave amplitude for spatial, time, and frequency separations. These are called the mutual coherence functions and characterize the angular spread of the received transmissions (spatial separation), Doppler spread (time separation) and coherent bandwidth (frequency separation). Our results predict the ensemble average behavior of the mutual coherence functions [Dashen, Flatté, and Reynolds, 1985].

Spatial and Frequency Coherence: Sample Results

As an example of the effects predicted by the formalism we will present numerical results for a 1950 km path in the polar region. The ionosphere is modelled as a single nighttime F layer with a critical frequency of 5.1 MHz at a height of 310 km. The electron density profile is assumed to be a Chapman layer with a scale height of 37 km. Figure 5 shows the ray path of an 11.1 MHz transmission in the rectangular coordinate system used for the calculation; the curved arcs indicate the surface of the earth and the altitude one scale height below the layer maximum. The low-ray, which we consider here, has an elevation angle with respect to the earth's surface of 12.55°. The ray path is oriented magnetic east-west; we assume a dip angle of 80° for the field.

For this example we assume that the variance of the relative electron density fluctuations is independent of altitude and equal to 0.01. The density fluctuations follow the Shkarofsky distribution with an outer scale of 10 km, a spectral index of 1.65, and an inner scale of 0.01 km. For these parameters, the variance of the phase fluctuations, Φ^2, is 4160 rad^2. The spatial correlation lengths of the fluctuations are 10.2 km in the vertical direction and 2.1 km in the horizontal direction. The relatively large correlation length in the vertical direction is a consequence of the elongation of the structure along the steeply sloping magnetic field.

The calculated mutual coherence for receiver separations in the transverse and vertical directions are shown in Figure 6. In the transverse direction, the coherence length is approximately 80 m while in the vertical direction it is

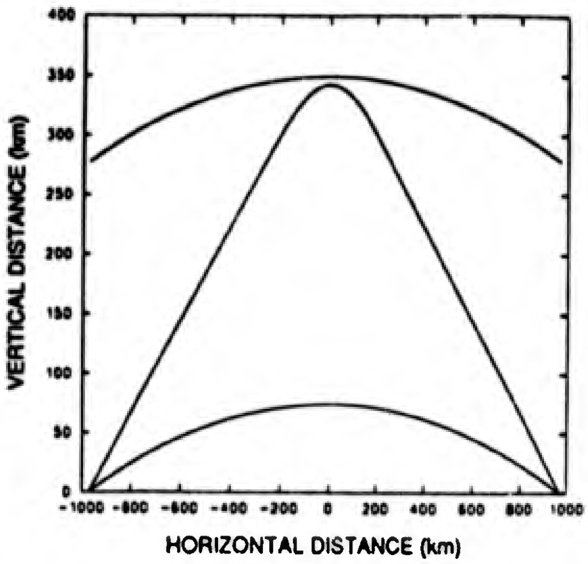

Figure 5. Raypath in rectangular coordinates used for numerical simulation. We assume a single layer, Chapman-profile, electron density distribution with a maximum at 312 km altitude. The lower curve represents the surface of the earth; upper curve is at an altitude of one scale height below that of the maximum.

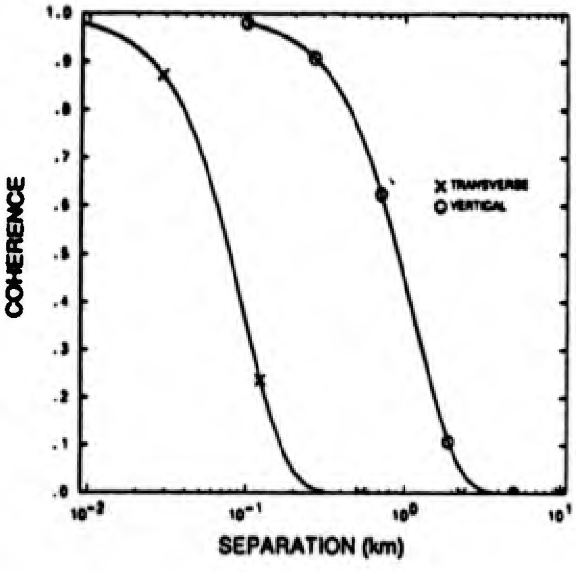

Figure 6. Caculated mutual coherence for receiver separations in the transverse and vertical directions for the ray shown in Figure 5.

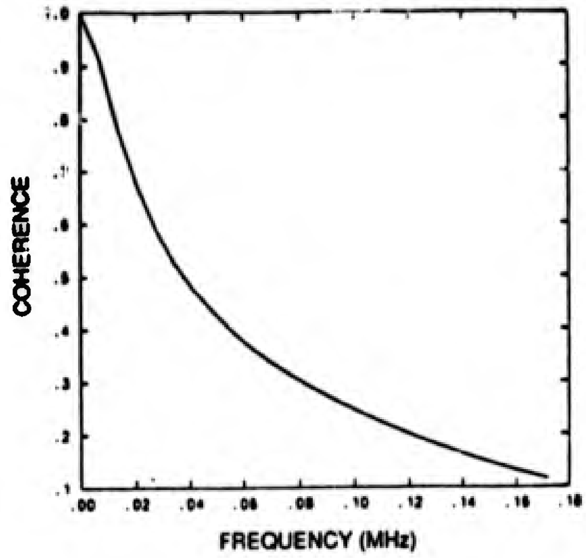

Figure 7 Calculated frequency coherence for the ray shown in Figure 5; the estimated bandwidth is 40 kHz.

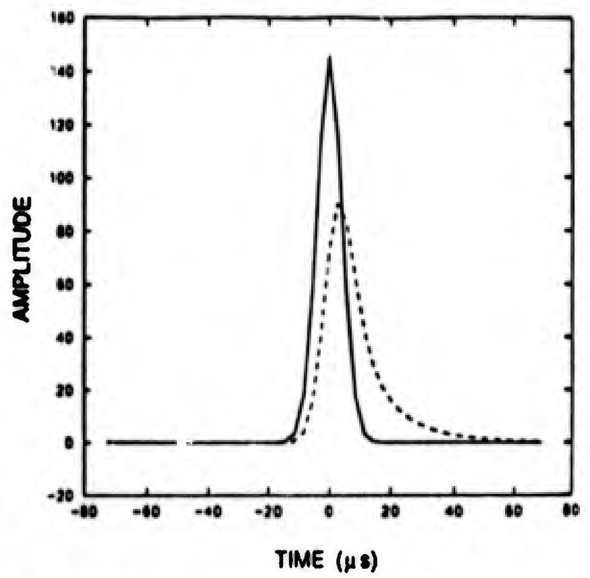

Figure 8 Ensemble average pulse response for ray shown in Figure 5. The solid curve represents the amplitude of the transmitted pulse, a Gaussian with a full width at half-maximum of 10 μs. The dashed curve represents the ensemble average of the received pulse which shows a delay and spread relative to the transmitted pusle.

approximately 900 m. The difference in coherence lengths for the two directions reflects the fact that the structures are elongated in the vertical direction. The angular spread of the received signal in the transverse direction, given the calculated coherence length, corresponds to a half angle of approximately 10°.

The results of the simulation for the frequency coherence are shown in Figure 7 where we estimate a bandwidth of 40 kHz. The ensemble average pulse response is illustrated in Figure 8 where we assume a transmitted pulse of Gaussian profile with a full width at half maximum of 10μs. The average delay, τ_1, is 5.3 μs while the average spread, τ_o, is 6.8 μs. These parameters depend greatly on the electron density profile; for example, the Chapman layer has a relatively steep bottom edge so that paths reflecting below the nominal ray path do not contribute as much as these reflecting above the nominal path. Thus the ensemble average pulse tends to be delayed compared to the unperturbed pulse. A less steep profile, for example, a parabolic profile, would tend to enhance lower paths and lead to a spread towards early arrivals.

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