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REVIEW OF HIGH-FREQUENCY RADIOWAVE DUCTING IN THE MAGNETOSPHERE OF THE EARTH

By J. Ramasastry

Electronics Research Center
Cambridge, Mass.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

This memorandum is intended to provide a basis as for any further theoretical or experimental work on HF radiowave ducting phenomenon in the magnetosphere of the Earth. Past theoretical work and observational evidence on ducting is reviewed. The justification for field-aligned ionization structures is discussed in the light of previous observations and conclusions. Previous HF experiments aimed at verifying the existence of ducts and shells in the magnetosphere are reviewed and possible causes of their failure are indicated. Similar information obtainable through VLF investigations is described and a comparison is made between the HF ducting techniques and the VLF techniques. Available ray-tracing programs are discussed from the point of view of deriving the experimental parameters and the propagation characteristics of guided HF radiowaves. A few of the magnetospheric phenomena which may be investigated by using HF duct propagation techniques are discussed.

INTRODUCTION

For a long time, guidance of HF electromagnetic waves by ionization structures which are aligned with the magnetic field lines of the Earth has been suspected. Many observations have given credence to such a suspicion, but no ground-based experiment has been able to demonstrate beyond doubt the existence of ducts. The few monostatic experiments which have reported receiving long-delay echoes characteristic of field-aligned propagation are not universally accepted since alternate propagation mechanisms to account for the long delays have often been proposed. Long-delay echoes and their time-frequency structure observed in many topside ionograms of Alouette I, II, and Explorer XX satellite experiments have been explained by invoking HF waveguidance by ionization structures along the geomagnetic field lines. While the invoked mechanism explains the observational data, it does not uniquely establish the existence and properties of the field-aligned structures. So far, the whistler observations have provided more information on the field-aligned irregularities than any other propagation technique. It will be interesting if a thorough analysis of the problem is made and the feasibility of HF ducting through the field-aligned ionization structures is established. The analysis will be helpful in carrying out a well designed experiment. It may also be possible to utilize such a propagation mechanism to study the magnetospheric phenomena to evaluate its communications potential.

REVIEW OF PAST THEORETICAL WORK

The magnetosphere of the Earth presents some evidence of being organized in laminae and columns of ionization aligned with the magnetic field lines. It also behaves as a multiple whispering gallery. Electromagnetic waves can be trapped in a guided mode by these columns of ionization between any two geomagnetic conjugate points. Gold (ref. 1), Hines and Axford (ref. 2), and Laird and Sonnerup (ref. 3) have provided theoretical arguments in support of such field-aligned structures. Booker (refs. 4, 5) has discussed in detail the theory of guidance of radio and hydromagnetic waves in the magnetosphere of the Earth. He has neglected the anisotropy of the medium and has used a longitudinal approximation for refractive index. This requires large values of track width (w) of the waveguide and larger percentage enhancement of ionization ($\Delta N/N$) in each column. Walker (ref. 6) has taken the anistropy of the medium into consideration and has used a quasi-longitudinal approximation for refractive index. It is then possible to obtain realistic estimates of w and $\Delta N/N$. But, both the authors use simplified dipole models of the magnetic field of the Earth and fairly crude models of magnetospheric electron density distribution. Muldrew (ref. 7) has utilized Swept Frequency Topside Sounder data from the Alouette satellite experiment to study HF ducting below 1000 km. But an integrated theory to account for such a ducting phenomenon in the ionosphere, through the ionosphere-magnetosphere interface, and in the magnetosphere is lacking.

REVIEW OF PAST OBSERVATIONAL RESULTS

Experimental Evidence for Field-Aligned Ionization Structures

Many radar observations have revealed auroral curtains and columns at the base of the magnetosphere with structures aligned with the magnetic field of the Earth. HF radar echoes with delays of the order of a few seconds have been observed and interpreted in terms of waveguidance in the laminar structure of the magnetosphere. Such long delay echoes have been observed and interpreted in this manner by Obayashi (ref. 8), Gallet and Utlaut (ref. 9), and DuCastel (ref. 10).

Investigation of the scintillation of discrete sources of cosmic radio noise has led to the hypothesis of laminar structure of the magnetosphere (refs. 11, 12).

Ariel I results of geomagnetically controlled diffusion has provided a sound justification for field-aligned ionized layers.

Alouette I and II and Explorer XX Topside-Sounder experiments have provided evidence of the laminar structure and waveguidance. Radio propagation that can be consistently explained in terms of propagation along field-aligned sheets of ionization has been observed on Topside-Sounder ionograms at frequencies as high as 5.6 MHz (ref. 7). The Alouette satellite orbiting at an altitude of about 1000 km has confirmed the findings of previous rocket-borne sounders (refs. 13, 14, 15), and has indicated the existence in the lower part of the magnetosphere of field-aligned laminae, about 0.6 km thick, and characterized by a gradient of electron density four times larger than that of the regular ionosphere and opposite in sign. The maximum density in the sheet was estimated to be 1 percent above the background ionization.

Certain peculiar characteristics of whistlers (ref. 16) also indicate the existence of a laminar structure of the magnetosphere. The whistler phenomenon, per se, cannot be invoked in support of such a magnetospheric structure. Whistlers (ref. 17) can propagate in a magneto-ionic medium of constant electron density as extraordinary, longitudinal modes of propagation and when $X >> 1$, $Y >> 1$ and $X >> Y$ $\left[X = \omega_N^2/\omega^2\right.$ where ω_N is the angular plasma frequency and $Y = \omega_H/\omega$ where ω_H is the angular gyrofrequency$\left.\right]$.

In other words, whistlers are possible in a magnetosphere of constant electron density when wave frequency is much smaller than both the plasma frequency and the electron gyrofrequency at any point along the path.

The propagation of individual components in multinose whistlers indicates the existence of discrete paths spaced in latitude. The low attenuation and low divergence experienced in some whistlers after travelling several times back and forth between two geomagnetic conjugate points (refs. 4, 5) suggest waveguidance along field-aligned structures in the magnetosphere.

In the recent past, a remarkable correlation (ref. 18) has been found between whistler occurrence and the presence of auroral field-aligned ionization structures in the E and F layers near the base of the field line that guided the whistler. Those structures appear as the bases of laminae and columns that extend upward in the magnetosphere and guide the whistler, at least in the lower sections of the path.

Previous Experiments

Even in those early times when rudimentary HF radar arrangements experienced echo delays of the order of a few seconds, some authors interpreted the long delays as resulting from propagation in a magnetic cavity extending in space to several Earth radii from the surface of the Earth.

The first "cosmic echoes" were observed by experimenters (refs. 19, 20) working at 9.5 MHz with delays from 3 to 15 seconds. It is not proper to attribute the long delay echoes to reflections from intense ionized clouds in space. Various plasma mechanisms (ref. 20) have recently been invoked to explain such echoes. A coded pulse previously stored in some part of the ionosphere can be recovered in the form of a train of echoes by triggering the ionosphere with a similar pulse or an impulse.

Other observations made by Appleton (ref. 21) were successful at 6.7 and 9.5 MHz. Further tests carried on by Budden and Yates (ref. 22) at 13 and 20 MHz were, on the other hand, unsuccessful in observing long-delay cosmic echoes. Table I gives some information on the previous experiments.

TABLE I

Observers	Frequency (MHz)	Peak Power (kW)	Pulse Energy (Joules)	Pulse Duration	Experiment Type	Conclusion as to Waveguidance
Obayashi (ref. 8)	27	25		100 μs	Monostatic	Yes
Gallet & Utlaut (ref. 9)	14	100	100	1 ms	Monostatic	Yes
Thomas, McInnes & Crouchley (ref. 23)	16 & 55	50 & 4	-	-	Monostatic	No
DuCastel (ref. 10)	11	35	210	6 ms	Monostatic	Yes
Watkins & Sutcliffe (ref. 24)	32	100	-	1.5 ms	Monostatic	No
Gassman, Barrett & Pratt (ref. 25)	10 10 to 18	50 5	- -	cw 40 μs	Bistatic Bistatic	Doubtful

The greatest detection success was claimed by Obayashi (ref. 8). However, his conclusions were criticized by Thomas et al (ref. 23) who offered an alternative interpretation to Obayashi's (ref. 8) observations based on phenomena other than magnetospheric propagation. Gallet and Utlaut (ref. 9) concluded that the signals recorded during 1 percent of the listening time in their experiment were caused by magnetospheric ducting. DuCastel (ref. 10) reported a similar rate of successful detection. These experiments were all monostatic. The echo detected at the transmitting end itself was supposed to be the backscatter at the conjugate point or some dense plasma cloud in space. The measured time delays and losses agreed very well with those obtained using ray tracing techniques on a field-aligned path in a model of the terrestrial magnetic field. In their cw experiment Gassman et al. (ref. 25) had available much greater signal energy than any of the other workers. Theirs was a bistatic experiment. Unfortunately, other characteristics of the experiment made their results difficult to interpret, and it is not surprising that they themselves considered the results to be very doubtful.

The detected signals and echoes have always been reported as very weak. Thus, previous experiments have not been able to provide conclusive direct evidence for the existence of HF magnetospheric ducting. Guidance of HF radio waves along a field-aligned path is still an intriguing problem. An analysis of all previous experiments points to a great need for improvement in receiver sensitivity. While some improvement could be expected from increasing antenna directivity, it may be very helpful to increase pulse energy or to perform pulse averaging at the receiver, or both. The development of a magnetospheric sounder would involve digital integration techniques. However, the effectiveness of such an operation would be limited by short term changes in magnetospheric conditions. At the same time, integration could be performed only at the expense of time resolution in studying such changes. Therefore, an increase in pulse energy probably would also be necessary and, in any event, desirable.

Possible Explanation for Failure of Past HF Sounding Experiments

It is possible that the electromagnetic wave gets reflected at the vertical incidence reflection level at the conjugate point of the transmitter location. Spread F and other phenomena in the ionosphere may result in heavy attenuation and scattering. Very little signal energy can get to the exact conjugate location on the ground under such conditions. Thus bistatic experiments have a very slight chance of success if they are performed as in the past. A monostatic setup has greater chance of success, but is ambiguous to interpret. The theory of HF ducting in the magnetosphere has so far been unable to determine the exact conditions necessary for a successful experiment. No reliable techniques based on sound theory have yet been developed. One should be careful in improvising VLF techniques to study HF ducting. The physical problems involved in HF ducting are different from those of whistler mode propagation. Injection of the signal into the duct at a proper mode angle is very important. If the signal is not injected into the duct at a proper mode angle, it will simply escape. Thus, signal launching has to be very carefully designed.

At auroral zone latitudes, one has the distinct advantage of the presence of auroral curtains. Injection of the signal into the duct is easier under such conditions. But there are a few problems which preclude high latitude HF ducting phenomena. The maximum frequency usable is relatively low (< 5 MHz). At these latitudes, guiding is feasible at the base of the field lines but not throughout the remaining path. The field lines go far into the magnetosphere where the medium can hardly be distinguished from free space at these frequencies. Then, the value of $\Delta N/N$ required for a sufficient fractional change in refractive index to ensure trapping is extremely high and may be difficult to realize physically. Under such conditions, the duct acts like a leaky waveguide, and the wave energy escapes very quickly. It may be possible to conduct a successful experiment based on the following considerations:

1. Very careful selection of the conjugate points based on most recent experimental models of the magnetospheric electron density distribution and the magnetic field;

2. A group of receivers located at the conjugate point instead of just one; the receivers should be so located that the reception probability is very high;

3. Careful selection of signal frequency based on sound theoretical arguments;

4. Increase in the transmitted power and a good technique of signal injection;

5. Extremely refined signal processing techniques.

Thus, it is advisable that more analytical and theoretical work be done before conducting an experiment. Any experiment which employs slightly different versions of past techniques has small probability of success and provides no further insight into the general problem of HF ducting. Since such experiments are expensive, each new venture warrants very careful planning on a sound theoretical basis.

In this context, it is instructive to discuss in more detail the experiment conducted by Budden and Yates (ref. 22) in 1949. They made a search for long delay echoes on 13.455 MHz (30 kW) and 20.675 MHz (9 kW). Observations, however, were made at several selected intervals of an hour or two in length one day each fortnight only. If conditions permitting such echoes exist for short periods, a small percentage of time, the relatively infrequent periods of observation might explain why long range echoes were not observed. (Budden and Yates (ref. 22) at that time thought that the source from which the signals were reflected was the highly ionized regions or plasma clouds in space.) Budden and Yates (ref. 22) did conclude that the echoes of long delay heard by previous observers were associated in some way with ionized regions fixed relative to the Earth and that the failure to observe the echoes was caused by the choice of frequencies which were probably too high. However, they did make the following suggestions:

1. It is advisable to use lower frequencies (frequencies less than 10 MHz).

2. Proper signal launching techniques need to be developed. It is undesirable to use aerials, the directions of maximum transmission or sensitivity of which radiate outwards from the Earth. Better results might be achieved with aerials having horizontal directivity. If a study could be made as to how the strength of the echoes depends on the directivity of the aerials, it would give some useful information about the nature of the waves responsible for the echoes. Successful launching also depends critically on the ionospheric conditions.

VLF INVESTIGATIONS

Introduction

Whistler frequencies range from 1 to 10 kHz. They are RH-polarized waves (extraordinary) and generally lie in the range $\Omega_H << \omega < \omega_H$ and satisfy $\omega^2 << \omega^2_o/w_H$. Waves of this type propagate well in the plasma in a wide range of angles with respect to the magnetic field direction. In this frequency band also, self-excitation of the ionospheric plasma may occur and has been observed in some cases (refs. 26-30). Such radiation has been detected at frequencies of from 1 to a few kHz.

The whistler signal energy travels along discrete paths in the magnetosphere and spreads out under and through the ionosphere. The nose frequency of the whistlers depends only on f_H (electron gyrofrequency). Non-ducted whistler signals have never been observed on ground. The reasons for very scarce observations of non-ducted signals are:

1. The waves are totally reflected at the lower boundary at the conjugate point;

2. The waves do undergo heavy absorption.

For h > 100 km, the absorption A is:

$$A = \left[K \frac{\omega_o \, \nu \, \omega^{1/2}}{(\omega_H \cos \theta)^{3/2}} \right] \text{decibels}$$

As θ approaches 90 degrees, the absorption becomes extremely high. There are a few features in the Whistler investigations, in addition to those previously mentioned, which lead to the hypothesis of field-aligned enhancements of ionization. Constancy of time-delay between the echoes and representation of a purely longitudinal mode of propagation by a fully developed nose-whistler are just two of them. The time-constant of duct structure as deduced from Whistler investigations is on the order of an hour. Such ducts seem to fill approximately 1 percent of the magnetosphere. Variability of duct conditions is not well known.

Application of Whistler Investigations to Measurements of Electron Density

Information on magnetospheric electron density is obtained from whistlers through an integral relation between whistler travel-time and the electron plasma frequency:

$$\text{Time delay, } \tau = \frac{1}{2C} \int^{\text{Path}} \frac{f_o(S)\, f_H(S)}{f^{1/2}\, (f_H - f)^{3/2}}\, ds$$

Electron gyro frequency f_H is obtained by the nose frequency information. Electron plasma frequency f_o is obtained by the analysis of Alouette satellite data. Alouette data seem to fit very well with the diffusive equilibrium model inside the plasma pause. Outside the plasma pause, delays are much smaller and a collisionless model fits fairly well. In performing an analysis, it is customary to assume a model of the distribution of electrons along the field lines and then obtain the following parameters from observational data:

1. The equatorial radius of the field line whistler path;

2. Scale factor of the electron density distribution.

Uncertainty in the field-line model of the distribution of ionization has relatively little effect on calculations of total tube content (ref. 31). In the case of equatorial profiles, lack of accurate knowledge of the model has relatively little effect on determinations of slope. But it introduces an uncertainty in equatorial radius on the order of $\pm$ 0.15 R_E and an uncertainty by a factor of $\pm$ 2 in the absolute value of the electron density (ref. 32). Errors of this magnitude are of minor importance in the detection of the presence and approximate position of the magnetospheric knee region ($\approx$3.5 R_E), but special efforts to reduce error are necessary while investigating details of distribution of ionization near the knee.

Study of the Appropriate Field-Line Models

For the high density region inside the plasma-pause, a diffusive equilibrium distribution (refs. 33, 34) is found to be appropriate. For the outer region beyond the knee, a collisionless model behaving approximately as $N_e \, \alpha^{\ell} \, r^{-4}$ is used. The knee represents a transition region between an inner region where collisions are important in determining the field-line distribution and an outer region where the distribution is primarily dependent on a collisionless model. During even mild disturbances caused by solar activity, the region of high density (the knee) moves in. Thus, the depleted number density in the path of the electromagnetic wave should result in reduced group values of group delay and absorption.

The knee in the magnetospheric ionization is more abrupt than the corresponding variation with latitude of ionospheric parameters such as ion density, electron temperature, and the like (ref. 7). This is particularly true during daytime. If a diffusive equilibrium model were applied on both sides of the knee, the whistler calculations would show an abrupt decrease near L = 4 by a factor of about 7 in distinct contrast to Alouette satellite measurements. A proper detailed study reconciling whistlers and Alouette satellite data has not yet been made. There are agreements in slopes but not in levels.

ANALYTICAL APPROACH

Introduction

The problem of interaction between the magnetospheric medium and the HF waves guided by field-aligned ionization is tackled, at first, by a geometrical optics approach. The geometrical optics approach has been utilized by many people in studies of propagation phenomena at HF and VHF in the ionosphere of the Earth (refs. 35, 36). Several ray-tracing programs have been developed by VLF investigators too. All the approaches are based on the original works of Hamilton (ref. 37), Poeverlein (refs. 38-40), and Haselgrove (ref. 41). The geometrical optics approach provides not only a quick means of specifying the basic parameters of an experimental link but also a basis for evaluation of consequent effects.

Ionospheric Ray-Tracing

The Snell's law program developed by Croft and Gregory (ref. 42) is both efficient and versatile. Of special interest to the present problem is the simplicity with which the program can be applied to model ionospheres involving horizontal as well as vertical gradients. In particular, account must be taken of the possibility of tilts in the equatorial ionosphere. Such tilts have been invoked by Thomas et al (ref. 23) as an alternative interpretation of the alleged magnetospheric returns of Obayashi (ref. 8). Tilted models of equatorial ionosphere are provided by Nielson (ref. 43).

The program is versatile in its acceptance of vertical electron density profiles. An arbitrary profile may be inserted using either discrete data points via punched cards or a standard analytical model such as a Chapman ionosphere.

Magnetospheric Ray-Tracing

The information desired in a magnetospheric analysis is more extensive and must have greater accuracy than that obtained in ionospheric ray tracing programs. For this part of the work, a Haselgrove type of program, first developed for application to magnetospheric problems by Yabroff (ref. 44), is extremely useful. This program has been used and modified extensively (refs. 45,46). A three-dimensional ray tracing program has been developed by Jones (ref. 47).

For a model of the electron density distribution in the magnetosphere, the following are found to be very useful.

1. A three-dimensional model is derived from experimental data obtained by other authors (refs. 48-50).

2. Gross characteristics of electron density along the presumed magnetospheric path are provided by Frihagen (ref. 51) and are based on data from whistlers, incoherent scatter experiments, and other sources.

Models of field-aligned laminae and columns of enhanced ionization are imposed on the equilibrium electron density profile. Considerable experimental evidence is available for guidance in selecting structural models. Field-aligned sheets or shells, such as those reported by Muldrew (ref. 7) and other workers, can form one model. Another will be field-aligned columns of ionization enhancement and depletion with Gaussian transverse density distributions. The latter model has been found to be very useful by VLF investigators.

For the model of the magnetic field of the Earth, the 63-term spherical harmonic expansion model of Cain, Daniels, Hendricks, and Jensen (ref. 52) is very suitable. Models based on extensive space probe magnetometer observations will also be useful in the analysis.

There is always some intrinsic error in assuming a dipole field in the presence of compressed outer geometry. The changed equatorial crossing of the field line and changed path length tend to have opposing effects. In a compressed field, a field line path crossing the equator at 8 R_E produces a whistler of nose frequency corresponding to 7 R_E in the dipole model (ref. 53). However, when the electron density calculation is made, the path length assigned in the calculations is too short, being the path length for the dipole field line passing through 7 R_E rather than the distorted longer line through 8 R_E. The equatorial electron density is then too high (for 8 R_E), but it is plotted for 7 R_E and thus tends to fall near the correct profile. The result is to place points on an approximately correct equatorial profile, but at geocentric distances that are too low.

Propagation Characteristics

The geometrical optics approach can be used to derive the following propagation characteristics of the guided HF waves. As mentioned before, electron density models of the magnetosphere are used in such an analysis.

The inverse problem would be to correlate measured characteristics with the assumed electron density models. The model which best fits the measured characteristic is the final output. Any dynamic correlations (spatial and temporal) with solar activity, localized disturbances, and the like, have to be based on such an output as a function of time and space.

Group Delay--

$$\tau_g = \frac{1}{c} \int_0^S n \left[1 + \frac{f_o}{n} \frac{dn}{df} \right] \cos \alpha \, ds$$

where

f_o is the electron plasma frequency

S is the geometric path length from the transmitter to the receiver

α is the angle between the wave normal and the ray direction

ds is the incremental distance along the ray path

n is the phase refractive index.

Phase Delay--

$$\tau_p = \frac{1}{c} \int_0^S n \cos \alpha \, ds$$

where

$\int_0^S n \cos \alpha \, ds$ is the phase path length.

The time variation of phase path length gives a measure of the doppler shift in the frequency.

Frequency dispersion along the path--Frequency dispersion along the path is obtained by expressing the wave phase constant, β, as a Taylor expansion containing sequential derivatives of the index of refraction with respect to the frequency:

$$\beta(f) = \beta(f_o) + (f - f_o)\,\beta'(f_o) + \frac{(f - f_o)^2}{2!}\,\beta''(f_o) + \cdots$$

where

$$\beta(f_o) = \frac{2\pi}{c}\Big[f\,n(f)\Big]_{f = f_o}$$

$$\beta'(f_o) = \frac{2\pi}{c}\Big[n(f) + f\,n'(f)\Big]_{f = f_o}$$

and

$$\beta''(f_o) = \frac{2\pi}{c}\Big[2\,n'(f) + f\,n''(f)\Big]_{f = f_o}.$$

Other measurable propagation characteristics are path losses (including losses caused by absorption and refraction), wave polarization (Faraday rotation), and the like.

Comparison of HF Ducting Techniques with VLF Techniques

A pulsed magnetospheric link at 5 to 10 MHz presents a time dispersion of the pulses much smaller than at whistler frequencies (10 to 30 kHz) and, therefore, allows a more accurate measurement of the propagation time along the path.

Injection into and extraction from the waveguidance can be optimized with directive antennas much more feasibly at HF than at whistler frequencies.

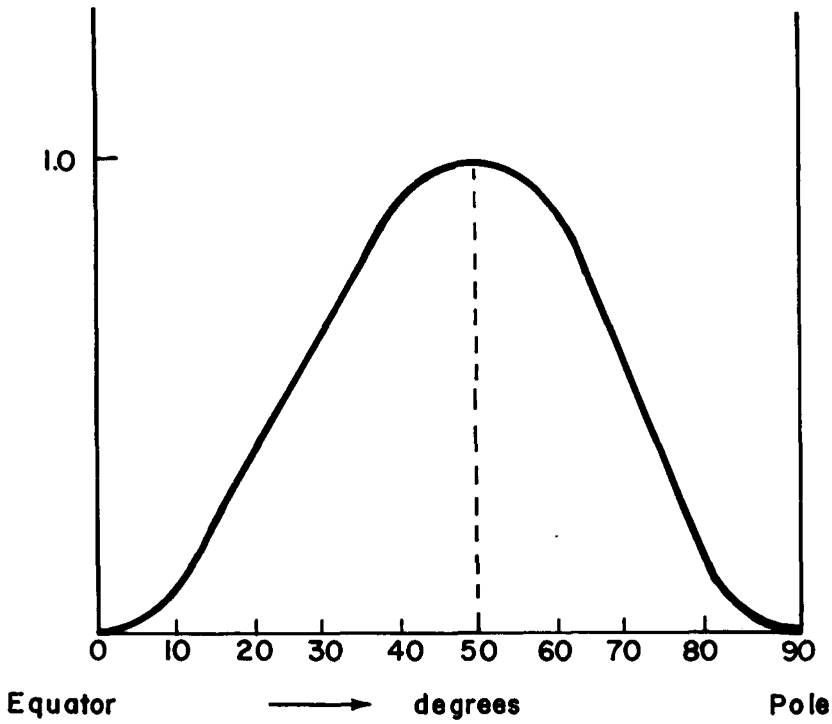
The HF equipment is not so cumbersome as the VLF gear.

Doppler shift resulting from changes in the phase path length is about 2 to 3 orders of magnitude larger at HF than at VLF.

On the assumption that HF ducting is possible in a bistatic experiment, the sensitivity of the experiment can be controlled since the signal input parameters like power, frequency, and the like, can be changed as needed. Whistlers are naturally occurring phenomena except for those observed during nuclear bursts.

The preferred arrangement would be an HF link between two terminals located at magnetically conjugate points instead of a monostatic radar setup with the transmitter and the receiver located at the same point. Reception of the signals can be expected to be more frequent in the bistatic than in the monostatic arrangement. This advantage overcompensates the more complex logistics that characterize a bistatic configuration.

The relative frequency of whistler occurrence is plotted as a function of latitude in the following figure:



Whistler observations are very scarce in higher latitudes, particularly in auroral zones. Nose whistlers are high latitude phenomena and are particularly attributed to field-aligned ionization ducts. Even though HF ducting itself has its limitations (the maximum usable HF frequency decreases with increasing latitude), the full potential of HF ducting has not been yet understood. Its usefulness for high latitude observations should not be underestimated. There are no experimental observations available to warrant any conclusions.

DISCUSSION OF A FEW MAGNETOSPHERIC PHENOMENA

Introduction

The following discussion considers a few of the physical features of the magnetosphere and certain phenomena occurring within it. Proper performance and interpretation of a HF duct propagation experiment may lead to a better understanding of these phenomena and features. Whatever knowledge that has been acquired about them is through VLF investigations and satellite experiments. These experiments have not provided definitive answers concerning many important phenomena. The nature of the HF duct propagation technique to investigate the magnetospheric phenomena is similar to that of VLF techniques. But, the advantages of the HF ducting technique over the VLF technique have been discussed in the earlier sections. The capacity of these techniques to study any dynamic phenomena in the magnetosphere instantaneously is unique. It would otherwise require a string of satellites along a magnetic field line to conduct such an investigation.

All the discussion here is based on an assumed success of such an experiment. But the problems involved in setting up and operating such a propagation link are complex and every effort must be made to study the technical and scientific feasibility of such an experiment before conducting it.

Thus, it may be possible to take advantage of a mode of propagation requiring a laminar structure of the magnetosphere to test the existence and properties of such sheets of ionization at large distances from the Earth. Such a propagation mode would be useful for observing from ground-based experiments, in a quasi-continuous manner, certain magnetospheric characteristics, such as the permanent ring current and the plasma-pause.

It can also be used to determine the relationship between the density distribution of the low-density, high-energy electrons in the Van Allen belts and the more numerous thermal electrons forming the bulk of the exosphere. Some of the other problems which can be investigated with the proposed technique are the magnetospheric electron density distribution, trapping phenomena in the Van Allen belts, compression of magnetic field lines, effects of dynamic disturbances and magnetic storms, and other phenomenological behavior of the magnetosphere.

The Knee Region

At distances of 15,000 to 25,000 km from the surface of the Earth in the direction of the sun, more complicated processes take place in the plasma and the so called "knee" is formed. It is reasonable to regard the knee region (3 to 4.5 R_E) as the outer ionospheric boundary. The interval between the knee region and the magnetosphere boundary (8 to 10 R_E) is a transition region from the ionosphere to the interplanetary medium.

At heights of about 15,000 to 25,000 km, it has been found from whistler observations that during periods of relatively weak magnetic disturbances, the electron density decreases very fast, almost abruptly, over a small height interval (600 to 700 km). Above the 15,000 to 25,000-km region, the time variation of charged particle concentration is highly speculative. Also, the neutral particle concentration coincides closely with the minimum values of the charged particle concentration (ref. 34).

It may thus be possible to say that during certain types of perturbations, "particles" are swept towards the ionosphere. Precipitation of particles takes place which can give rise to additional particle belts, electric fields, the plasma oscillatory structure, and complicated plasma processes.

At distances of 3 to 3.5 R_E and higher, the Maxwellian distribution is not valid, quasi-neutrality is absent, and large electric fields are present. This indicates that the plasma is non-stationary and that its condition is essentially regulated by particle streams incident on the Earth. Thus, it is proper to call this region the outer ionospheric boundary. The minimal value of N corresponds to the neutral particle concentration.

The similarity between the equatorial electron density variations at the knee (satellite observations) and the variations in the electron density content of the field line tube passing through the knee (whistlers and magnetic field observations) suggests that the knee phenomenon is under strong geomagnetic control. Direct observations of a knee effect at points well removed from the equatorial plane have recently been made on the orbiting geophysical observatory (OGO-1) by Taylor et al (ref. 54) through mass spectrometer measurements and by Whipple and Troy (ref. 55) using an ion trap. For a field-aligned tube passing through the knee, the total content and the density level vary only slightly from day to night.

The equatorial distance of the knee may change significantly during the period of an hour. This temporal variation in the position of the knee cannot be attributed to diffusion of ionization along the field lines. If, for example, an inward movement were attributed strictly to a downward flux depleting certain tubes of ionization, the flux would have to be at least on the order of 10^{10} electron/cm^2/sec. It would also have to be highly restricted in its distribution over latitude. Although the process giving rise to the knee may greatly influence the night time ionosphere, the shape of the knee and its movements are not directly controlled by the coupling between the protonosphere and the ionosphere.

Above 10,000 km, the effective temperature rapidly increases from $kT_{eff} \approx 1$ ev to $kT_{eff} \approx 10$ ev at an altitude of 30,000 km. At 30,000 to 40,000 km, the particle energy remains almost constant. These strong variations of kT_{eff} agree qualitatively with electron density variations. In the knee region, where fast changes of N (Z) take place and the plasma is non-stationary, the particle energy also varies rapidly.

In the 20,000- to 30,000-km region:

$$\frac{(N\bar{v})_e}{(N\bar{v})_i} \sqrt{\frac{m}{M}} > 1.$$

Presently suggested values based on measurements and theory for this ratio vary from 1.3 to 2.6. As a consequence, the electron energy density is higher than the ion energy density. Their difference:

$$\Delta W = \left[(NkT)_e - (NkT)_i \right] \approx 10^2 \text{ to } 10^3 \text{ ev.}$$

If it is assumed that this is caused by the absence of quasi-neutrality and the magnetic field effects are negligible, then $\Delta W \approx E_0^2/8\pi$. This results in a strong electric field of strength $E_0 \approx 1$ to 4×10^{-2} volts/cm. Forthcoming experiments should show whether this important conclusion is correct.

The Inhomogeneities in the Outer Ionosphere

The ionosphere is known to be statistically inhomogeneous. The dimensions of the inhomogeneities vary from hundreds of meters to hundreds of kilometers. The relative variation in density, $\delta N = \Delta N/N$, varies from 10^{-2} to 1. At the same time, there are other types of inhomogeneities which cannot be described statistically. These are mainly large-scale inhomogeneities of the ionosphere.

The ionospheric statistical inhomogeneities are closely connected with oscillations and wave properties of the plasma, and with interaction effects of the plasma with incident particle streams and radiation.

It is important to study the shapes of the inhomogeneities, the character of their orientation along the magnetic field, and the degree of their ellipticity.

In the lower regions of the ionosphere, ellipticities of 0.5 to 0.25 have been observed. At high latitudes, the inhomogeneities of a "sausage-like" type extending considerably along the magnetic field have been assumed. This assumption is based on the fact that cross-diffusion in a weakly collisional plasma takes place much slower than longitudinal diffusion does. The discovery of such inhomogeneities would enable us specifically to interpret the propagation of whistlers at great distances.

Thus, the attitude distribution of the properties of the inhomogeneities may help to determine better the character of the processes occurring in the ionosphere.

Of great significance will be the simultaneous measurements of the density fluctuations in the inhomogeneities and the frequencies of plasma oscillations in local regions of the outer ionosphere. Such experiments are not being carried out at all. If conducted, they will help to identify the types of waves excited in the plasma and to diagnose them properly.

Magnetic Storms and the Ring Current

During a magnetic storm, there is an initial increase of the surface field (indicating increased plasma flow), followed by a larger decrease. The decreasing part is called the main phase of the storm. Certain physical features associated with a magnetic storm are described below.

1.	Initial increase in the H field (lasting a few minutes)	-	Enhanced plasma flow.
2.	Subsequent larger decrease in the H field (main phase)	-	Ring current growth.
3.	Recovery phase (lasting a few days)	-	Ring current decay.

The ring current, which was originally postulated by Chapman and Ferraro to account for the geomagnetic surface field variations during a magnetic storm (solar corpuscular event), is now thought to be produced by the motion of the particles trapped in the magnetic field of the Earth. The main phase of the storm occurs when the number density or the energy of the particles is increased. But the energy increase on the order of $E > 10^6$ ev in the trapped particles is still not sufficient to account for the magnitude of the main phase decrease in many magnetic storm events.

The ring current is postulated to exist at an altitude between 3 and 4 R_E from the surface of the Earth on the sunlit side of the magnetosphere. Many characteristics attributed to the ring current have not yet been clarified. The existing experimental data are scarce and vague. Many investigators have been forced to suggest various localized phenomena to produce the required acceleration of the charged particles. Such acceleration processes would provide the extra energy needed to account for the various features of magnetic storms, aurorae, and other ionospheric events.

In the following analysis, Parker's approach (ref. 56) is used to study some of the characteristics of the ring current. Let us assume that during a magnetic storm, the total disturbed field has a distortion $\nabla \times \bar{B}$.

Then:

$$B(r) = B_o + \Delta B(r).$$

By carrying on an analysis of various energy sources capable of producing such distortions in the magnetic field, we obtain

$$\frac{\Delta B}{B_o} = \frac{2 E}{3 E_m (R_E)}$$

where E is the total kinetic energy of the plasma particles that the ring is composed of and E_m is the total magnetic field energy at the surface of the Earth. A ring current at an arbitrary distance from the Earth is assumed to be the source of ΔB:

$$E_m = \frac{1}{3} B_o^2 R_E^3 .$$

For a given pitch angle distribution for particles inside the ring, $\Delta B/B$ is independent of position. For any L value, it just depends on the total kinetic energy of the particles in the ring. Enhancement in the total energy of the particles in the ring current is assumed to be responsible for the main phase of magnetic storms.

The total magnetic energy of the particles at an arbitrary distance r from the surface of the Earth is:

$$E_m (r) = E_m (R_E) (R_E/r)^3 .$$

Let $E(r) = \alpha E_m (r)$ where $\alpha < 1$. $\alpha = 0.5$ is a reasonable value.

If $\Delta B = 100 \gamma$,

$$\frac{\Delta B(r)}{B(r)} = \frac{2}{3} \left(\frac{E(r)}{E_m (r)} \right),$$

then, $r \approx 5.5 R_E$

If $\Delta B \approx 300 \gamma$, then $r \approx 3.67 R_E$.

Thus, the position of the ring current can be tentatively placed at distances between 3. 67 R_E and 5. 5 R_E from the surface of the Earth.

It is difficult to identify the source of these particles in the ring current. Some of the sources may be:

1. The neutral particles (H and He) in the solar corpuscular radiation, which penetrate through the magnetospheric boundary, suffer collisional ionization or charge exchange and get trapped to form a ring current.

2. The ambient ionized gas, the thermal velocity of which gets considerably enhanced by hydromagnetic shock waves.

The problems still to be answered are:

1. The general location of these current systems responsible for such phenomena as magnetic storms, aurorae, and so forth;

2. The delay phase of magnetic storms and processes leading to cooling off of these energized particles. It is possible that convection and charge exchange interactions are two such sinks for cooling processes.

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