PROGRESS IN RADIO SCIENCE

1960-1963

VOLUME IV

PROGRESS IN RADIO SCIENCE 1960-1963

VOLUME IV

RADIO NOISE OF TERRESTRIAL ORIGIN

PROCEEDINGS OF COMMISSION IV ON RADIO NOISE
OF TERRESTRIAL ORIGIN DURING THE
XIVth GENERAL ASSEMBLY OF URSI, TOKYO, SEPTEMBER, 1963

edited by

F. HORNER

Radio Research Station, Department of Scientific and
Industrial Research, Slough, Great Britain

ELSEVIER PUBLISHING COMPANY
AMSTERDAM/LONDON/NEW YORK
1965

ELSEVIER PUBLISHING COMPANY
335 JAN VAN GALENSTRAAT, P.O. BOX 211, AMSTERDAM

AMERICAN ELSEVIER PUBLISHING COMPANY, INC.
52 VANDERBILT AVENUE, NEW YORK, N.Y. 10017

ELSEVIER PUBLISHING COMPANY LIMITED
RIPPLESIDE COMMERCIAL ESTATE
BARKING, ESSEX

LIBRARY OF CONGRESS CATALOG CARD NUMBER 61-18616
WITH 14 ILLUSTRATIONS AND 2 TABLES

PRINTED IN THE NETHERLANDS

CONTENTS

Session on Properties of the Lightning Flash Source

Session on IGY Results and IQSY Programmes

Session on Whistlers

Session on VLF and Noise Phenomena

Session on Guided Waves in the Troposphere and the Ionosphere

REPORT OF THE CHAIRMAN OF COMMISSION IV (RADIO NOISE OF TERRESTRIAL ORIGIN)

R. A. HELLIWELL

Stanford University, Stanford, California (U.S.A.)

From the program of Commission IV it is seen that atmospheric noise of terrestrial origin continues to provide new and challenging problems. In addition to the newer topics of whistlers and VLF emissions, there has been much work in the more classical aspects of the subject as evidenced by the papers and discussions in the two sessions on atmospheric noise.

Atmospherics of the sub-ionosphere type were considered over a wide frequency range, from extremely low frequencies to high frequencies. As in the past, the effects of ionospheric propagation played a dominant role in the interpretation of the observations. Of particular interest were the changes in VLF propagation characteristics as determined by atmospherics observed about the times of nuclear explosions. In discussions of the nature of the source, the distribution of energy of atmospherics among the different components of multiple-stroke flashes, the distribution between cloud-to-ground and cloud-to-cloud flashes and the geographical variations of the ratio of low-frequency to high-frequency noise were considered. Questions were raised requiring further study. Discussion indicated the need for further measurements in which the spectrum of the radiation is compared with the current waveforms of individual strokes.

From the review of IGY results and IQSY programs relating to sub-ionospheric noise, it appears that there are problems which warrant further attention from Commission IV. Thus the directional properties of noise and its variations in polar regions are not yet well defined. Observed noise levels have yet to be fully related quantitatively to source distributions. Our attention is drawn to the opportunities for world-wide observation of terrestrial storms using wideband receivers in satellites. Coordination of such experiments with ground-based observations is clearly important and is an activity in which Commission IV can play a useful part.

The study of whistlers and related phenomena occupied much of the work of Commission IV at Tokyo. These subjects grew rapidly in importance following the presentation by J. A. Ratcliffe of Storey's pioneering work on whistlers at the General Assembly of URSI held in Sydney, 1952. During the Tokyo Assembly there were two sessions on whistlers and VLF emissions and one informal discussion of whistlers and VLF emissions. In addition, two sessions were held jointly with other commissions, in which whistler data and the theory of whistler propagation played an important part.

In the session on electron density profiles in the ionosphere and magnetosphere, held jointly with and organized by Commission III, the role of whistlers was outlined by Commission IV. Not only was an equatorial profile estimated from whistler data, but a number of new and unexpected characteristics of the variation of density in the magnetosphere were found. Annual and semi-annual variations in magnetosphere density have been found, although not explained. The diurnal variation, though small, is complex, showing puzzling changes with latitude, season and solar cycle. Solar cycle variations in magnetospheric density appear to be substantially less than those in the F region. On the other hand, during magnetic storms the density in the magnetosphere is often severely depressed. A "knee" in the distribution of electron density with latitude has been found and should provide valuable data for the development of realistic theories of magnetospheric dynamics.

The subject of guided waves was reviewed in a session held jointly with Commissions II and III. New aspects of guiding, so important in tropospheric and ionospheric work, have been introduced through the studies of whistlers in Commission IV. The review of this topic brought together some of the important theoretical ideas that are applicable in all three areas of study. There remains much work to be done on this subject.

A number of new and interesting whistler and emission phenomena have been found in the preliminary analysis of VLF data from the Alouette satellite, indicating that satellites and rockets can be expected to make significant contributions to progress in this field.

From the papers and discussions presented at Tokyo, it becomes increasingly clear that whistlers and VLF emissions have close connections with certain topics under active consideration by other commissions and other unions. Thus, study of the magnetosphere using whistlers is related to high-frequency measurements of the cislunar medium based on radar astronomy techniques considered in Commission V. The variations in electron density in the magnetosphere show correlations with satellite drag variations, which is of interest to the UGGI as well as to the URSI. The ducting of whistlers may be closely connected with field-aligned irregularities which are observed by various techniques such as radio star scintillation and backscatter measurements, of interest in Commission III. The postulated mechanisms for the production of VLF emissions are all based on streams of energetic particles trapped in the earth's magnetic field, which are of interest to UGGI and COSPAR as well as to URSI.

In the area of VLF emissions, much quantitative information on the spectral characteristics of various kinds of emissions has been obtained. No satisfactory explanation for any of these has yet been worked out, although a number of possible mechanisms have been described and studied in some detail. Those based on certain kinds of instability appear particularly promising. The complexity of the experimental data as well as the mathematical difficulties in determining the detailed properties of these instabilities will make this study one of the most challenging for the next few years. The possibility that whistler-mode electromagnetic waves may be a significant factor in the production and removal of charged particles in the radiation belt is of interest in connection not only with VLF emissions but also with energetic particle dynamics. Close associations have been found between VLF emissions and other geophysical phenomena such as magnetic disturbance and aurora; owing to the complex nature of the VLF emissions, it is reasonable to suppose that intensive study of these associations may go far towards solving some of the remaining mysteries connected with the production of the aurora and magnetic storms.

Because of the importance of the energetic particle components of the earth's atmosphere, as well as the thermal component in the behavior of whistlers and VLF emissions, these subjects are rapidly extending into areas of plasma physics which are considered by Commissions V and VII as well as Commission III. Close cooperation with these groups is therefore indicated so that maximum progress in the understanding of these new phenomena can be made and at the same time the implications of such understanding can be most effectively utilized by students of plasma physics.

Finally, I should like to draw attention to the role being played by Commission IV in the organization of further synoptic studies of whistlers and VLF emissions. Through resolutions prepared by Commission IV, a program in synoptic whistler observation has been drafted and sent to the URSI–CIG Committee. This resolution outlines a program of synoptic observations in which extension to higher frequencies is recommended and the inclusion of VLF timing signals is urged. It was also recommended that certain stations supply numerical values of whistler dispersion for one typical whistler for each day. This recommendation is based on the experience gained during the IGY in which such dispersion data were found to lead to synoptic pictures of the variation of electron density in the magnetosphere. Another change from the IGY program is the recommendation for continuous recordings of VLF noise so that special events may be recorded in complete detail. Special emphasis is given to conjugate station pairs as in the past, but in the future program the special importance of the auroral zones in the polar caps is emphasized. Attention is drawn to the usefulness of observing man-made VLF transmissions for the study of whistler-mode propagation. Rocket and satellite observations of VLF ionospheric noise as well as whistlers are recommended, and finally, it is recommended that, wherever possible, these observations be made at locations where routine recordings of other geophysical phenomena are made. These include auroral observations, geomagnetic micropulsations, and ionospheric measurements, including density and absorption.

SESSION ON PROPERTIES OF THE LIGHTNING FLASH SOURCE

LIGHTNING FLASHES AND ATMOSPHERICS

A. KIMPARA
Faculty of Engineering, Nagoya University (Japan)

SUMMARY

Since the last General Assembly of URSI, extensive studies of characteristics of atmospherics radiated from lightning discharges have been made experimentally and theoretically all over the world, and remarkable progress has been attained, for example their frequency spectra have been obtained for almost all the frequency range from ELF to UHF, for each stage of ground and cloud discharges.

Propagation characteristics of VLF waves and atmospherics have been made clear for the ELF and VLF ranges, e.g. the attenuation of atmospherics was found to be almost the same for the frequency range 4–10 kc/s (about 7 to 9 dB/1,000 km at 6 kc/s) and to decrease to about 1 to 3 dB/1,000 km on frequencies higher than 10 kc/s. These values are fairly well coincident with those obtained for CW radio waves.

The intensity and phase characteristics of VLF waves and atmospherics have been investigated in normal and abnormal propagation conditions, including solar flares, geomagnetic storms, and nuclear explosions.

RÉSUMÉ

Depuis la dernière Assemblée Générale de l'URSI, des études étendues ont été entreprises expérimentalement et théoriquement sur les caractéristiques des émissions atmosphériques provoquées par les éclairs orageux et des progrès remarquables ont été atteints; c'est ainsi, à titre d'exemple, qu'on a obtenu leurs spectres de fréquence pour presque toute la gamme des fréquences depuis les extrêmement basses (EBF) jusqu'aux ultra hautes (UHF), et cela pour chaque stade des décharges entre nuages et celles au sol.

References p. 12

On a éclairci les caractéristiques de la propagation des ondes de très basses fréquences (TBF) et des émissions atmosphériques dans la gamme des fréquences extrêmement basses (EBF) et, pour celle des très basses fréquences (TBF), on a constaté, par exemple, que l'affaiblissement des émissions atmosphériques était à peu près le même pour la gamme de 4 à 10 kHz (environ 7 à 9 dB par 1000 km à 6 kHz) et qu'il diminuait de 1 à 3 dB par 1000 km pour des fréquences supérieures à 10 kHz. Ces valeurs concordent assez bien avec celles obtenues pour les ondes radioélectriques continues.

On a étudié les caractéristiques de l'intensité et de la phase des ondes de très basse fréquence et des émissions atmosphériques dans des conditions normales et anormales de propagation telles que les éruptions solaires, les orages géomagnétiques et les explosions nucléaires.

1. INTRODUCTION

This paper is a survey of the general features of developments in the study of atmospherics since the last General Assembly of URSI in London in 1960.

Atmospherics propagate through the space between the ionosphere and the earth in the waveguide transmission modes or in the ray modes reflecting between them. The frequency spectrum of atmospherics at the source, which depends on the characteristics of the lightning discharges and on geographical features, is very useful in the study of propagation characteristics of LF and VLF waves without installing expensive transmitters.

Although the intensity and phase of VLF waves are disturbed by solar flares, geomagnetic storms and allied phenomena, their intensity does not change appreciably to disturb the radio communications on VLF waves. Generally speaking, VLF waves propagate long distances with very low attenuation in all cases, and so they are very useful in the international comparison of frequency standards, and in radio methods of navigation. Atmospherics in the VLF range, emitted from meteorological disturbances such as thunderstorms, typhoons, tornadoes, fronts, troughs, etc., are indispensable to modern weather forecasting.

2. LIGHTNING FLASHES AS SOURCES OF ATMOSPHERICS

Ishikawa [*1*] has reported that in regular peaked and quasi-sinusoidal types of broadband atmospherics the polarity of the first pulse depends on whether the origins are ground or cloud discharges; the former is positive and the latter negative. Takagi [*2*] investigated discharges inside a thundercloud and suggested that the process of an intracloud discharge involves a slow streamer, which develops simultaneously upwards and downwards from the boundary layer between the two main oppositely charged portions, and fast dart-type streamers, which track back along the slow streamer channel from a local charge centre tapped by the arrival of the slow streamer. Takeuti [*3*] showed that a cloud discharge often leads indirectly to the initiation of a ground discharge process. Kitagawa [*4*] found that in the vicinity of the lightning channel the thunder wave front propagates very quickly as a shock wave. Within the range of about 500 m, the propagation velocity is higher than the sound velocity, e.g. more than 1,000 m/s in the immediate vicinity, and diminishes gradually to the normal velocity. The initial velocity and the range of supersonic velocity propagation vary appreciably depending upon the energy of the associated stroke. Takagi and Takeuti [*5*] observed atmospherics on 100 kc/s to 500 Mc/s within a distance of 30 km from the source, and found that the quasi-peak amplitude decreases generally in inverse proportion to the frequency, but on frequencies higher than about 3 Mc/s it decreases more rapidly and shows more fluctuation than on lower frequencies. The radiation from a discharge is usually composed of many intermittent pulses associated with electrostatic pulses, though in the vicinity of the source it sometimes shows continuous radiation of long durations over 0.1 s. The radiation from a leader process of a ground discharge covers a wide range of frequency, and that from dart leaders of subsequent strokes is not essentially distinguishable from that of a junction (J) process filling up an interstroke period, especially on high frequencies. The return stroke produces in general the most intense radiation on frequencies less than 1 Mc/s, but its radiation is indistinguishable from that of the leader strokes on frequencies higher than 10 Mc/s. The process of an intracloud discharge is similar to that of the junction process between return strokes of a multiple ground discharge, and consequently on high frequencies continuous radiations are observed both in cloud and junction discharges. After the initial burst of activity the pulses become more and more spaced in time. With increasing frequency the intermittent impulsive radiations change gradually into continuous radiations, but on frequencies higher than 100 Mc/s they are very often associated with electrostatic pulses.

Horner [*6*] made observations of atmospherics in the vicinity of the source on 6 kc/s and 11 Mc/s, and found that at 6 kc/s the largest pulses could be attributed to return strokes. Some of the smaller pulses may have been from return strokes but were more likely to have originated in partial discharges within the cloud. It was concluded therefore that these partial discharges may have characteristics comparable with those of the return strokes. At 11 Mc/s the return stroke radiates negligible energy, and although the stepped-leader discharge appears to be a minor source of energy, the main sources have not been quantitatively identified with any of the well-known lightning processes.

Recently Horner and Bradley [7] observed atmospherics on 6, 10, 45 and 550 kc/s, and 11, 200 and 400 Mc/s and concluded that waveforms at 45 kc/s are impulsive as on lower frequencies, while those at 550 kc/s are more similar to high frequency atmospherics. The most marked change in character therefore appears to take place between 45 and 550 kc/s. Atmospherics from cloud and ground discharges become more similar as the frequency is raised, and this is one factor tending to reduce the variations in amplitude and energy at higher frequencies.

Employing models assumed to be typical of multiple and single ground discharges, Watt [8] calculated the expected radiation field frequency spectra from 1 c/s to 100 kc/s. Radiation spectra obtained from 1 to 100 kc/s for observed ground discharge field variations normalized to 1 km agree within expected limits with calculated values. The models employed indicate that below 300 c/s multiple discharges produce much more energy than single discharges, and that inter- and intracloud discharges may produce as much energy as ground discharges.

Malan [9] made simultaneous recordings of electrostatic field changes and radiation on 11 frequency bands from 3 kc/s to 12 Mc/s and reported the salient points regarding the radiation field of ground discharge as follows. At 3 kc/s the radiation is confined to the return strokes. This remains true up to about 20 kc/s except that preliminary and interstroke pulses occasionally appear with amplitudes 1 % to 2 % of those of the return strokes. With increasing frequency up to about 1–2 Mc/s, return strokes still have the largest amplitude, but radiation from other parts of the discharge increases progressively. On 4–12 Mc/s these latter surpass the return strokes in amplitude. On these higher frequencies the radiation is intense and continuous during the course of the first few strokes of a flash, except for pauses varying from 2 to 20 ms immediately following a return stroke, a phenomenon also observed by several other workers. In the intra-cloud discharges rapid field changes associated with sudden bursts of bright luminosity are usually superimposed in sporadic fashion on the slow field change. On frequencies from 3 to 10 kc/s there are usually only 1 to 3 very small radiation pulses which are associated with rapid but not necessarily the largest of the so-called *K* field changes in the electrostatic field. As the frequency increases to 2 Mc/s, more and more radiation pulses appear, those associated with *K* field changes remaining the largest. On 4–12 Mc/s the radiation becomes practically continuous and pulses associated with *K* changes can no longer be distinguished from the rest of the radiation.

The cloud discharge has high frequency characteristics somewhat similar to the J process in the ground discharge and it is generally composed of slow J-like streamers and many rapid local streamers. On frequencies higher than 100 Mc/s both continuous and intermittent types of radiation, independent of any process like stepped leaders, are observed. Lightning flashes within 5 km show very often a continuous radiation, which has a duration larger than 100 ms, accompanied by complicated electric field variations.

3. PROPAGATION OF ATMOSPHERICS

Taylor [*10*] computed daytime attenuation characteristics by comparing the amplitude spectra of atmospheric waveforms recorded at four widely separated stations. The results of these attenuation measurements were presented for the band of frequencies from 3 to 30 kc/s and involving distances of 1,000 to 10,000 km. It was found that the attenuation was about 7 to 9 dB per 1,000 km at 6 kc/s and decreased to about 1 to 3 dB per 1,000 km on frequencies greater than 10 kc/s. The attenuation rate of west-to-east propagation relative to east-to-west propagation was about 3 dB per 1,000 km less for frequencies lower than 8 kc/s and about 1 dB per 1,000 km less for frequencies higher than 10 kc/s. These results are fairly well coincident with those obtained for radio stations by Wait.

Jean *et al.* [*11*] calculated propagation attenuation rates for frequencies in the ELF region (30 to 3,000 c/s) from the spectra of atmospherics observed at widely-spaced stations. Data are presented for east–west propagation with sunset approaching the eastern station. Under these conditions, the attenuation rates are about 1 dB per 1,000 km at 75 c/s and increase with increasing frequency, attaining about 3 dB per 1,000 km at 200 c/s. The attenuation rates observed seem to be consistent with a two-layered ionosphere model with its lower region 90 km above the earth.

Hepburn [*12*] made an extensive study of smooth-type atmospheric waveforms and considered that a fixed ionosphere height of 83 km may be equally acceptable for the analysis of day- and night-time waveforms. At a distance between 1,750 and 2,000 km an abrupt transition from peaked to smooth type waveforms was observed and the method of analysis applied to peaked waveforms observed at 1,500 to 1,750 km distance yielded results in conformity with sferics fixes; the calculation of attenuation coefficients has provided additional evidence of the very close similarity of day- and night-time propagation conditions for these waveforms, in that relatively negligible attenuation was found in the range 4–10 kc/s. Hepburn's assumption of a constant height of reflection, day and night, and the low attenuation at 4 kc/s are in contrast with the results of other workers.

4. SUDDEN ENHANCEMENTS OF ATMOSPHERICS (SEA) DUE TO FLARES AND NUCLEAR EXPLOSIONS

Pierce [*13*] deduced attenuation coefficients for propagation in sudden ionospheric disturbance (SID) conditions from records of atmospheric noise for the frequency range of 3.5 to 50 kc/s. Comparing these with the values under normal daytime circumstances, he found that the advent of an SID implies little change in attenuation between about 12 and 20 kc/s; above this range there is a decrease in the attenuation coefficients and below 12 kc/s there is a more marked increase. He suggested the use of a recorder based on changes in the relative intensities of atmospheric noise on 35 kc/s and 9 kc/s to discriminate between source effects independent of the SID and propagation influences solely attributable to the SID. Later he improved the recorder to indicate the intensity ratio of 35 kc/s to 6 kc/s to obtain satisfactory results.

On the occasion of a nuclear explosion at Johnston Island on 9 July 1962, SEA phenomena were observed at Toyokawa and at Hiraiso Stations. At Toyokawa 27 kc/s noise suddenly increased 0.5 dB and 21 kc/s noise 3.5 dB above normal values, at the moment of explosion, while 10 kc/s noise decreased 2 dB; these indicate that the explosion generated remarkable SEA phenomena. At that time Kamada [*14*] found 150 % increase of electron density in the D layer. At Hiraiso, frequency spectra (1–100 kc/s) were taken and the lowest observable frequency suddenly increased from 3 to 6 kc/s at the instant of explosion.

This explosion also generated a remarkable variation in the intensity and phase of VLF received signals at Bagneux, France, as reported by Decaux [*15*]. Except for waves from Rugby (GBR), they were propagated almost entirely through the ionosphere; on 9 July their phase indicated an advance corresponding to the lowering of the reflecting D layer, and a decrease of propagation time of about 10 μs for NAA (14.7 kc/s, Cutler, Maine) and for NPG (18.6 kc/s, Jim Creek, Washington), and 35 μs for NBA (18 kc/s, Balboa, Panama), while a retardation of 18 μs occurred for GBR (16 kc/s, Rugby, England). At Issy-les-Moulineaux the amplitude of NBA increased corresponding to each phase advance. Decaux tried several explanations of these phenomena, but he postponed the conclusion for future study.

During this nuclear explosion Zmuda *et al.* [*16*] observed the following perturbation on the relative phase of three frequency-stabilized VLF transmissions on propagation paths shielded by the earth from the direct effects of the explosion. The temporal variation of these three disturbances differed in major respects. On the NPG (Jim Creek, Washington) to APL* (Silver Spring, Maryland) path, the onset and maximum were essentially instantaneous, a characteristic which generally fits the burst-related neutron-decay model of Crain and Tamarkin [*17*] in which sudden ionization in the ionospheric D region is produced by neutron-decay electrons geomagnetically guided into the lower ionosphere. In addition, the NPG–APL variation shows a secondary perturbation having a 10-second period and stemming from a hydromagnetic disturbance associated with temporarily trapped neutron-decay protons of 0.4 MeV. In contrast to the NPG–APL perturbation, and among other differences, the perturbations to the transmissions from NBA (Balboa, Panama) and WWVL (Boulder, Colorado) are marked by a delay in the onset and maximum. The disturbance observed for the NBA–APL path, which lies almost along a geomagnetic meridian, resulted from ionization of the lower ionosphere by electrons that were produced in the radioactive decay of fission fragments and that formed an artificial radiation belt. Here there is good qualitative agreement between the temporal variation of the VLF perturbation and the energy obtained in the stream of trapped fission-decay electrons drifting azimuthally from the burst region over Johnston Island to the NBA area. The temporal VLF phase variation for the WWVL–APL path (which lies along a line of nearly constant geomagnetic latitude) indicates that the major part of this perturbation is due to ionization resulting

---

* Applied Physics Laboratory of Johns Hopkins University.

from the effects of geomagnetically trapped neutron-decay electrons. A relatively early and small part of this disturbance also results from the contribution of trapped fission-decay electrons.

REFERENCES

1. H. Ishikawa, *Proc. Res. Inst. Atmospherics, Nagoya Univ.*, 8A (1961).
2. M. Takagi, *ibid.*, 8B (1961).
3. T. Takeuti, *ibid.*, 9 (1962) 1.
4. S. Kitagawa (private communication).
5. M. Takagi and T. Takeuti, *Proc. Res. Inst. Atmospherics, Nagoya Univ.*, 10 (1963) 1.
6. F. Horner, *J. Atmos. Terrest. Phys.*, 21 (1961) 13.
7. F. Horner and P. A. Bradley, *J. Atmos. Terrest. Phys.*, 26 (1964) 1155.
8. A. D. Watt, *J. Res. Natl. Bur. Std.*, 64D (1960) 425.
9. D. J. Malan, in: *Recent Advances in Atmospheric Electricity*, edited by L. G. Smith, Pergamon, Oxford 1958, p. 557.
10. W. L. Taylor, *J. Res. Natl. Bur. Std.*, 64D (1960) 349.
11. A. G. Jean, A. C. Murphy, J. R. Wait and D. F. Wasmundt, *ibid.*, 65D (1961) 475.
12. F. Hepburn, *J. Atmos. Terrest. Phys.*, 19 (1960) 37.
13. E. T. Pierce, *J. Res. Natl. Bur. Std.*, 65D (1961) 543.
14. T. Kamada, *Bull. Res. Inst. Atmospherics, Nagoya Univ.*, 13 (1963) 7.
15. B. Decaux, *Compt. Rend.*, 256 (1963) 481.
16. A. J. Zmuda, B. W. Shaw and C. R. Haave, *J. Geophys. Res.*, 68 (1963) 745.
17. C. M. Crain and P. Tamarkin, *J. Geophys. Res.*, 66 (1961) 35.

A POSSIBLE LIGHTNING MECHANISM AS ORIGIN OF AN ELF RADIO WAVE

H. ISHIKAWA

Research Institute of Atmospherics, Nagoya University (Japan)

In the problem of identifying the source of ELF radio-waves we have observational evidence that some of the ELF noise of terrestrial origin comes from lightning discharges. Simultaneous ELF recording at two well-separated field sites gave us oscillatory ELF components and the corresponding ordinary short range atmospherics, respectively. The frequency range of each ELF waveform was distributed somewhere between 10 to 30 c/s, and the number of oscillations on each of them was somewhere between 5 and 15. If we consider the separation of the two sites, of the order of 1000 km, and the occurrence rate of atmospherics, one in each successive 5 minute period, it is reasonable to suppose that they originated from some discharge mechanism characterizing the lightning. We have not yet sufficient experimental evidence on this point, but a possible discharge mechanism that radiates an oscillatory ELF component could be found in the continuous process involved in a lightning discharge, that is, the process that produces a slowly-varying continuous luminosity. It was difficult to record the luminosity variation in every thunderstorm at night. However, when we succeeded in recording it, continuous variation could be found both in a cloud discharge and in a ground discharge. The estimated quasi-frequency of the luminosity variation was about 14 c/s, and the maximum number of cycles about 4. These results, therefore, even though very rough, seem to explain the source mechanism of some ELF phenomena.

Further measurements using extended baselines by international collaboration are required to confirm these results.

SUDDEN ENHANCEMENTS OF ATMOSPHERICS ON FREQUENCIES BETWEEN 10 AND 30 kc/s

T. KAMADA
Geophysical Institute, University of Tokyo (Japan)

From many statistical results, the correlations between solar flares, solar radio outbursts and sudden enhancements of atmospherics (SEA) on a frequency of 27 kc/s are very good. It is generally accepted that an SEA (at 27 kc/s) occurs as a result of enhancement of the electron density in the D region, caused by the abnormal increase of X-ray radiation from the solar flare. Four basic types of change in atmospherics during an SEA have been found, using the results for five years. These differ in the relative changes in noise at 10, 21, and 27 kc/s. Generally the noise decreases at 10 kc/s and increases at the higher frequencies. Simple models to explain the occurrence of the four types have been deduced by using the wave-guide mode theory of Wait.

The abnormal increase in noise at 27 kc/s due to a high altitude nuclear explosion in 1958, reported by Dr. Kimpara, is the most important of all abnormal variations. Later, in 1962, the same phenomenon was studied by T. Kamada. Applying the wave-guide mode theory to the results, the author has estimated the extent of disturbances in the lower ionosphere. The electron density in the D region was increased by about 1.5 times and the height of the layer reduced by about 5 km.

DISCUSSION

There was some evidence for differences in spectra of atmospherics in different parts of the world. Some measurements indicated proportionately greater energy at VLF, compared with HF, in the tropics than in temperate regions *(F. Horner)*. The spectrum might also be quite different for the first stroke of a multiple ground discharge than for subsequent strokes. It has been stated that the current surge is more rapid in subsequent strokes owing to the previous ionisation of the channel *(D. Müller-Hillebrand)*. However the length of the channel must also be taken into consideration and some reasonable models for the first and subsequent strokes have been found to have similar spectra except at frequencies well below 10 kc/s *(E. T. Pierce)*. Experimental evidence also suggests that there is no marked systematic difference in either the amplitudes or the spectra, in the VLF range, between first and subsequent strokes. Neither did the subsequent strokes appear to contain greater HF energy *(F. Horner)*. It was suggested that slow rates of rise of current in first strokes which had been observed in Switzerland might result from the development of leaders in an upward direction *(M. M. Newman)*.

Variations in mean spectra in different parts of the world might also be related to different relative numbers of cloud and ground discharges. There could be very large variations in one location, for example in Sweden one storm was said to have had 780 cloud discharges and only 5 ground discharges, but over a long period the cloud discharges exceeded those to ground by a factor of only 2.2 *(D. Müller-Hillebrand)*. Typically the proportion of discharges striking the ground (R) appeared to depend on the latitude λ according to the formula *(E. T. Pierce)*

$$R = 0.1 + 0.25 \sin \lambda.$$

When the ELF energy in an atmospheric is being considered, the whole of the discharge must be examined. It was suggested that as there is a tendency for successive return strokes in multiple discharges to occur at intervals of about 40 ms, though with considerable variation, this might lead to a broad peak of noise in the range 10–40 c/s *(E. T. Pierce)*.

A summary was given of some radiation phenomena accompanying high-altitude nuclear explosions *(E. T. Pierce)*. The X-ray radiation resulted in ionization at a height of about 70 km; gamma rays penetrated to about 30 km, there producing short-lived ionization. Electrons produced by neutron-decay could have prompt effects even at points remote from the explosion, but the influence of those occurring in fission debris was initially more local. However the electrons became trapped in the earth's magnetic field and then presumably drifted longitudinally round the earth, occasionally losing energy in the production of ionization at about 70 km. The enhanced ionization at this height, produced either by X-rays or by electrons, led to the changes in atmospheric noise, and also in VLF signals.

SESSION ON IGY RESULTS AND IQSY PROGRAMMES

REVIEW OF IGY RESULTS AND IQSY PROGRAMME ON ATMOSPHERIC NOISE

F. HORNER

D.S.I.R. Radio Research Station, Slough, Bucks (U.K.)

SUMMARY

Topics for study in the IGY programme included the measurement of various characteristics of atmospheric noise and their correlation with ionospheric variations, the study of VLF propagation by recording atmospheric waveforms, and the use of lightning flash counters. The IQSY is likely to involve increased effort in the recording of VLF and ELF integrated noise. Some planned experiments involving measurements of noise in satellites may take place within the IQSY period, and consideration should be given to the need for an adequate supporting programme of ground observations.

RÉSUMÉ

Les sujets à étudier d'après le programme de l'AGI comprenaient la mesure de différentes caractéristiques des bruits atmosphériques et leur corrélation avec les variations ionosphériques, l'étude de la propagation des très basses fréquences par enregistrement de la forme des atmosphériques et par l'emploi de compteurs d'éclairs. Il est probable que le programme de l'AISC prévoira une augmentation de l'effort pour l'enregistrement du bruit intégré des très basses et extrêmement basses fréquences. Certaines expériences englobant des mesures du bruit par satellites peuvent avoir lieu au cours de la période de l'AISC et il conviendrait alors de considérer la nécessité d'un programme conjoint d'observations au sol.

1. SCOPE OF REVIEW

Investigations covered in this review include those designed to measure and describe the characteristics of noise and those in which the primary aim is to use noise records for the study of ionospheric properties and radio propagation in the space between the earth and the ionosphere. The study of whistlers, ionospheric noise, and the nature of the source are not included, since they are being dealt with elsewhere.

2. IGY RESULTS

2.1. *Measurement of Characteristics of Noise*

The main effect of the IGY in the field of noise measurement was an increase in the number of stations, coupled with the introduction of new and more standardized methods in the measurements and in the presentation of the results. Some of the programmes have continued since the IGY and it is neither practicable nor desirable to attempt to differentiate rigidly between the actual IGY programme, the IGC programme and subsequent activities. Few if any of the investigations were intended to relate specifically to sunspot maximum conditions, but the continuing programmes, when extended through the IQSY, may reveal significant solar cycle effects.

IGY results on the general level of noise exist mainly in the form of data on noise power, amplitude probability distributions and, when appropriate, numbers of atmospherics per unit time. Many of the results have been given wide circulation in the form of either published papers or specific compilations of data [*1–8*]. Catalogues of records held in the world data centres have been published but the atmospheric noise records are rather incomplete, and it seems unlikely that much use will be made of them, in view of the wide circulation of data through other channels.

An immediate application of the accumulated data has been to problems of interference to radio communications. This aspect has been given close attention under the auspices of the International Radio Consultative Committee (CCIR) and a new report has been prepared which gives not only information on the world distribution of noise power, but also those details of the noise structure which are needed in assessing the required signal to noise ratios for a satisfactory radio service. The more urgent needs of the communication circuit designers have thus been met, although there is a continuing need for additional measurements at existing and new stations, to improve the accuracy of the data. There are, however, some problems for which new types of scientific information are required. For example there are conflicting reports on the characteristics of the noise to be expected when highly-directional receiving aerials are used; improvements are required in the methods by which the details of the world distribution of noise are filled in, from measurements at a few stations; estimates of the variations of noise in polar regions are still rather speculative; and the suggestion that the noise from tornadoes differs in kind from that from ordinary thunderstorms needs to be verified. Advances on these topics require a better understanding of the properties and distribution of noise sources. As a result of the IGY and subsequent programmes much of the noise data needed for such studies are available, but there appear to have been few attempts to determine whether the observed values are in quantitative agreement with what could be expected from a knowledge of the source distributions and of propagation factors.

The IGY results also contain much information on the amplitude probability distributions of noise [*7*, *8*, *9*, *10*]. The variations in these distributions from one station to another, at any given frequency, are not large, and it has been found possible to present the main features in summarised form to an accuracy sufficient for use in communications problems.

The IGY provided opportunities for measurements of the same parameter to be made, in close proximity, by different methods and equipment. Comparisons between the results suggest that measurements of noise power can be made in general to an accuracy of one or two decibels, the residual errors probably being in the absolute calibrations.

A disappointing feature of the IGY results has been the scarcity of reliable data from polar regions. There were two contributory factors. The first was that the general service equipment used by scientific expeditions tended to be electrically noisy, and the severe climatic conditions precluded the operation of the noise measuring sets far from the main camp. The second was that the measurements were not always made by individuals to whom the noise investigation was of primary interest; otherwise some of the inevitable difficulties might have been overcome. This lack of success is unfortunate because the diurnal and seasonal variations in the noise are likely to be quite different from those at lower latitudes. The results would also be of practical interest since the low noise levels should make it possible to receive signals of correspondingly low field strength, if man-made noise could be avoided.

2.2. *Recording of VLF Noise*

Noise measurements at 27 kc/s have long been used to detect disturbed ionospheric conditions and, by observing sunrise and sunset effects, to measure the height and diurnal changes in the D region. The technique is continuing to provide useful information on both the normal and the disturbed ionosphere and on the distribution of noise sources [*11*, *12*, *13*]. This type of measurement was part of the IGY programme for meteorology. The diurnal characteristics in Japan have been found to be different from those in Europe and the parameters recommended for reporting on the form of these variations, during the IGY, were not entirely appropriate for Japanese results [*14*].

2.3. *Recording of Waveforms*

During the IGY, attempts to organise programmes of simultaneous recording of waveforms, which had been an aim of Commission IV for many years, met with success. The resulting data on the variations of the frequency spectrum with distance provided new information on VLF propagation. Additional confirmation of the poor propagation characteristics in the region of 2–4 kc/s was obtained, and observed differences in propagation in east–west and west–east directions supported theoretical work on the subject [*15*]. The frequency for minimum attenuation has been found to lie in the range 7–20 kc/s, depending on direction of propagation and on time. There appears to be some divergence of opinion on what the lower limit for this range should be.

2.4. *Location of Sources of Atmospherics*

Meteorological services have been responsible for making regular observations of sources of atmospherics, mainly by direction-finding techniques. The results are available in the meteorological data centres, and in the U.S.S.R. some use of them has been made by deducing maps showing contours of equal frequency of lightning occurrence. In principle the data can be used to assist in the preparation of noise charts, but no attempt appears to have been made to investigate the possibilities.

2.5. *Local Lightning Flash Counters*

Records of the incidence of local lightning have been made at a number of places, widely dispersed though not world-wide. Most stations were equipped with one of two types of counter, one being of the design described in the

IGY Annals and the other a design widely adopted by power engineers with the intention of counting ground strokes only. Although there is considerable controversy on the interpretation of the records in absolute terms, for example in deriving the number of discharges per unit time and per unit area of the earth's surface, the continuation of the observations over several years with the same instruments may well indicate long-term variations in the incidence of thunderstorms.

2.6. *General Comments on IGY Programme*

The IGY programme of noise measurements was somewhat late in starting and did not yield as much reliable quantitative information as had been hoped. Nevertheless, considering the previous lack of standardization of techniques, and the newness of some of those introduced for the IGY, a satisfactory start was made and the continuing programme has yielded data of both practical value and scientific interest.

3. IQSY PROGRAMME

The types of atmospheric noise measurement to be made during the IQSY follow substantially the lines laid down for the IGY and no significant changes appear to be necessary in the recommendations on techniques to be used, as published in the *Annals of the IGY*, Part IV. It is difficult to obtain a clear picture of the entire programme on noise and related subjects, for the following reasons:

(a) Some countries have not yet announced their programmes, and others have given only brief outlines.

(b) The published programmes do not, in many instances, include long-term measurement programmes which are known to be continuing. Presumably they are not regarded as part of a special IQSY effort.

(c) Certain topics on the borderline of meteorology and ionospheric physics have been reported under different headings by different countries.

Nevertheless it is possible, from the summaries in *IQSY Notes*, to give an approximate indication of the total programme and this is done in the following paragraphs.

Headings have been chosen to subdivide the work, but they have no formal status, and there is overlap between some of them.

3.1. *Direct Measurements of Noise Power*

This category is represented mainly by the network of stations using the American CRPL recorder, a long-term programme in which several countries are participating. No enhanced programme appears to be planned for the IQSY.

3.2. *Detailed Characteristics of the Noise Structure, including Amplitude Probability Distributions*

The main centres of activity for this work will be in the U.S.S.R., Eastern European countries and Japan, but the CRPL network gives limited information on the topic by measuring more than one parameter. The European work includes tape-recording of noise during expeditions to low latitudes, the analysis to be completed later.

3.3. *Diurnal and other Characteristics of Noise at Low Frequencies and below*

There will be a continuing programme of recording on 27 kc/s, the frequency most commonly used for the purpose, and also on other frequencies in the VLF and LF ranges. The objective is to study ionospheric phenomena by examining particularly the diurnal variations and special events. The IQSY will provide an opportunity for observing the characteristics widely under quiet conditions. Eastern European countries have planned a strong programme, including measurements in Arctic and Antarctic regions, and France, India, Japan, Spain and the United States will also be active. The Japanese plans include the measurement of noise on rockets at heights up to 800 km.

Many workers previously involved in VLF measurements are now extending their interests to ELF, down to about 1 c/s, where atmospheric noise phenomena merge with those known as micropulsations. France, Germany, Hungary, Japan, the United Kingdom and the United States will be studying this part of the spectrum.

3.4. *Waveforms of Atmospherics*

Simultaneous observations of low-frequency waveforms of atmospherics at several stations during the IGY provided useful data on propagation at these frequencies. It seems unlikely that there will be corresponding measurements on the same scale during the IQSY, although Hungary and the United Kingdom have relevant items on the programme. Some of the workers previously recording waveforms are now studying ELF noise, and simultaneous measurements at several stations, in this frequency range, would be useful for propagation studies.

3.5. *Other Measurements*

Routine location of sources will be continued through the IQSY, mainly as part of national meteorological services, and some countries have listed this item specifically in their programmes. A number of countries will be continuing to use counters for estimating the number of lightning flashes occurring locally.

4. GENERAL COMMENTS ON IQSY PROGRAMME

On the whole, the characteristics of atmospheric noise may be expected to be less dependent on solar cycle variations than are many other phenomena. Ways in which there may be an influence are:

(a) the total amount of thunderstorm activity or its distribution may vary;

(b) the properties of the lightning discharges may change;

(c) ionospheric propagation will certainly vary;

(d) changes in noise caused by disturbed ionospheric conditions will vary in their frequency of occurrence.

One possible result of these factors is a change in the received noise power at a given station. If a single source and a single receiving station are considered, changes in ionospheric conditions will undoubtedly lead to changes in the high frequency noise. The changes may not be obvious however if, for example, a decrease in noise from one source is more-or-less compensated by an increase in noise from another. The largest change is likely to occur in places where a normally high atmospheric noise level is, by a decrease in critical frequencies, replaced by a much smaller galactic noise level. The difference will probably be marked only near the tropical thunderstorm areas, and even then the noise received by ground-wave propagation from near storms will tend to obscure the changes in the ionospherically-propagated noise.

Any solar cycle variations of the type described should become evident by examination of the results of the long-term survey of noise power. No such effects have yet been reported, but the extension of the programme through the IQSY will improve the chances of their detection. In addition to the possible changes in high frequency noise, the low frequency results can be compared with those of some early work in which a 7 dB sunspot variation in low frequency noise was observed. The continued recording of noise on 27 kc/s and other low frequencies may reveal such changes.

Whatever the changes in the received noise power, it would be useful to determine whether there are any significant changes in the noise generated. Unfortunately there have been few systematic measurements of the incidence of lightning over the period since the IGY, but observations could be extended for the IQSY with the intention of studying the effects of subsequent increases in solar activity. Two approaches to this problem are possible. The first is to increase the number of lightning flash counters, with the object of deducing the density of the discharges. The second involves the measurement of ELF noise, which has been said to be a measure of world-wide thunderstorm activity.

5. MEASUREMENT OF ATMOSPHERIC NOISE BY USE OF SATELLITES

With the increasing activity on space research, the time is opportune for a consideration of the possible use of rockets and satellites in furtherance of research on atmospheric noise. Some rocket experiments designed for atmospheric noise measurements have been flown, although the results are not yet generally available, and the IQSY programme of Japan includes further rocket flights. Some satellite experiments, such as those in Lofti I [*16*], Lofti IIa and Alouette have provided information about noise from terrestrial storms and a number of organizations have under consideration satellite experiments specially designed for the purpose. These would operate at various frequencies from the VLF to the UHF range, and estimates of the expected noise amplitudes and other characteristics have been based largely on the work of the past few years on the energy levels and numbers of lightning discharges. Although it is unlikely that the experiments will be flown before the end of the IQSY, they may possibly come to fruition soon afterwards, and before the next General Assembly of URSI. Apart from the design of the experiments themselves, there will be a need to discuss the ground facilities such as thunderstorm-locating networks which will be required to obtain the maximum value from the satellite data.

REFERENCES

1. Science Council of Japan, *Data on Atmospherics, Whistlers and Solar Radio Emissions,*
   Vol. 1, 1957
   Vol. 2, 1959 IGY Data
   Vol. 3, 1959
   Vol. 4, 1960 IGC Data
   Vol. 5, 1960
   Vol. 6, 1961
   Vol. 7, 1961 Post IGC Data
   Vol. 8, 1962
2. Science Council of Japan, *Compilation of data in Japan for Atmospheric Radio Noise during the IGY 1957/8,* 1960.
3. Science Council of Japan, *Series on Japanese contribution to the IGY and the IGC,* Vol. 1 (1958)–Vol. 4 (1962).
4. W. Q. Crichlow, R. T. Disney and M. A. Jenkins, *Natl. Bur. Std. Tech. Notes,* Nos. 18–1 to 18–16 (1959–63). Quarterly Radio Noise Data.
5. Centre National de la Recherche Scientifique, *AGI—Participation Française, Sér. V: Ionosphère,*
   Fasc. 2, Niveau moyen et radiogoniométrie des atmosphériques.
   Fasc. 3, Dépouillement des enregistrements radiogoniométriques d'atmosphériques.
6. J. Lugeon, A. Junod, P. Wasserfallen and J. Rieker, *Mesures des Parasites Atmosphériques d'Électricité Atmosphérique et de Radioactivité de l'Air à Murchison Bay (Spitsberg), Payerne et Zurich,* Institut Suisse de Météorologie, 1960.
7. Y. I. Likhter and G. I. Terina, Some results of the investigation of the intensity of atmospheric radio noise at Moscow, in: *Some Ionospheric results obtained during the IGY,* edited by W. J. G. Beynon, Elsevier, Amsterdam, 1960, p. 376.
8. C. Clarke, Atmospheric radio-noise studies based on amplitude-probability measurements at Slough, England, during the IGY, *Proc. IEE (London),* B109 (1962) 393–404.
9. T. Nakai, A study of atmospheric noise at 50 kc/s, *Proc. Res. Inst. Atmos., Nagoya Univ.,* 6 (1959) 22–37.
10. T. Nakai, The study of the amplitude probability distributions of atmospheric radio noise, *ibid.,* 7 (1960) 12–27.
11. T. Kamada, Statistical properties of the sudden enhancement of atmospherics in the VLF range, *ibid.,* 7 (1960) 28–39.
12. R. Lauber and E. A. Lauter, Variation of atmospheric noise (27 kc/s) during the summer over central Europe, *Z. Meteorol.,* 16 (1962) 51–68.
13. E. T. Pierce, Attenuation coefficients for propagation at very low frequencies (VLF) during a sudden ionospheric disturbance (SID), *J. Res. Natl. Bur. Std.,* 65D (1961) 543–546.
14. A. Kimpara and Y. Kimura, On field intensity recording of atmospherics at 27 kc/s in accordance with the recommendation of WMO, *Proc. Res. Inst. Atmos., Nagoya Univ.,* 5 (1958) 21–29.

15. W. L. Taylor, Daytime attenuation rates in the very low frequency band using atmospherics, *J. Res. Natl. Bur. Std.*, 64D (1960) 349–355.
16. J. P. Leiphart, R. W. Zeek, L. S. Bearce and E. Toth, Penetration of the ionosphere by very-low-frequency radio signals. Interim results of the Lofti I experiment, *Proc. IRE*, 50 (1962) 6–17.

DAILY VARIATIONS OF ATMOSPHERIC NOISE LEVEL AT VLF

E. A. LAUTER
Observatorium für Ionosphärenforschung, Kühlungsborn (Germany)

The characteristics of the daily variation of atmospheric noise level at VLF can be interpreted mainly as a result of varying propagation conditions between the great quasi-permanent thunderstorm areas and the point of observation and as an effect of the daily variations of the intensity of the sources themselves. Besides the statistics needed for radio-interference, there are requirements in ionospheric and meteorological work for a description of the principal parameters of noise and of the factors which determine its geographical distribution. They include sunrise effects for studying the behaviour of the lower ionosphere; night-time to daytime ratios for studying sunspot-cycle effects in the lower parts of the D region; VLF propagation losses in the D region, the night-time E region and when crossing the twilight zones; effects of high energy radiation at high latitudes; SEA effects due to natural X-ray radiation and nuclear explosions; research on the contribution from specific thunderstorm areas at various times of the day and the influence of special meteorological conditions when nearby sources have to be taken into account.

[Professor Lauter then showed results illustrating these various effects. Diurnal curves of received noise in different seasons at 27 and 40 kc/s were interpreted in terms of sources and varying propagation conditions. During the day, D region propagation is important and at night E region propagation predominates. Propagation losses were estimated to be 3 to 4 dB per 1000 km when D region propagation was good, near noon, and 7 to 9 dB per 1000 km when the path crossed the dawn zone. Noise at 27 kc/s was strongly dependent on UT, indicating the influence of the sources. Diurnal maxima in received energy could occur in the daytime in the Arctic and at night in the Antarctic. At high latitudes the effect on propagation of incoming energetic particles could be detected.

It was important to record the variations in the source intensities, for which purpose a network of flash counters was needed. A knowledge was required of the contribution of distant sources to the noise at 27 kc/s.]

FREQUENCY VARIATIONS OF ATMOSPHERIC RADIO NOISE INTENSITY AT LOW FREQUENCIES ON THE OCEAN AND ON LAND

Y. I. LIKHTER and G. I. TERINA
IZMIRAN, Moscow (U.S.S.R.)

It is known that the investigation of the spectra of atmospherics allows important conclusions to be drawn about the propagation characteristics of electromagnetic waves of low and very low frequencies. Within this frequency range few radio-transmitters operate and lightning discharges, radiating high energy, are used to investigate experimentally the amplitude and phase characteristics of the field of very long radio waves propagating in the spherical waveguide bounded by the earth and the ionosphere. These investigations can deal with the electromagnetic radiation from separate lightning discharges when by one method or another it is possible to define the distance to the lightning and also to investigate the initial spectrum of the source.

In investigating the intensity of atmospheric noise, an integrated field is measured, caused by electromagnetic radiation from many lightning discharges, situated at different distances and in different directions from the recording point. As a result, the influence of propagation conditions on the measurements is usually disguised to a large extent. It is known that the most noticeable propagation effects lie in the diurnal variations in intensity (for instance, the morning minimum and the night maximum); however even then it is difficult to distinguish clearly the propagation effects, because during the day the storm activity also changes.

In 1961, during the passage of the expedition ship "Vityaz" through the Pacific Ocean, one of us measured the statistical properties of atmospheric noise at frequencies of 3–100 kc/s. The method of measurement has been given in reference [*1*]. Analysing the values of the noise intensity measured on the ocean, it was found that the propagation conditions substantially influenced the character of the variations with frequency.

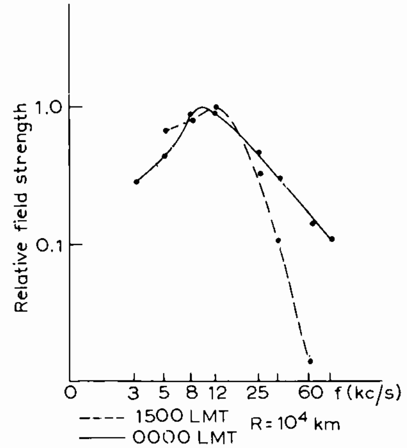

Fig. 1. Frequency variations measured in the central part of the Pacific in October 1961.

Fig. 1 shows the frequency variations measured in the central part of the Pacific (near the equator and longitude 155°W) in October 1961. The intensity at 1500 LMT decreases with increase in frequency much more rapidly than at night. From a chart of the storm distribution for October [2] it is possible to deduce that over this period the distances to the storm

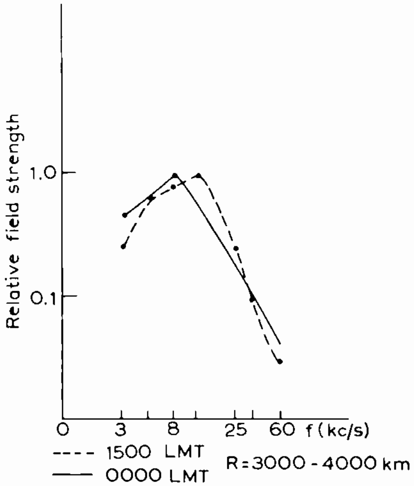

Fig. 2. Data obtained in August–September 1961 during the passage Vladivostok to Honolulu.

sources (the central part of South America and the Indonesian Islands) were about 10,000 km. It was also found that when the ship was nearer to the possible sources of noise, the difference in steepness of the frequency variation curves at night and by day decreases. Fig. 2 represents data, obtained in August–September 1961 during the passage from Vladivostok to the port of Honolulu. This shows the data obtained on the outward journey, in the South-Eastern direction, during which time the distance to the shore was increasing. It is difficult therefore to define the exact distance, but it was estimated to be 3000–4000 km. It is clear that in this case the contribution of the comparatively nearer sources was greater.

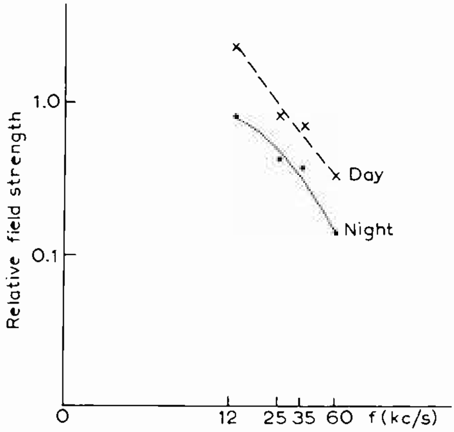

Fig. 3. Data obtained in Moscow in summer 1959.

It is instructive to compare these results, measured on the ocean, with similar data taken on land. Fig. 3 shows data taken in Moscow in summer. The afternoon curve is higher than that for night and the curves have the same slope. Probably this can be attributed to the nature of the storm distribution over land; after midday a significant proportion of the storms are near the measurement point, and at the same time the remote storms also give a substantial contribution. As a result it can be considered that the storms are distributed all over the area surrounding the point where the measurement is made.

Considering other results on land, in winter the difference in the frequency variation of the noise intensity at night and by day becomes more marked. Fig. 4 gives the results of measurements at 1500 in Moscow on February 25th

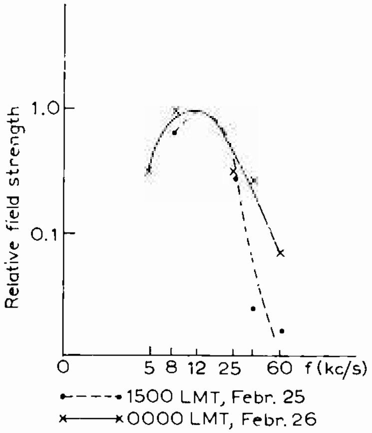

Fig. 4. Results of measurements at 1500 in Moscow on February 25th and at 0000 on February 26th, 1963.

and at 0000 on February 26th, 1963. From the data from a cathode ray direction finder network the storms at that time were, from Moscow, on the 25th from 2500 km to 4000 km, and on the 26th from 2000 km to 3000 km. When data are averaged over a longer period of time, the difference in frequency variation is partly smoothed out (Fig. 5).

These effects are also noticeable in the diurnal variations of noise intensity on the oceans at different frequencies. It is known that in summer

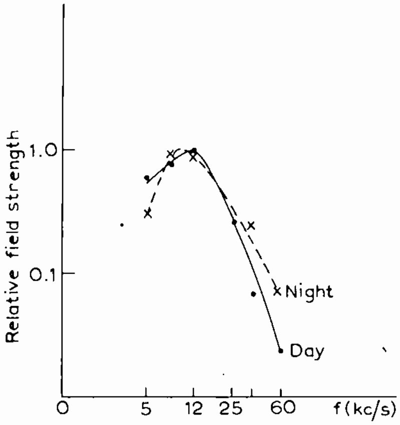

Fig. 5. Data obtained in Moscow in winter 1962–1963.

on land, during the afternoon, a maximum of the noise intensity is apparent. Usually this maximum exceeds the level at night. While the night maximum is explained by the improvement of the propagation conditions, the afternoon maximum is connected with the increase in local storms. This afternoon maximum is observed over the whole range of frequencies 3 to 100 kc/s, and depending on the season it appears and disappears simultaneously at all the frequencies.

On the oceans it was often found that the afternoon maximum, being rather clearly seen at very low frequencies (12 kc/s), became less clear as the frequency was raised and disappeared almost completely at a frequency of 60 kc/s.

A smaller change in intensity with frequency at night compared with that by day, as well as the general rise of the night intensities at all frequencies, can be explained by the fact that at night the absorption of radiowaves in the earth–ionosphere waveguide is less than by day. Moreover the geometrical properties of the waveguide at night and by day are different – at night its height is greater than by day. This brings a change in the wave structure which forms the field at the reception point. A displacement of the maximum in the frequency curves (at night this maximum is at lower frequencies), can probably be explained by this circumstance.

It is evident from our results that the effects investigated are much more pronounced in the data measured on the ocean. Probably this is favoured by the fact that over the oceans thunderstorms occur more seldom than over land [*2*, *3*]. During measurements on the ocean the sources of noise are nearly always located a long way from the ship and so there is little contribution to the noise intensity from local storms.

In conclusion, the different frequency variation of the atmospheric noise intensity over the oceans and over land is not taken into account in the noise data (Report No. 65) of the CCIR. It should be allowed for in any future revision of this report.

REFERENCES

1. Y. I. Likhter, A. G. Nalivaiko, V. L. Rosin, G. I. Terina and D. S. Shevchenko, Measurements of atmospheric radio noise in the U.S.S.R. during the IGY, *Ionospheric Investigations,* No. 10, Academy of Sciences of the U.S.S.R., Moscow, 1962.
2. World Distribution of Thunderstorm Days, Pt. 2, *Tables of Marine Data and World Maps WMO,* No. 21, Organis. Météorol. Mond., Geneva, 1956.
3. H. C. Krumm, Der weltzeitliche Tagesgang der Gewitterhäufigkeit, *Z. Geophys., Deut.,* 28 (1962) (2) 33.

SOME EXPERIMENTAL RESULTS FROM LIGHTNING FLASH COUNTERS

D. MÜLLER-HILLEBRAND*
Uppsala University (Sweden)

In his report, Horner has suggested that observations with lightning counters continued over several years will indicate long-term variations in the incidence of thunderstorms. Results have been obtained in Sweden over a period of 5 years. It is also important to verify the counting operation by independent methods. For a control in the observations of near storms, i.e. to about 20 km, a mobile field station was built, with facilities for recording the electric field and the field change with different sensitivities and different velocities of the time sweeps of the cathode ray oscilloscopes; seven oscilloscopes were used. In addition a field mill was used for recording the electrostatic field. The time base velocities were 8 cm/100 ms and 8 cm/0.5 ms for the oscilloscopes and 2 cm/min for the field mill. Several lightning counters of different designs and sensitivities were in operation; every count was registered on paper. Amongst other observations two kinds of counter were studied particularly:

(a) A "CCIR" counter with 4 different sensitivities (3 V/m to 20 V/m). Maximum sensitivity at 10 kc/s; −3 dB points at 2.4 and 32 kc/s.

(b) The electrostatic counter based on the proposals of Pierce. A commercially made model was used, with some alterations. Maximum sensitivity at 0.5 kc/s; −3 dB points at 0.2 and 1.8 kc/s. Only one polarity of the field change was effective. Four sensitivities were used; 2.5, 5, 10, and 20 V/m. A standard sensitivity of 5 V/m was adopted for 140 stations in Sweden, 100 stations in Norway and 40 stations in Finland.

The CCIR counter gives a local index of lightning activity as a source of radio long-wave disturbances. The limits of the range can vary between

---

* Deceased.

wide limits. With near thunderstorms (up to 12 km) the counter is triggered to a greater extent by cloud-discharges than at larger distances. With multiple discharges, triggering is possible twice if the time difference between the first and the last strokes is of the order of magnitude of about 100 ms. It is not possible to get reliable information on lightning days; counts of 100–200 in 2 hours have occurred without thunderstorms nearer than 50 km. Diurnal

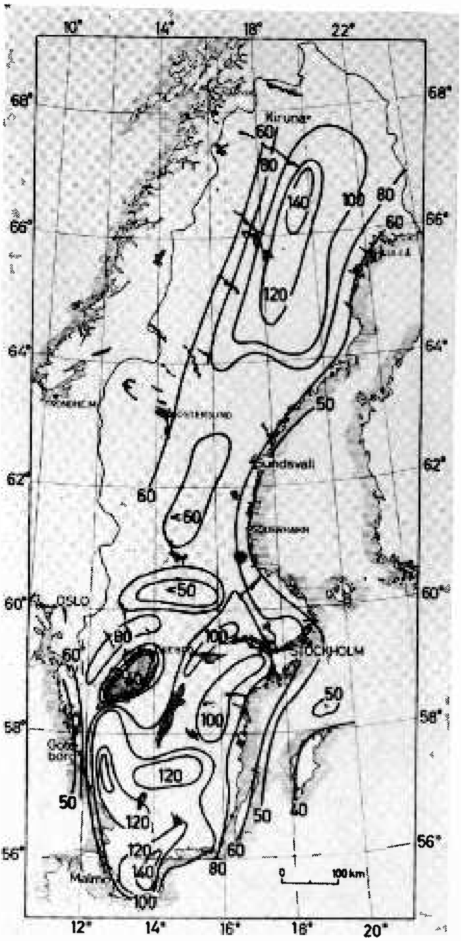

Fig. 1. Lightning density (number of flashes against earth per 100 km² per year), average values 1958–1962.

values of the lightning flash density (number of flashes per 100 km^2 per year) are also open to question.

The electrostatic counter has a rather limited effective range. According to our measurements the effective range for 5 V/m sensitivity is 12.5 km (effective area 500 km^2). The number of earth flashes in Sweden (with 2.2 times more cloud flashes than earth flashes) has been calculated as 70 % of

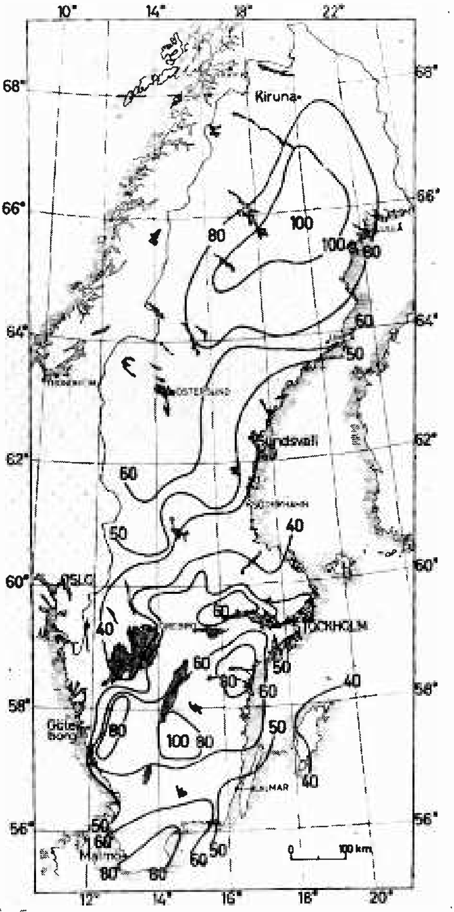

Fig. 2. Lightning intensity (number of flashes against earth per 100 km^2 and 10 lightning days), average values 1958–1962.

the number of counts. The 5-year average values of 140 stations in Sweden (Fig. 1) show a flash density of 30–150 flashes per 100 km^2 per year. The lightning intensity, defined as the number of flashes to earth per 100 km^2 and 10 lightning days, varies between 40 and 100 (Fig. 2). Most surprising was the discovery of a large area in the northern part of Sweden with violent frontal thunderstorm associated with warm air from Finland. Days with violent frontal lightning storms over a large part of Sweden occurred twice in 1959 (July), five times in 1960 (June, July and August) and eight times in 1961 (June and July), but there were none in 1962.

DISCUSSION

Further theoretical work has been done to explain the characteristics of noise at low frequencies. From reasoning based on the superposition of a number of elemental disturbances, with Poisson distributions, the two-dimensional amplitude probability distribution has been expressed in the form

$$P(R) = R \int_0^\infty J_0(\lambda R) \cdot f(\lambda) \cdot \lambda \, \mathrm{d}\lambda$$

where R is the instantaneous envelope voltage,

$P(R)$ is the amplitude probability density function,

λ is an amplitude parameter of the elemental pulse,

$f(\lambda)$ is a characteristic function of this pulse,

J_0 is the Bessel function of zero order.

The distribution has been calculated for conditions when local sources predominate and also for the more continuous type of noise from distant sources. Good agreement with experimental distributions has been claimed, and derived parameters such as the ratio of the r.m.s. to average voltages also agreed well. It was concluded that at Ohira, Japan, local sources were important at HF but negligible at VLF *(T. Ishida)*.

Poisson distributions of elementary idealised pulses have also been invoked to derive theoretical estimates of the average number of received pulses per second, their average duration, probability distributions of the pulse lengths and durations, and the probability that a given interval will be occupied by noise. This work has also been extended to the consideration of the interrelation between amplitude and crossing-rate probability distributions and of the dependence of each of these on bandwidth. Results were claimed to agree well with experimental data at the high voltage levels but agreement was less satisfactory at medium and low voltages *(T. Nakai)*.

The problems arising in the operation of lightning flash counters, and in the interpretation of the results were discussed. There was a conflict of opinion on the reliability of the parameters which could be derived, and there appeared to be real differences of experience in different locations. High counts observed on occasion at Boulder, Colorado, in the absence of local thunderstorms, were thought to result from precipitation static on the aerial in snow, rain and dust storms accompanied by high winds *(W. Q. Crichlow)*. The particular weather conditions at Boulder which led to the abnormal counts might be uncommon elsewhere. Use of an insulated aerial wire of small diameter would reduce the effect but a large plastic tube surrounding the aerial would provide a better solution, as the impact charges on the tube would then be further removed from the aerial itself. The plastic tube should have a slightly conducting surface, with resistance low enough to shield the aerial from corona effects in strong electrostatic fields, but high enough not to affect the more rapid field changes which were required to trigger the counter *(M. M. Newman)*. It was noted that loop aerials had been adopted for observing whistlers and hiss, and these might possibly have advantages for lightning counters.

The accuracy of the locations of thunderstorms by direction finders, particularly narrow-sector-recorders, had been studied by making comparisons with thunderstorm reports *(J. Lugeon)*. Errors of 5° to 20° could occur at ranges of a few hundred kilometres, but errors were smaller at long ranges, where a typical displacement would be 100 km at 6000 km. The measurement of directions of arrival at 27 kc/s was advocated, and it was generally agreed that recording amplitudes as well as the directions of atmospherics would be of great benefit to research. Even an indication of the threshold levels used in direction finding observations would be useful.

A substantial part of the IQSY programme would be the continuation of the noise measurements by the network sponsored by the CRPL (Central Radio Propagation Laboratory, National Bureau of Standards, Boulder). The relationship between the VLF measurements in this programme and the proposed continuous measurements on 27 kc/s by other workers was discussed. It appeared that some of the CRPL measurements, say at 50 kc/s, could be integrated with the general 27 kc/s programme, and used in the study of ionospheric and source effects, despite the difference in frequencies. The optimum frequency for the study of these effects was only broadly defined, and might be different by day and by night. The CRPL plans also included the tape recording of noise in three bandwidths, 20 c/s, 200 c/s and 2 kc/s with provision for extracting data on distributions of amplitudes, crossing rates and pulse durations, and also autocorrelation functions. A study of the occupancy of the frequency spectrum by both noise and transmitters would be made by using receivers sweeping slowly through the range 40 kc/s to 550 kc/s, or any part of this. This technique might also be applied at high frequencies *(W. Q. Crichlow)*.

A proposal discussed was that no attempt should be made to supply large quantities of IQSY data to the World Data Centres, but that these centres should contain summaries and complete catalogues of what detailed data were available. This change of procedure would ease the problem of preparing data for the centres, and individual workers would be able to exchange information directly, which appeared to be the most satisfactory arrangement. This proposal met with general approval.

SESSION ON WHISTLERS

WHISTLERS

G. McK. ALLCOCK

Physics and Engineering Laboratory, Lower Hutt (New Zealand)

SUMMARY

New developments in whistler research during 1960–63, notably those using satellites and man-made signals, are reviewed. Attention is drawn to gaps in our present knowledge of the relationship between whistler characteristics and solar and magnetic activity. Other aspects requiring further study include the calculation of transmission losses and the interpretation of low-latitude spectrograms.

RÉSUMÉ

L'auteur passe en revue les progrès réalisés dans les recherches sur les sifflements au cours de la période 1960–63, en particulier ceux concernant les signaux d'origine humaine et ceux émis par satellites. L'attention est attirée sur les lacunes de nos connaissances actuelles sur les relations entre les caractéristiques des sifflements et l'activité solaire et magnétique. D'autres questions nécessitent une étude plus approfondie, parmi lesquelles le calcul des pertes de transmission et l'interprétation des spectrogrammes de basses latitudes.

1. INTRODUCTION

This paper reports progress since the XIIIth General Assembly of URSI [*1*], emphasis being placed on new developments. Aspects of whistler research relating to guided waves and electron densities are treated in companion papers [*2*, *3*]. All latitudes quoted are geomagnetic latitudes.

2. TEMPORAL VARIATIONS IN WHISTLER DISPERSION

Further analyses of regular temporal variations in dispersion have been made for latitudes between 25° and 53° [*4–8*]. Diurnally, a maximum in local late afternoon or early evening, and a minimum in the early morning hours is found in all cases studied. At the December solstice the ratio of these dispersions decreases from 1.8 to 1.2 as the latitude increases, but at the June solstice the ratio appears to be independent of latitude (about 1.1).

For early morning observations during the IGY, a large annual variation was found at Stanford (44°N) and Port Lockroy (53°S) with dispersion in December about 50 % greater than in June. On the other hand, at Toyokawa (25°N) the variation was of similar magnitude, but of opposite phase. At the intermediate latitude of Wakkanai (35°N) a semi-annual variation was evident, with maxima at the equinoxes and minima at the solstices. The magnitude of this variation was, however, smaller, being about 10 %. A similar semi-annual variation found at Poitiers (50°N) suggests that the short whistlers received there normally travel along paths having equivalent latitudes as much as 10° lower than that of Poitiers. This has already been suggested by Rivault and Corcuff [*7*] and could arise from geomagnetic field distortion near the Capetown anomaly, together with the low-latitude nature of the sources. Variations of path latitude can be significant, as has been shown by Carpenter [*6*] from a study of nose time delays; almost one-half of the annual variation at Stanford is ascribed to this cause. There is also evidence that some of the month-to-month variations are related to variations in sunspot number for one month earlier [*9*, *10*].

Solar-cycle variations in dispersion are not yet clearly defined. Nose time delays at Stanford decreased by 20–25 % between 1958 and 1961 near the December solstice, but little change was found there or at Port Lockroy at the June solstice. At Wakkanai the dispersion decreased by about 15 % at all seasons during the same period, but no significant change is indicated by the Toyokawa data. There is no obvious relationship at any station with long-term variations in F-region parameters.

3. RELATIONSHIP TO GEOMAGNETIC PHENOMENA

3.1. *Occurrence Characteristics*

Several papers [*11–17*], together with some unpublished work by the author, give results from 23 stations ranging in latitude from 25° to 80°. Unfortunately, the data are not homogeneous; nevertheless, the following trends are indicated:

(i) During winter nights at middle and high latitudes, the level of whistler activity is a maximum for a certain magnetic *K*-index, whose value depends almost linearly on latitude, being about 5 for latitude 40° and 1 for latitude 75°. Whistler activity is markedly less for higher values of *K*.

(ii) At the equinoxes at middle and high latitudes, it appears that the higher the *K*-index, the less is the whistler activity.

(iii) In winter at low latitudes (25–35°) periods of high whistler rates follow severe magnetic storms by 1–3 days [*11*, *15*]. This delayed effect is not evident at higher latitudes.

(iv) Few summer night results are available, and no conclusions can be drawn.

3.2. *Dispersion Characteristics*

From recent work [*4–6*, *15*, *18–20*] it would appear that the effect of a severe magnetic storm ($K \geqq 6$) is to reduce the dispersion at all latitudes. The normal diurnal variation becomes exaggerated, the lowest dispersion being observed 1–3 days after the commencement of the storm, followed by a slow recovery taking several days. In the most severe cases, the dispersion drops by about 50 %. This is probably due mainly to decrease of exospheric electron content rather than to change of latitude of whistler path [*6*, *19*]. For certain storms, however, there is no change in dispersion; on these occasions, Corcuff [*18*] has observed that the whistlers at Poitiers are very pure, being often followed by numerous echoes, with little attenuation.

Carpenter [*21*] has found that multi-path nose whistlers sometimes have the property that the graph of values of nose frequency plotted on log–log paper against nose time delay departs appreciably from the usual negatively-sloped straight line [*22*]. The departure can be so marked that, within a limited frequency range, the nose time delay decreases instead of increasing as the nose frequency decreases. Carpenter attributes this to the presence of a "knee" in the equatorial electron-density profile, such that at some height the electron density drops rapidly to perhaps one-sixth of its normal value. Carpenter suggests that the knee exists at all times; during quiet magnetic conditions it is situated at a geocentric distance of at least 5.5 R_e, where R_e is the earth's radius, whilst for severely disturbed conditions it may move inwards to 2.5–3.5 R_e. The presence of this knee was found to account for a significant number of observations of depressed dispersion values during magnetic storms. It may also account for the Poitiers observations described above.

4. OBSERVATIONS USING SATELLITES

The first *in situ* demonstration that whistlers propagate in the exosphere was made in 1959 by Cain *et al.* [*23*, *24*], using the Vanguard III satellite. Whistlers were detected throughout the altitude range covered by the satellite (510–3750 km). The approximate latitude range was from 17° to 45° in each hemisphere. There appeared to be no strong latitude dependence of whistler occurrence, such as is found at ground-based stations. 83 % of the whistlers occurred during local darkness. In general, dispersions increased with distance along the geomagnetic field line from the earth's surface. The intensity of the H component of the whistlers was estimated to lie between 0.001 and 5 gammas.

Signals at 18 kc/s from transmitters NBA (Panama) and NPG (Seattle), received on the low-latitude satellite Lofti 1 in 1961, have been partially analysed by Leiphart *et al.* [*25*]. The amplitude probability distribution of NBA signal intensities (averaged over 1-minute intervals), when the satellite was 1000–2000 km north of the transmitter, was log-normal both by day and by night. The daytime median signal intensity was 26 dB less than the night-time value. This difference is nearly the same as the difference between the computed day and night absorption for vertical penetration of the lower ionosphere of 18 kc/s waves, using a plausible ionospheric model.

Since September 1962, whistlers have been regularly observed on the Alouette satellite over a wide range of latitudes, at an altitude of 1000 km. Simultaneous recordings are being made at many ground stations in North- and South-America and Antarctica. Barrington and Belrose [*26*] have reported preliminary observations. Whereas low-latitude (circa 20°) whistlers were relatively pure, high-latitude (circa 50°) whistlers were usually swishy. This agrees with ground-based observations. Occasionally at low latitudes whistlers were recorded having a limited frequency range. In one case a whistler was recorded in the range 1–2.5 kc/s, whilst 1 sec later another was recorded in the range 3.5–6 kc/s. Another phenomenon, this time at middle latitude, consisted of two cases of very short whistlers W_1 (dispersion about 3 $\sec^{\frac{1}{2}}$), each followed by whistlers W_3 having three times the dispersion. Barrington and Belrose tentatively suggest that an irregularity near the satellite height partially reflected some of the W_1 energy, which then returned to the ground, where it was reflected back to the satellite, giving rise to the W_3 components.

Only a small fraction of the sferics observed at a ground station were observed also on Alouette when 1000 km above the station. It appears that a satellite-borne receiver detects only those sferics that have been generated by lightning flashes close to the sub-satellite point, since the same sferics observed on the ground have clearly discernable components below the earth-ionosphere waveguide cut-off frequency of about 1.6 kc/s. On the satellite the sferics appear as whistlers with very little dispersion (2–3 sec$^{\frac{1}{2}}$). They are also somewhat diffuse, possibly because of scattering by irregularities in the ionosphere below the satellite.

New and important results are thus being obtained by observing whistlers and whistler-mode signals in satellites. At the same time it is clear that simultaneous observations at ground stations are necessary for full interpretation of the satellite data.

5. OBSERVATIONS IN POLAR REGIONS

Analyses [*27–30*] of whistler data from polar stations continue to support the hypothesis [*31*] that whistlers reach polar regions by propagation from middle latitudes in the earth–ionosphere waveguide mode. To date, the fullest discussion of results from a polar station is due to Ungstrup [*27*], who has analysed observations at Godhavn, Greenland (79.9°N) obtained mainly during 1960–1. Apparently all whistlers recorded at Godhavn were short whistlers. Maximum occurrence in winter, with almost no whistlers in summer, was found, in agreement with results from the Antarctic stations South Pole [*30*], Mirny [*28*], and Scott Base [*1*], at the same latitude. However, the diurnal variation of whistler occurrence at Godhavn was anomalous. Whereas Antarctic stations show diurnal variations similar to those at middle latitudes, with maximum occurrence near or before local midnight, Godhavn data showed a maximum near 0800 local time. This is the same universal time at which stations in the Pacific observe maximum occurrence. That the whistlers observed at Godhavn probably arrive from the northern Pacific is also suggested by an examination of day-to-day occurrence statistics. During the period November 1960–February 1961, maximum positive correlation was found with New Zealand stations, somewhat less with Western

North American stations, and no correlation with Japanese, Eastern North American and conjugate stations. Moreover, diurnally the whistler rate is a minimum at Godhavn just when it is a maximum at middle latitude stations to the south. Ungstrup suggests that there may be a region of anomalously high VLF absorption in the Auroral Zone to the south and east of Greenland, near the conjugate of the Capetown magnetic anomaly.

The dispersions of Godhavn whistlers were similar to those at middle latitudes of 52° to 61°. The previously found [*32*] high values of minimum detectable frequency (4–6 kc/s) were still observed. The minimum frequency was often nearly constant for several hours on end. Since a greater range of minimum frequencies would be expected from the large variability of source energies, Ungstrup concludes that the later evidence supports his earlier supposition that the minimum frequency is due to cut-off whilst the whistler is travelling in the earth–ionosphere waveguide mode.

Byrd Station (70.5°S) is situated near the maximum of the visual Auroral Zone. An undistorted dipole field line through it would reach a geocentric distance of 9 R_e in the geomagnetic equatorial plane. The dipole field line through a point 500 km to the north of Byrd would likewise extend to 6 R_e. Recently, Carpenter [*33*] has found evidence from whistler spectrograms that whistlers are often recorded at Byrd, during both quiet and severely disturbed magnetic conditions, having nose frequencies as low as 800 c/s. This corresponds to propagation along an undistorted dipole field line to a geocentric distance of 8 R_e. The diurnal occurrence pattern of such high-latitude whistlers differs markedly from that of middle-latitude whistlers, in that it shows a maximum near local noon, i.e. the paths are apparently on the sunlit side of the earth. Thus Carpenter suggests that these whistlers may possibly find use in detecting the outer boundary of the geomagnetic field.

6. OBSERVATIONS USING MAN-MADE SIGNALS

6.1. *Observations using Special Pulses*

The potential advantages of using man-made VLF transmissions for certain observations have been recognized for some time. For example, a measurement can be made of transmission loss, since the location, power output and antenna directivity can be defined. Fading characteristics can also be studied using regularly spaced pulses of constant amplitude. However, such observations do not supplant observations of natural whistlers, but rather supplement them. For instance, a man-made single-frequency signal does not directly indicate path latitude as does the nose property of a natural whistler [*22*, *34*].

The earliest successful observations were made by Helliwell and Gehrels [*35*] on 17 January 1957, when whistler-mode signals from station NSS (Annapolis, Md., USA) on 15.5 kc/s were detected near Cape Horn. Later successful observations known to the author [*36–41*] are listed in Table 1. Note that whistler-mode signals have now been detected at large distances from the transmitter or its conjugate point.

The most comprehensive study yet reported is that of the Stanford group [*38*]. Their results are based on data from the following paths:

NSS–Byrd Station	(1-hop)
NSS–Ushuaia	(1-hop)
NPG–Stanford	(2-hop)
NSS–Greenbank	(2-hop)

Over all paths, the general pattern of occurrence variations supports the hypothesis that absorption in the lower ionosphere has a major influence. Since the diurnal patterns at Greenbank and at Byrd are similar, it is concluded that both one-hop and two-hop signals are affected similarly by absorption at the Southern Hemisphere end of the exospheric path. Thus it appears that two-hop signals penetrate the absorbing region before reflection, rather than being reflected higher in the ionosphere. This conclusion is supported by the NPG–Stanford observations, which show a marked decrease in occurrence at the time of first sunrise at the ends of the path, regardless of whether this occurs at the receiver or at its conjugate point.

Periodic deep fading of the whistler-mode signals (up to 20 dB or more) was commonly recorded. The modal fading periods at Stanford were 40 and 60 sec, whilst those at Byrd and Ushuaia were 20 and 30 sec. The nature of the fading suggests that it arises from interference between two signals of comparable amplitude and of nearly the same group delay, but whose relative phase was slowly varying.

Group delays were found to be closely related to the geomagnetic latitude of the receiving station, the higher-latitude stations observing higher average delays. The high-latitude stations often observed low-latitude paths as well, but the reverse seldom occurred. Helliwell *et al.* interpret this to mean that, after injection into the earth–ionosphere waveguide, the whistler-mode signals travel mainly in the direction of the geomagnetic pole, as predicated theoretically by Helliwell [*42*]. Group delays decreased during

TABLE 1

(a) Successful Observations of Pulsed Whistler-Mode Signals

Date	*Transmitter*	*Receiving Site*	*Geomagnetic Latitude*	*Distance from*		*Reference*
				Conjugate Point	*Transmitter*	
Jan. 1957	NSS	Cape Horn	43°S	1800 km		35
April 1958	NPM	East Cape, N. Z.	42°S	3200 km		36
Sept. 1958	NDT	Hobart, Tas.	52°S	3000 km		39
Oct. 1958	NSS	Ushuaia	43°S	1800 km		38
Feb. 1959	NSS	Byrd Station	71°S	1700 km		38
Spring 1959	NSS	Riverhead, N. Y.	53°N		410 km	37
July 1959	NSS	Greenbank, W. Va.	50°N		270 km	38
June 1960	NPG	Stanford, Calif.	44°N		1100 km	38
July 1960	NBA	Santiago, Chile	22°S	1300 km		38
Oct. 1960	NPG	Seattle, Wash.	54°N		60 km	40
Nov. 1960	NPG	Wellington, N. Z.	45°S	2600 km		
Mar. 1961	NPM	Wellington, N. Z.	45°S	3700 km		
May 1961	NPG	Ashland, Ore.	50°N		500 km	41
Aug. 1961	NAA	Wellington, N. Z.	45°S	6400 km		38
	NAA	Ushuaia	43°S	1900 km		38
	NAA	Byrd Station	71°S	1600 km		38
	NAA	South Pole	79°S	2000 km		38
	NAA	Stanford, Calif.	44°N		4600 km	38
Feb. 1962	NAA	Greenbank, W. Va.	50°N		1200 km	38
Feb. 1962	NAA	ELTANIN (U.S. research ship)	20–60°S	Up to 5000 km		38
1962	NPG	Byrd Station	71°S	3100 km		

(b) Transmitter Details

Call Sign	*Location*	*Geomagnetic Latitude*	*Frequency (kc/s)*
NAA	Cutler, Me.	56°N	14.7
NBA	Balboa, Panama C.Z.	20°N	18.0
NDT	Yokohama, Japan	25°N	17.44
NPG	Seattle, Wash.	54°N	18.6
NPM	Hawaii	22°N	16.6 (19.8 since 1959)
NSS	Annapolis, Md.	50°N	15.5 (22.3 since Dec. 1960)

magnetic storms, and were less in June than in December, in agreement with data from natural whistlers.

Willard [*40*, *41*] has studied two-hop signals from NPG received at Seattle, close to the transmitter, and at Ashland, 500 km to the south. Rapid and large fluctuations in amplitude, both from pulse to pulse, and also within each individual pulse, suggested interference between signals propagating over paths with slightly different delay times. At both stations similar occurrence patterns were found. Maximum activity occurred in the early morning hours, with a secondary evening peak. Seasonally, fewest signals were recorded at the June solstice. The average occurrence rate at the higher-latitude station (Seattle, 54°N) was 23 % greater than at Ashland. The delays ranged from 0.4 to 2.3 sec, with most frequent values between 1.0 and 1.2 sec. Seattle recorded more of the very short, as well as very long delay signals.

Of the three transmissions regularly recorded at Wellington (NAA, NPG, NPM) whistler-mode signals are most frequently observed from NPG, whose conjugate point is nearest to the receiver. The amplitude of all signals often varies greatly from one pulse to the next, becoming uncorrelated after a few seconds. The amplitude probability distribution of a special long sequence of pulses was approximately log-normal. A comparison of the delays of signals from NPG and NPM showed that only for 10 % of the time were the delays identical. At other times the delay for NPG was greater than that from NPM, indicating a dependance of the delays on the location of the transmitter.

A consistent feature of NPG reception at Wellington at the solstices is the occurrence of multiple signals in which the delay of a later component is twice that of an earlier component. This occurs about 2.5 times as often as would be expected for propagation by different exospheric paths, and has been interpreted as evidence of hybrid propagation [*43*].

The observation of whistler-mode signals in satellites was reported in Section 4.

6.2. *Observations using Continuous Waves*

A method has been developed whereby variations in the phase-path of a whistler-mode signal can be recorded [*44*]. The whistler-mode signal is made to beat with that of a highly stable local oscillator, using a receiver with effective bandwidth of 1 c/s. Observations on NPG at Wellington show that the frequency of the whistler-mode signal is often shifted. However, on a significant number of occasions, whistler-mode signals were detected following special pulse transmissions, without evidence of the frequency being shifted.

On occasions when periodic beats were observed, the average frequency shift near local midnight was about 5 cycles/minute (5 parts in 10^6), with higher values (7–10 cycles/minute) near sunset and sunrise. Some preliminary observations suggest that the frequency shift may be positive before, and negative after, local midnight. Although the frequency shifting is presumably due to some dynamic process, no correlation has yet been found with magnetic activity.

6.3. *Effect of Nuclear Explosions*

Lippmann [*45*, *46*] has suggested that, under favourable circumstances, a nuclear explosion might give rise to an artificial whistler. Successful observations of this type have been made by Helliwell and Carpenter [*47*] and by Allcock *et al.* [*48*]. In all cases the spectrograms of the artificial whistlers and of nearby natural whistlers were identical, indicating that the same exospheric paths were followed. Short whistlers excited by explosions in the same hemisphere have been recorded, lending support to the concept of the hybrid whistler [*43*].

After the high-altitude explosion of 9 July 1962 over Johnston Island, there was a complete cessation of natural whistler activity at Wellington, 3000 km south of the conjugate point, for 17 minutes, followed by a slow recovery with a time constant of over an hour. Spectrograms of whistlers recorded one hour after the explosion indicated a reduced dispersion implying a possible reduction of 20–40 % in exospheric electron density. The sferic from the explosion had similar characteristics to those of lightning sferics, and was thus probably generated below the ionosphere.

7. ATTENUATION PROCESSES

Several authors have discussed certain aspects of transmission loss in the whistler path. The following loss processes may occur to varying extents over different sections of the total path:

7.1. *Ionospheric Reflection*

Energy may be lost by reflection at the lower boundary of the ionosphere. The fraction of energy lost will depend on the gradient and extent of electron density change, on wave frequency, and on the angle between the ray direction and the geomagnetic field. Several estimates [*49–53*] of this loss have been made, assuming a sharply-bounded ionosphere and other approximations; values up to 12 dB have been calculated.

Partial or total reflection may occur at other discontinuities in the ionosphere, including perhaps the start of a field-aligned column of ionization which later traps any remaining whistler energy.

7.2. *Absorption by Electron Collision*

Absorption by collision between electrons and other particles has been computed for various ionospheric models [*49, 50, 52–57*]. The major source of loss is collisions between electrons and neutral molecules in the D and E regions. These may account for about 28 dB loss at noon and 2 dB at night at middle latitudes, for a single longitudinal passage of 18 kc/s waves through the lower ionosphere, the absorption at lower frequencies being approximately proportional to the square root of the frequency. During polar blackout conditions, the absorption may increase to 44 dB [*57*]. These figures are subject to revision when more accurate values of electron density and collisional frequency in the D region are available.

The effect of electron–ion collisions in the F region is not always negligible, but can produce a secondary absorption peak [*52, 53, 57*]. Whereas at night this may be less than 1 dB, for sunspot minimum daytime conditions it could amount to several dB.

7.3. *Scattering by Irregularities*

A system of irregularities in the whistler path may cause scattering of energy. The ionosphere is known to contain such irregularities, but no quantitative estimates have yet been made of their effect on whistler propagation. Qualitatively, Budden [*58*] has considered a set of random field-aligned irregularities with transverse dimensions much smaller than a wavelength, and has concluded that whistler propagation will be modified by their presence, unless they are infinitely extended along the geomagnetic field.

7.4. *Landau Damping*

Several authors [*59–63*] have shown that a train of electromagnetic waves travelling in the exosphere should be damped by those thermal electrons whose velocity component in the direction of the wave-normal is such that they are in gyro-resonance with the Doppler-shifted wave frequency. The attenuation is strongly dependent on frequency for electron-velocity distributions that are either Maxwellian [*61*, *62*] or cubic Cauchy [*63*] (equivalent to an energy distribution with exponent -2.5 at high velocities). In a particular case, the attenuation increased from 5 to 50 dB within a 300 c/s range. Thus a sharp high-frequency cut-off is predicted, which is found to change significantly with variation in temperature or gyro-frequency. The theory has been applied [*63*] to a high-latitude nose whistler with sharp cut-off at about 0.6 of the minimum gyro-frequency along the path. Temperatures of order 5×10^5 °K and 10^5 °K, at a geocentric distance of about $4R_e$, are inferred for Maxwell and Cauchy distributions, respectively.

7.5. *Imperfect Guiding*

Smith [*64*] has shown that the properties of a field-aligned duct of enhanced ionization should change abruptly when the wave frequency is approximately one-half the local electron gyro-frequency, and that at higher frequencies the duct ceases to trap the whistler energy. Thus a cut-off frequency somewhat greater than one-half the minimum electron gyro-frequency along the path, would be expected for this reason.

7.6. *Attenuation in the Earth–Ionosphere Waveguide*

Crary [*65*] has calculated the variation of field-strength along the ground for a wave radiating from a point source just within a sharply-bounded summertime ionosphere. He finds that the field-strength at 5 kc/s decreases by about 20 dB in the first 1000 km from the sub-exit point, both by night and day. Thereafter, over sea, the loss rates about 5 dB/1000 km. Over poor ground, however, the initial loss rate persists for a further 1000 km before changing to 4 dB/1000 km.

Experimentally, using four stations with separations of about 150 km, Crouchley and Duff [*66*] have found that significant changes in strength occur in a distance of 300 km. The more common swishy whistlers showed similar amplitude spectra at all stations, but varied in strength by up to 8 dB.

7.7. *Comments*

Before calculating transmission loss, the path must be known. At present the major difficulty is apparently that of locating the exit point. Crary [*65*] has attempted this, using a rotating goniometer system, but concludes that polarization and other errors are too great for the method to have general use. Delloue *et al.* [*67*] have measured the time delay of 5.5 kc/s waves over base lines of several tens of km. The directions of arrival of most measured whistlers were grouped around either the geomagnetic field direction or the vertical. Anomalous results [*68*] were attributed to the interference of multiple waves produced by irregularities in the D layer.

Some of the difficulties in locating exit points are apparently associated with the changing frequency of a natural whistler. These may be overcome by using man-made single-frequency signals.

It appears that a comprehensive treatment of transmission losses has yet to be undertaken. Experimental measurements to assist in the calculation of specific cases are rare.

8. THE EFFECT OF IONS ON WHISTLER SPECTRA

Storey [*69*] has shown that the presence of protons would modify whistler propagation at low frequencies at low latitudes, because of proton gyro-resonance. At such frequencies, if the effect of protons or other ions is neglected, the product $tf^{\frac{1}{2}}$, where t is the time delay at frequency f, will be constant for a given whistler [*70*]. The presence of ions can produce a maximum increase in $tf^{\frac{1}{2}}$ of 8.9 % at twice the ion gyro-frequency; if protons were the dominant ions, this maximum would occur at a frequency somewhat below 1 kc/s. Several attempts [*71–74*] have been made to infer the presence of protons by demonstrating the experimental existence of this effect. Various models of electron density distribution have been assumed; all except Patterson [*74*] have assumed a proton density equal to the electron density. Although all apparently show agreement between experiment and theory, the values of $tf^{\frac{1}{2}}$ are still increasing when the lowest frequency is reached; none of the experimental dispersion curves show a maximum in $tf^{\frac{1}{2}}$.

Recent rocket [*75–77*] and satellite [*78*] observations have disclosed electron density profiles which indicate that in the region of interest the dominant ions may be helium ions rather than protons. This possibility was forseen by Nicolet [*79*]. Thus increases in $tf^{\frac{1}{2}}$ found experimentally may not necessarily demonstrate the existence of protons. Moreover, the spectrogram of a low-latitude whistler received on the Alouette satellite [*26*] shows an increase in $tf^{\frac{1}{2}}$ of about 15 % at the lowest recorded frequency (about 600 c/s); this is greater than the maximum possible increase due to ions.

A possible alternative explanation has already been suggested by Storey [*80*], viz. that the increase is due to a waveguide cut-off as the wavelength approaches the transverse dimensions of a whistler duct. In this connection, we note that the wavelength at 600 c/s is likely to be in the range 1–15 km for typical conditions in and above the F region. Field-aligned irregularities having transverse dimensions of this order have been postulated to account for certain features of equatorial spread-F [*81*].

9. CONCLUSION

The use of satellites and man-made signals has already yielded important new results. Co-ordination between these methods and continuing observations of natural whistlers on the ground should facilitate the solution of some outstanding problems such as the calculation of transmission losses, the interpretation of low-latitude spectrograms, and the study of variations in whistler characteristics in relation to solar and magnetic activity.

ACKNOWLEDGEMENT

The ready-co-operation of fellow workers in many countries in providing up-to-date reports of progress in their individual research projects, is gratefully acknowledged.

REFERENCES

1. G. McK. Allcock, in: *Radio Noise of Terrestrial Origin*, edited by F. Horner, Elsevier, Amsterdam, 1962, p. 116.
2. H. G. Booker, Guidance and Beaming in the Magnetosphere at Hydromagnetic, Audio and Radio Frequencies, this volume p. 113.
3. D. L. Carpenter, Whistler Measurements of the Equatorial Profile of Magnetospheric Electron Density, Commissions III and IV, URSI General Assembly, Tokyo, 1963, in: *The Ionosphere*, edited by G. M. Brown, Elsevier, Amsterdam, 1965, p. 76.
4. A. Kimpara, *Proc. Res. Inst. Atmospherics, Nagoya Univ.*, 9 (1962) 5.

5. Y. Corcuff, *Ann. Géophys.*, 18 (1962) 334.
6. D. L. Carpenter, *J. Geophys. Res.*, 67 (1962) 3345.
7. R. Rivault and Y. Corcuff, *Ann. Géophys.*, 16 (1960) 550.
8. P. D. Gomez, M. G. Morgan and T. Laaspere, paper in preparation.
9. G. McK. Allcock and M. G. Morgan, *J. Geophys. Res.*, 63 (1958) 573.
10. A. Kimpara, *Proc. Res. Inst. Atmospherics, Nagoya Univ.*, 7 (1960) 40.
11. A. Kimpara, *Nature*, 186 (1960) 230.
12. J. Crouchley, *Australian J. Phys.*, 14 (1961) 22.
13. G. McK. Allcock and M. F. Rodgers, *J. Geophys. Res.*, 66 (1961) 3953.
14. S. Yoshida and T. Hatanaka, *J. Phys. Soc. Japan*, 17 (1962) Suppl. A-II, p. 78.
15. J. Outsu and A. Iwai, *Proc. Res. Inst. Atmospherics, Nagoya Univ.*, 9 (1962) 19.
16. R. E. Barrington and W. E. Thompson, *Can. J. Phys.*, 40 (1962) 775.
17. T. Laaspere, M. G. Morgan and W. C. Johnson, *Proc. IEEE*, 51 (1963) 554.
18. Y. Corcuff, *Ann. Géophys.*, 17 (1961) 374.
19. D. L. Carpenter, *J. Geophys. Res.*, 67 (1962) 135.
20. D. L. Carpenter, The Magnetosphere during Magnetic Storms: a Whistler Analysis, *Stanford Univ. Rept.* SEL-62-059, Stanford, Calif., 1962.
21. D. L. Carpenter, *J. Geophys. Res.*, 68 (1963) 1675.
22. R. L. Smith, *J. Geophys. Res.*, 66 (1961) 3709.
23. J. C. Cain, I. R. Shapiro, J. D. Stolarik and J. P. Heppner, *J. Geophys. Res.*, 66 (1961) 2677.
24. J. C. Cain, I. R. Shapiro, J. D. Stolarik and J. P. Heppner, *J. Phys. Soc. Japan*, 17 (1962) Suppl. A-II, p. 84.
25. J. P. Leiphart, R. W. Zeek, L. S. Bearce and E. Toth, *Proc. IRE*, 50 (1962) 6.
26. R. E. Barrington and J. S. Belrose, *Nature*, 198 (1963) 651.
27. E. Ungstrup, Observations of VLF Radio Noise at Godhavn, Greenland, *Ionosphere Lab. Rept.* No. 12, Roy. Tech. Univ., Copenhagen, Denmark, 1962.
28. O. Praus, *Byul. Soviet Antarkt. Eksped.*, No. 27, p. 32 (1961).
29. G. McK. Allcock, *Nature*, 188 (1960) 732.
30. L. H. Martin, *Nature*, 187 (1960) 1018.
31. L. H. Martin, *Nature*, 181 (1958) 1796.
32. E. Ungstrup, *Nature*, 184 (1959) 806.
33. D. L. Carpenter, *J. Geophys. Res.*, 68 (1963) 3727.
34. R. L. Smith and D. L. Carpenter, *J. Geophys. Res.*, 66 (1961) 2582.
35. R. A. Helliwell and E. Gehrels, *Proc. IRE*, 46 (1958) 785.
36. G. McK. Allcock, at: *A.N.Z.A.A.S. Conference*, Adelaide, 1958 (Australian and New Zealand Association for the Advancement of Science).
37. H. O. Peterson, R. Ewing, D. Riggs, R. Lending and E. R. Schmerling, *IRE Trans.*, AP-8 (1960) 112.
38. R. A. Helliwell, J. Katsufrakis and G. Carpenter, Whistler-Mode Propagation Studies using Navy VLF Transmitters, *Stanford Univ. Rept.* SEL-62-035, Stanford, Calif., 1962.
39. R. L. Dowden and G. T. Goldstone, *Nature*, 183 (1959) 385.
40. H. R. Willard, *J. Geophys. Res.*, 66 (1961) 1976.
41. H. R. Willard, *Trans. Am. Geophys. Union*, 43 (1962) 441.
42. R. A. Helliwell, in: *Proceedings of International Conference on the Ionosphere, London*, 1962, Bartholomew, Edinburgh-London, 1963, p. 452.
43. R. A. Helliwell, *Can. Defence Res. Telecomm. Establ. Publ.* No. 1025, Ottawa, Canada, 1960, p. 165.
44. D. D. Crombie, F. A. McNeill and G. McK. Allcock, *J. Geophys. Res.*, 68 (1963) 6229.
45. B. A. Lippmann, *Proc. IRE*, 48 (1960) 1778.
46. B. A. Lippmann, *IRE Trans.*, AP-10 (1962) 506.

47. R. A. Helliwell and D. L. Carpenter, *J. Geophys. Res.*, 68 (1963) 4409.
48. G. McK. Allcock, C. K. Branigan, J. C. Mountjoy and R. A. Helliwell, *J. Geophys. Res.*, 68 (1963) 735.
49. R. A. Helliwell, *Low-Frequency Propagation Studies*, Pt. I, Whistlers and Related Phenomena, Radio Propagation Lab., Stanford Univ., Calif., 1956.
50. K. Maeda and I. Kimura, *Rept. Ionosphere Res. Japan*, 10 (1956) 105.
51. H. Hodara, *Proc. IRE*, 50 (1962) 2000.
52. C. Altman and H. Cory, *Bull. Res. Council Israel*, C11 (1962) 1.
53. C. Altman and H. Cory, *J. Geophys. Res.*, 67 (1962) 4086.
54. B. N. Gershman and V. A. Ugarov, *Usp. Fiz. Nauk*, 72 (1960) 235.
55. D. W. Swift, *J. Geophys. Res.*, 67 (1962) 1175.
56. H. G. Booker, *J. Geophys. Res.*, 67 (1962) 4135.
57. R. A. Helliwell and N. Dunckel, paper in preparation.
58. K. Budden, *J. Res. Natl. Bur. Std.*, 63D (1959) 135.
59. K. N. Stepanov, *Zh. Eksperim. i Teor. Fiz.*, 35 (1958) 283.
60. B. N. Gershman, *Zh. Eksperim. i Teor. Fiz.*, 38 (1960) 912.
61. F. L. Scarf, *Phys. Fluids*, 5 (1962) 6.
62. H. B. Liemohn and F. L. Scarf, *J. Geophys. Res.*, 67 (1962) 1785.
63. H. B. Liemohn and F. L. Scarf, *J. Geophys. Res.*, 67 (1962) 4163.
64. R. L. Smith, *J. Geophys. Res.*, 66 (1961) 3699.
65. J. H. Crary, The Effect of the Earth–Ionosphere Waveguide on Whistlers, *Radioscience Lab. Tech. Rept.* No. 9, Stanford Univ., Calif., 1961.
66. J. Crouchley and K. J. Duff, *Australian J. Phys.*, 15 (1962) 470.
67. J. Delloue, M. Garnier, F. Glangeaud and P. Bildstein, *Compt. Rend.*, 257 (1963) 1131.
68. J. Delloue and M. Garnier, *Compt. Rend.*, 257 (1963) 1327.
69. L. R. O. Storey, *Can. J. Phys.*, 34 (1956) 1153.
70. L. R. O. Storey, *Phil. Trans. Roy. Soc. London*, A246 (1953) 113.
71. J. Outsu and A. Iwai, *Proc. Res. Inst. Atmospherics, Nagoya Univ.*, 6 (1959) 44.
72. R. E. Barrington and T. Nishizaki, *Can. J. Phys.*, 38 (1960) 1642.
73. J. Ondoh and S. Hashizume, *J. Geomagnet. Geoelec.*, 12 (1960) 32.
74. T. N. L. Patterson, *Planet. Space Sci.*, 8 (1961) 71.
75. W. B. Hanson, *J. Geophys. Res.*, 67 (1962) 183.
76. R. E. Bourdeau, E. C. Whipple, Jr., J. L. Donley and S. J. Bauer, *J. Geophys. Res.*, 67 (1962) 467.
77. S. J. Bauer and J. E. Jackson, *J. Geophys. Res.*, 67 (1962) 1675.
78. J. W. King, *Nature*, 197 (1963) 639.
79. M. Nicolet, *J. Geophys. Res.*, 66 (1961) 2263.
80. L. R. O. Storey, in: *Radio Noise of Terrestrial Origin*, edited by F. Horner, Elsevier, Amsterdam, 1962, p. 134.
81. M. L. V. Pitteway and R. Cohen, *J. Geophys. Res.*, 66 (1961) 3141.

DISCUSSION

Investigations are still proceeding on the identification and location of the sources of whistlers. The occurrence in France has been found to be a maximum at the time of sunrise at the level of the F region above the conjugate point, and decreases to a low rate at ground sunrise. Absorption by the D region is therefore not the only controlling factor, and the F region effects may help in defining the place where the energy penetrates the ionosphere *(R. Rivault)*. Field-aligned irregularities have been observed in the F region by backscatter at 16 Mc/s and have extinction times corresponding with sunrise at the 400–450 km level. Spread-F shows a similar phenomenon. The irregularities, which typically extend for about 200 km in the north–south direction, and rather more in the east–west direction, may have some connection with whistler mode ducts *(J. A. Thomas)*. Correlation between F region scattering centres and gyro-electric echoes of man-made signals has been found to be high *(R. A. Helliwell)*.

The annual variation in whistler occurrence depends on both geographic latitude, which controls the prevalence of thunderstorms, and geomagnetic latitude, which determines the propagation. Whistler activity is relatively much greater in winter than in summer at locations where the geographic latitude greatly exceeds the geomagnetic latitude. This leads to differences in the annual variations at different longitudes *(Miss K. Yoshida)*.

Direction finding on whistlers has been studied in France at 50° geomagnetic latitude. Normally most whistlers have a plane wavefront with a wave normal within 30° of the magnetic field and within 40° of the vertical. When the normal is within 15° of the vertical the polarisation is circular, but from 15 to 40° it is strongly elliptical. A few horizontally-incident whistlers were recorded, with linear polarisation. Evidence was found, at times, of whistlers with spherical wavefronts emerging from the D region over a small area. Direction finding observations could often be invalidated by distortion of the electromagnetic field near the ground, thought to be caused by irregularities in the D region *(J. Delloue)*.

Protons can have a marked effect on the propagation of audio frequency radio waves in a homogeneous magneto-ionic medium, particularly at the lower frequencies and when the angle between the wave normal and the magnetic field exceeds 80°. This transverse type of propagation may be involved when energy is received at high latitudes from lightning discharges at low latitudes *(J. Outsu)*.

New phenomena are being discovered through the study of whistlers received in satellites. Many more were observed in the satellite Alouette than are received on the ground, and rocket flights to 300 km have confirmed the increase with height. Many of the whistlers also had characteristics differing from those at the ground; for example some forms exhibited components with a much wider range of dispersions. There was evidence of several ray paths crossed in succession by the satellite during a 10-minute pass over one station *(D. L. Carpenter)*.

In addition to further satellite work, high-latitude whistlers, received over paths extending to 5 earth radii or more, require further study. Synoptic studies needed include an investigation of the latitude dependence of diurnal variations and magnetic storm effects, and measurement of the distribution of ionisation along field lines *(D. L. Carpenter)*.

SESSION ON VLF AND NOISE PHENOMENA

VERY LOW FREQUENCY NOISE FROM THE TERRESTRIAL MAGNETOSPHERE

G. R. A. ELLIS

Department of Physics, University of Tasmania, Hobart, Tas. (Australia)

SUMMARY

This paper reviews new developments in the study of the VLF emissions during 1960–63. Both observational and theoretical aspects are considered.

RÉSUMÉ

L'auteur passe en revue les réalisations effectuées au cours de la période 1960–63 dans l'étude des émissions à très basses fréquences. Il considère à la fois les points de vue observationnel et théorique.

INTRODUCTION

In this review the term VLF noise will be used to denote the radio emissions which occur principally in the frequency band from 100 c/s to 20 kc/s and which appear to originate in the terrestrial magnetosphere. VLF noise includes quasi-continuous emissions usually with a bandwidth of some kilocycles/second, called hiss, as well as many distinct types of temporally-discrete emissions which may have characteristic frequency–time variations. Recurring dispersive discrete emissions we will refer to as chorus.

OCCURRENCE

Information on the time variations and geographical distribution of VLF noise may be summarised as follows. Major magnetic storms are always as-

References p. 66

sociated with VLF noise storms. Noise storms normally occur during the main phase of the magnetic storm and begin on the average 6–7 hours after the magnetic sudden commencement [*1*]. Their mean duration is about 15 hours. The intensity of the noise is observed to fluctuate widely during the storm and sometimes the intensity variations are broadly reproduced in different storms. The frequency range varies with *K*-index and can extend from 100 c/s to 200 kc/s during intense magnetic storms ($K > 9$) although 1 kc/s to 10 kc/s could be considered more usual. The majority of VLF noise occurrences last for about 2 hours only and are observed during less magnetically disturbed conditions. About 50% of these shorter outbursts are coincident with magnetic activity *K* between 0 and 1. Good correlation with magnetic bays has been noted [*1*]. Many VLF noise bursts recorded during the night at middle latitudes are concurrent with red airglow (6300 Å) [*1*] and in a few cases good correlation between the detailed amplitude variations has been observed at 5 kc/s. Correlation has also been observed between aurorae and hiss at frequencies above 5 kc/s at high latitudes [*2*, *3*]. Neither chorus nor hiss below 5 kc/s at high latitudes appears to show any definite correlation with aurorae or auroral echoes [*4*]. Evidence has been presented that the intensity of hiss decreases during polar cap absorption [*4*].

Observations of hiss at frequencies near 5 kc/s both at middle latitudes and in the Antarctic [*2*] indicate that its intensity varies diurnally with a maximum near 1000 local time. However, at middle latitudes the number of observations of noise bursts does not appear to be a strong function of the time of day; those bursts observed during the morning hours are generally more intense [*1*]. At lower latitudes the intensity maximum is near 0300 LT for the same bursts, suggesting a modification of the diurnal variation as a result of propagation of the radiation beneath the ionosphere from higher latitudes. Without considering possible mechanisms at this stage we may note that the radiation occurs mainly in the whistler band of frequencies and will therefore propagate in the outer atmosphere in the whistler mode, that is along magneto-ionic ducts. It follows that wherever the noise is generated in the outer atmosphere, an image of the noise source will be thrown on the ionosphere and hence on the earth. It is conceivable therefore that the geographical distribution of the noise over the earth provides a picture of the luminous distributed regions of the outer atmosphere. It should further be noted that the radiation may propagate horizontally with little attenuation in the earth-ionosphere wave guide and that some smoothing of the image will result.

Investigations of the geographical pattern with spaced observing stations have yielded the following results [*5*, *6*].

1. Noise bursts are most easily detected at geomagnetic latitudes from 40° to 60°.
2. The short bursts of 2 hours or so duration are usually isolated geographically with an average size of 700 km. Some very small sizes less than 100 km have been recorded.
3. Major noise storms are very widespread and may well extend over most of the middle latitudes, although the noise illumination pattern in such cases frequently shows much fine spatial detail with a scale of the order of 100 km.
4. There appears to be some correlation between noise bursts and noise storms in opposite hemispheres.

SATELLITE AND ROCKET OBSERVATIONS OF VLF NOISE

Hiss has been observed from the Alouette satellite since 1962 over a wide range of latitudes at an altitude near 1000 km. Barrington and Belrose [*7*] reported that the bandwidth of hiss observed from the satellite was less than that observed from the ground at the same time. The satellite would be likely to sample a narrower range of field line latitudes than a ground station, which is able to detect hiss which may have emerged below the ionosphere perhaps 1000 km away. The low frequency boundary of the hiss was observed from the satellite to decrease with latitude approximately at the rate of 1 kc/s per degree in the range of geomagnetic latitudes of 55° to 60°. This effect, which is likely to be related to the lower minimum gyro-frequency along the higher latitude field lines, would be difficult to observe using ground stations. Barrington and Belrose further reported that the satellite observed much more radio noise below 1 kc/s than ground stations. Satellite observations are likely to provide a powerful means of studying the geographical distribution of VLF noise both from the point of view of intensity and frequency range.

INTENSITY

The flux density of VLF noise observed at the ground appears to fall rapidly with increase in frequency in the range 100 c/s to 250 kc/s (spectral index

−3) [*8*]. However when allowance is made for propagation beneath and through the ionosphere it seems likely that the spectrum is almost flat in the region of generation. Estimates [*8*, *4*] of the flux density in the magnetosphere range from 10^{-10} to 10^{-13} watts m^{-2} $(c/s)^{-1}$.

DISCRETE EMISSIONS

Discrete emissions may be classified according to their spectral shape [*9*] or according to their temporal occurrence. Using this latter criterion we may distinguish between isolated or irregularly occurring emissions and periodic discrete emissions. Both types may be either dispersive, i.e. with a centre frequency which changes rapidly with time, or more spectrally diffuse and non-dispersive. The minimum frequency of the dispersive types such as hooks appears to decrease with increase in geomagnetic latitude. Between 50° and 60°, 2–5 kc/s may be taken as characteristic while for observations at 79° [*10*] the corresponding frequency range appears to be 0.5–15 kc/s.

Periodic emissions have been observed to recur with the same period as whistler echoes recorded at the same time [*11*]. Some clearly follow whistlers directly or with a short delay. The whistler or whistler echo appears to initiate or trigger the emission which may have the same spectral slope at each appearance. Isolated noise bursts have been similarly observed to follow whistlers. On some occasions each whistler recorded over a period of several minutes was followed by a noise burst with a duration of about a second [*12*]. Again where long trains of whistler echoes are observed [*11*] the noise bursts may be triggered, not by the original whistlers but by the high order echoes. Helliwell [*11*] interpreted the above results in terms of the organization or phasing of a stream of fast electrons by the triggering electromagnetic wave so that the electrons radiate in phase. The electromagnetic wave may be either that of a whistler, a whistler echo, another VLF emission or its echo. In this way multiple discrete emissions such as "chorus" can be considered to be made up of a succession of self-maintaining periodic emissions. A similar interpretation of isolated hooks has been put forward by Mrs. Hansen [*13*].

THEORIES OF VLF NOISE

Good progress has been made in the explanation of VLF noise in the period under review. Čerenkov radiation from particles travelling along the geomagnetic field lines has been investigated as a possible mechanism by a number of authors [*14*, *15*, *16*, *17*, *18*]. At frequencies in the VLF band the refractive index for the whistler mode may be much greater than unity in the magnetosphere and many charged particles trapped in the geomagnetic field have sufficient velocity to radiate in Čerenkov mode almost continuously. However for incoherent radiation the integrated intensity would be only of the order of 10^{-19} watts $(\mathrm{m})^{-2}(\mathrm{c/s})^{-1}$ [*14*] and therefore far too small to explain the observed radiation. In addition, for the simple incoherent Čerenkov process the radiation is essentially wide-band, the wave frequency in the present situation being given by the relation

$$f \leqq \frac{V_2^2}{c^2} \cdot \frac{f_0^2}{f_H} \quad \text{for} \quad f \ll f_H \tag{1}$$

where f_0 is the plasma frequency, f_H the gyro frequency and V_2 the longitudinal velocity of the charged particles. It could not therefore account easily for the narrow band dispersive emissions.

Closely related to Čerenkov radiation is the idea of selective travelling-wave amplification in which a stream of electrons acts like the beam in a travelling-wave tube (TWT) and the ambient plasma like the slow wave structure [*19*, *20*]. A single frequency would be produced in this case, the actual value being given by the equality sign in Eq. (1). Gallet [*9*] has shown that spectra resembling those of hooks may result from the TWT process if a beam of fast electrons enters the ionosphere.

Another mechanism is Doppler-shifted cyclotron radiation from electrons [*21*, *22*]. Just as fast electrons must necessarily radiate in the Čerenkov mode at VLF when passing through the magnetosphere, so they will also emit cyclotron radiation. Seen from behind the radiating electron the wave frequency will be Doppler shifted to the VLF band according to the relation

$$f = \frac{\left(1 - \frac{V^2}{c^2}\right)^{\frac{1}{2}} f_H}{1 + n\frac{V}{c}\cos\theta\cos\phi} \tag{2}$$

where n is the refractive index of the medium, V the velocity of the electrons θ is the direction of the wave normal and ϕ is the pitch angle of the electrons.

Dowden [*21*] has calculated the variation of frequency with time which would be observed by an electron emitting cyclotron radiation when travelling along a high latitude field line for paths near the equatorial plane. He has shown that a better agreement with the measured spectra of hooks is obtained than with the TWT theory mentioned above. Further calculations using actual hooks enabled him to estimate the energy of the electrons, their pitch angle and the field line latitude [*23*]. Whatever the process, it is clear that it must be a coherent one, that is one in which large numbers of charged particles radiate in phase. Taking the flux density of the radiation in the magnetosphere to be 10^{-10} watts $m^{-2}(c/s)^{-1}$ at 5 kc/s we have 10^{21} °K for the equivalent temperature of the radiating electrons if the process is incoherent, or an electron energy of 10^{17} eV. These values are not acceptable for magnetospheric electrons and hence the process cannot be incoherent.

The conditions in which coherent generation and amplification of electromagnetic radiation can occur in a plasma have been investigated by a number of authors [*24*, *25*, *26*, *27*, *28*, *29*]. It has been shown that the radiation absorption coefficient may assume negative values for a particular frequency if there exists a radiative process for which this frequency is emitted only by electrons of particular energy, providing that the actual energy distribution of the fast electrons has a positive slope for this value of energy. Wild *et al.* [*26*] give for the absorption coefficient of an anisotropic plasma, in direction θ

$$k(\theta) = -\frac{c^2 N}{n^2 f^2}\int_0^\infty\int_0^{2\pi}\left[\left(\frac{\partial}{\partial E}+\frac{\Delta\phi}{hf}\frac{\partial}{\partial\phi}\right)F(E,\phi)\right]W_f(E,\theta-\phi)\,g(E,\phi)\,dE\,d\phi$$

where N is the electron density, $F(E, \phi)$ is the distribution of the electrons with respect to energy E and pitch ϕ, $W_f(E, \theta-\phi)$ is the electron emissivity function for a frequency f [*30*], $g(E, \phi)$ is the statistical weight and $\Delta\phi$ is the change in direction of the electron caused by emission or absorption of a photon. If the absorption coefficient is negative then a wave travelling through the (high-velocity) plasma will be amplified. The amplified wave may originate either externally (external excitation) or internally as radiation from individual electrons (internal excitation).

Of the processes mentioned earlier, Doppler-shifted cyclotron radiation fits the requirement for single frequency emission easily since the electron emissivity function $W_f(E, \theta-\phi)$ is a delta function of the energy whose value is determined by the Doppler equation (2). It is only necessary for negative absorption that (where $\Delta\phi$ is small) for this value of energy $\partial F/\partial E > 0$. An electron stream with a sufficiently narrow energy spectrum will therefore be unstable with respect to radiation by this process.

There does not appear to be any difficulty in explaining the observed characteristics of VLF noise, continuous or discrete, in this way. The problem is rather one of accounting for the necessary electron stream. However it should be noted that there is some observational evidence for such quasi-monoenergetic streams [*31*]. The triggered and discrete emissions also pose the problem of the localisation of the radiating region, which would require to be less than a few hundred kilometers in extent and travelling with high velocity to give the observed narrow dispersive spectrum. On the above theory of stimulated emission the initiating electromagnetic wave would slightly narrow the energy distribution of an almost critical pre-existing stream, producing a negative absorption coefficient. Because of the variation of the refractive index and cyclotron frequency along the path of the stream, this interaction would be likely to occur only at one point in the path for a wave of given frequency. Since the wave and the electrons travel in opposite directions for backward cyclotron radiation, the resulting negative absorption region would necessarily be limited in extent.

CONCLUSION

Much new information on the properties of the VLF emissions has been obtained in the period reviewed. New departures include satellite studies which promise to solve outstanding problems of the geographical distribution of the radiation. Developments in the theory have gone a long way towards elucidation of the emission processes. These developments should be seen also in the light of their relevance to other situations. For example, the nearly monoenergetic electron streams in the magnetosphere required to produce the VLF noise may also, in certain circumstances emit cyclotron radiation, Doppler shifted to higher frequencies. Unlike the VLF this would escape from the magnetosphere and would correspond in general properties to the burst radiation from Jupiter [*32*]. Conversely the observation of the VLF emissions provides good evidence for the type of radiation process needed to explain the Jupiter radiation [*33*] and some solar burst radiation.

References p. 66

REFERENCES

1. G. R. A. Ellis, *J. Geophys. Res.*, 65 (1960) 1705.
2. L. H. Martin, R. A. Helliwell and K. R. Marks, *Nature*, 187 (1960).
3. T. S. Jorgensen and E. Ungstrup, *Nature*, 194 (1962) 462.
4. T. Ondoh, *J. Geomagnet. Geoelec.*, 14 (1963) 133.
5. G. R. A. Ellis, *J. Geophys. Res.*, 66 (1961) 19.
6. G. R. A. Ellis, *J. Geophys. Res.*, 65 (1960) 839.
7. R. E. Barrington and J. S. Belrose, *Nature*, 198 (1963) 651.
8. R. L. Dowden, *Australian J. Phys.*, 15 (1962) 114.
9. R. M. Gallet, *Proc. IRE*, 47 (1959) 221.
10. E. Ungstrup and I. M. Jackerott, *J. Geophys. Res.*, 68 (1963) 2141.
11. R. A. Helliwell, *J. Geophys. Res.*, 68 (1963) 5387.
12. R. A. Helliwell, J. P. Katsufrakis, K. E. Marks, D. Reed and M. L. Trimpi, *Stanford Univ., Electronics Labs. Rept.* 62–046, Calif., March 1962.
13. S. F. Hansen, *J. Geophys. Res.*, 68 (1963) 5925.
14. G. R. A. Ellis, *J. Atmos. Terrest. Phys.*, 10 (1957) 302.
15. R. Gendrin, *Planet. Space Sci.*, 5 (1961) 274.
16. M. A. Ginsburg, *Phys. Rev. Letters*, 7 (1961) 339.
17. B. A. McInnes, *Australian J. Phys.*, 14 (1961) 218.
18. T. Ondoh, *J. Geomagnet. Geoelec.*, 11 (1961) 77.
19. R. M. Gallet and R. A. Helliwell, *J. Res. Natl. Bur. Std.*, D63 (1959) 21.
20. R. L. Dowden, *J. Geophys. Res.*, 67 (1962) 2223.
21. R. L. Dowden, *J. Geophys. Res.*, 67 (1962) 1745.
22. R. L. Dowden, *Planet. Space Sci.*, 11 (1963) 361.
23. R. L. Dowden, *Australian J. Phys.*, 15 (1962) 490.
24. R. Q. Twiss, *Australian J. Phys.*, 11 (1958) 564.
25. V. L. Ginsburg and V. V. Zelezniakov, *Soviet Astron.—AJ (English Transl.)*, 2 (1958) 653.
26. P. Wild, S. F. Smerd and A. A. Weiss, *Ann. Rev. Astr. Astrophys.*, 1 (1963) 291.
27. J. L. Hirshfield, *Nature*, 198 (1963) 20.
28. J. Schneider, *Phys. Rev. Letters*, 2 (1959) 504.
29. G. Bekefi, J. L. Hirshfield and S. C. Brown, *Phys. Rev.*, 122 (1961) 1037.
30. V. Eidman, *Soviet Phys. JETP (English Transl.)*, 7 (1958) 91.
31. C. E. McIlwain, *J. Geophys. Res.*, 65 (1960) 2727.
32. G. R. A. Ellis, *Australian J. Phys.*, 17 (1964) 63.
33. G. R. A. Ellis and P. M. Mc.Culloch, *Australian J. Phys.*, 16 (1963) 380.

MICROPULSATIONS OF THE EARTH'S ELECTROMAGNETIC FIELD IN THE FREQUENCY RANGE 0.1–10 c/s

J. A. JACOBS and T. WATANABE

Institute of Earth Sciences, University of British Columbia, Vancouver (Canada)

SUMMARY

This survey paper deals with micropulsation of the Earth's electromagnetic field whose ultimate source lies beyond the ionosphere. Pulsations initiated by causes at lower altitudes, such as those induced by lightning strokes, are not considered. The frequency range of ELF emissions is not well defined and an upper limit of 10 c/s has been rather arbitrarily chosen, although geomagnetic micropulsations at higher frequencies may occur. The lower limit has been set at 0.1 c/s. Pulsations in this frequency range have been broken into two classes depending on whether their period is greater or less than 3 seconds. The association of micropulsations with other upper atmospheric phenomena – magnetic storms, aurorae, cosmic rays and ionospheric absorption – is also discussed.

RÉSUMÉ

Cette revue a pour objet les micropulsations du champ magnétique terrestre dont la source fondamentale se trouve au delà de l'ionosphère. Elle ne s'intéresse pas aux pulsations provoquées par des causes provenant d'altitudes inférieures telles que celles induites par des éclairs. La gamme de fréquence d'émissions aux fréquences extrêmement basses (ELF) n'est pas bien définie et la limite supérieure de 10 Hz a été choisie d'une façon arbitraire bien que des micropulsations géomagnétiques peuvent se produire à des fréquences plus élevées. La limite inférieure a été fixée à 0,1 Hz. Les pulsations dans cette gamme de fréquence ont été classées en deux catégories suivant que la période est plus grande ou plus petite que 3 secondes. Les auteurs étudient

aussi l'association des micropulsations avec d'autres phénomènes de la haute atmosphère: orages magnétiques, aurores, rayons cosmiques et absorption ionosphérique.

1. INTRODUCTION

Geomagnetic micropulsations are fluctuations of the Earth's magnetic field with periods from about 0.1 sec to 10 min. Most work has been done in the lower frequency end of this range and the literature has recently been extensively reviewed [Jacobs and Westphal, 1963]. In recent years interest has spread to higher frequencies, particularly to oscillations around 1 c/s. Around the turn of the century, van Bemmelen noticed micropulsations with about a 1 sec period and Ebert [1906], using an induction magnetometer, reported the existence of pulsations with frequencies from 6 to 40 c/s. Harang [1936] observed micropulsations with periods less than 1 sec at Tromsö and in the same year Sucksdorff found them with periods around 2 to 3 sec at Sodankyla. Since the IGY a large number of investigators in many countries have studied the phenomena using equipment with higher sensitivity and a faster speed of recording. Campbell [1960] found that in California the transition of the dominant received natural signals from slow tail sferics to geomagnetic micropulsations occurred between 2.0 and 0.2 c/s, although Vladimirov and Kleimenova [1962] conclude that the highest frequency of geomagnetic oscillations is 20 c/s. This review paper will be limited to micropulsations of the Earth's electromagnetic field whose ultimate source is beyond the ionosphere. Thus Earth–ionosphere cavity resonances – predicted by Schumann [1952] – which are induced by lightning strokes, will not be considered. König [1959] has reviewed our knowledge of atmospherics in the frequency range under discussion.

The whole subject of micropulsations has been plagued by a lack of uniformity in notation and definitions of the different phenomena. Some attempt at rectifying this has been made [Jacobs *et al.*, 1963; Matsushita, 1963] and the subject was fully discussed at a committee meeting of IAGA at the last IUGG General Assembly, held at Berkeley (August, 1963). In this review the symbolism and notation of the various investigators will be clearly defined but will not be changed in order to avoid further confusion.

The most commonly used notation in the frequency range under consideration is that due to Benioff [1960], Troitskaya [1961] and Tepley [1961a, b]. Benioff's Type A oscillations are nearly sinusoidal in shape with periods ranging from about 0.3 to 2.5 sec. The wave trains usually exhibit beats and have been called "pulsations of the pearl beating type" by Troitskaya [1957]. Benioff's Type B oscillations have nearly sinusoidal forms with periods ranging from about 2 to 8 sec. Troitskaya [1961] recognizes four characteristic types of pulsations in the period range 1–15 sec:

(1) irregular pulsations with periods from 1 to 15 sec (SIP)
(2) pulsations of pearl type (PP)
(3) intervals of pulsations diminishing by periods (IPDP)
(4) continuous pulsations with small periods ($T < 15$ sec)

In an analysis of the data in the frequency range 0.5 to 5 c/s obtained from the Lockheed Magnetic Observatory at Palo Alto, Tepley [1961a, b] refers to the signals as "hydromagnetic (hm) emissions" since their properties seem consistent with their generation either above or high in the ionosphere and with their propagation downward through the ionosphere by hydromagnetic waves. Signals of similar appearance but of extremely high amplitude and associated with magnetic storms have been called "solar whistles" by Duffus *et al.* [1958, 1960b]. An hm emission is defined as an oscillation at a single frequency which may, however, vary slowly with time. In contrast pearls or Type A oscillations may include a number of frequencies, i.e. a pearl oscillation train may include a number of distinct hm emissions.

In a later paper, Tepley and Wentworth [1962] extend their classification of micropulsations in the frequency range 0.4–7 c/s into hydromagnetic emissions and noise bursts. Hydromagnetic emissions are characterized by well-defined frequency bands on a sonagram, and often exhibit a regular and reproducible fine structure. The corresponding waveforms are approximately sinusoidal and exhibit an irregular amplitude modulation pattern. In noise bursts, the signals are characterized by a broad spectral energy distribution. Well-defined frequency bands are not observed on sonagrams. The waveforms are jagged, and the signals are frequently superimposed on micropulsations of longer period, in which case they may be interpreted as the high-frequency components of the latter events. It seems likely that both SIP and IPDP [Troitskaya, 1961] consist of a superposition of both hm emissions and noise bursts. Furthermore, different SIP and IPDP events are likely to vary greatly in appearance so that classification of signals into these categories may be highly subjective. Both Type A and B [Benioff, 1960] oscillations fall into the category of hm emissions.

In the following discussion of the observational results, some of the variances may be due to different equipment with different sensitivity and frequency response. Moreover many investigations have been made using telluric (Earth current) measurements rather than magnetic records. Since some results depend on the location of the recording station, Table I gives both the geographic and geomagnetic coordinates of all stations referred to in this paper.

TABLE I

Geographic and Geomagnetic Coordinates of stations referred to in this report

	Geographic Latitude	*Geographic Longitude*	*Geomagnetic Latitude*	*Geomagnetic Longitude*
Bangui	4°26′N	18°34′E	4.8°N	88.5°
Byrd	79°59′S	120°01′W	70.6°S	336.0°
Chambon-La-Forêt	48°01′N	2°16′E	50.4°N	83.9°
Charcot	69°30′S	139°02′E	78.3°S	234.5°
Churchill	58°42′N	94°03′W	68.7°N	322.8°
College	64°51′N	147°50′W	64.7°N	256.5°
Dumont d'Urville	66°40′S	140°01′E	75.6°S	231.0°
Great Whale	55°17′N	77°46′W	67.8°N	350.0°
Isabella	35°40′N	118°28′W	42.6°N	303.1°
Kerguelen	49°21′S	70°12′E	56.5°S	127.0°
Legon	5°38′N	0°12′W	9.6°N	70.2°
Lovozero	68°01′N	34°01′E	63.1°N	126.1°
Macquarie Island	54°30′S	158°57′E	61.1°S	243.1°
Memambetsu	43°55′N	144°12′E	34.1°N	208.3°
Palo Alto	37°26′N	122°10′W	43.7°N	298.4°
Sodankyla	67°22′N	26°39′E	63.7°N	120.0°
Tamanrasset	22°47′N	5°32′E	26.0°N	81.5°
Tromsö	69°40′N	18°57′E	67.2°N	116.8°
Tucson	32°14′N	110°57′W	40.4°N	312.1°
Uppsala	59°53′N	17°39′E	58.7°N	104.5°

2. MICROPULSATIONS WITH PERIODS BETWEEN 3 AND 10 SEC

This section includes Benioff's Type B and Troitskaya's SIP, but not her PP or IPDP. Maple [1959a, b] carried out an intensive analysis of the magnetic records from Tucson covering a 12 day interval. Oscillations centred around an 8 sec period occurred chiefly during the night hours and were most numerous in the early morning (2300–0500 LMT) when sporadic E is least prevalent in that area. The oscillations in this frequency band were also closely related to the degree of magnetic disturbance, the threshold level for their appearance being at $K=3$. Campbell [1960] also observed sinusoidal pulsations in southern California with periods from 5 to 8 secs during the night hours, and rapid oscillations with average periods around 8 sec have been reported at Eskdalemuir [Holmberg, 1953] during times of large magnetic disturbances. Maple suggests that the oscillations are excited by moving irregularities of F-region ionization, the oscillations only appearing at times of magnetic disturbance when the excitation is near the resonance frequency of the ionospheric region.

Troitskaya [1961] found her SIP on records on both quiet and disturbed days, a preliminary analysis showing that a 6-sec period is observed most frequently. The pulsations have their largest amplitude in the polar regions and were frequently observed simultaneously in the Arctic, middle latitudes and the Antarctic. SIP always appear when pt* or bay disturbances are registered on standard magnetic records, i.e. they represent a micro-structure of these well-known macroscopic forms of disturbance of the Earth's magnetic field. When a bay is developing after pt, SIP are more intensive, their spectral distribution is more complicated, and their duration is longer. Yanagihara [1959] noticed that at Memambetsu a train of micropulsations with periods from 5 to 10 sec often appeared in association with pt beginning almost simultaneously with the accompanying pt. He also found, in contrast to pt activity, that the activity of these micropulsations is greater at sunspot maximum. A very important peculiarity of SIP is that they sometimes appear when notable macroscopic disturbances of the field are absent. The diurnal variation of SIP occurrence shows a maximum near local midnight during disturbed conditions and in the early morning hours for quiet field conditions. A high degree of correlation is found between SIP and aurorae – the predominant period of SIP coinciding with the main period of intensity change of aurorae.

Benioff [1960] also found that the occurrence of his Type B pulsations with large amplitudes coincided with times at which visible aurora were reported locally, and Alperovich [1961] found a very specific dependence between the amplitudes of these short period pulsations and the intensity of auroral activity at Lovozero.

Kato and Saito [1959] found that short period micropulsations appear

---

* Pulsations train usually occurring at night with a period from about 40 to 150 secs and lasting from several minutes to tens of minutes.

mainly at night in middle latitudes. Selzer [1961] observed micropulsations with periods from 3 to 10 sec (usually 6 sec) quite often, even under magnetically quiet conditions. They occur most frequently a little before local midnight, not only at the middle latitude stations Chambon-La-Forêt (in the northern hemisphere) and Kerguelen (in the southern hemisphere) but also at an equatorial station (Bangui). Hutton [1961] also found micropulsations with periods from 5 to 15 sec at an equatorial station (Legon) during night hours, although such micropulsations were a relatively rare phenomenon, having occurred on only 22 days during a 2-year period. According to Schlich [1961], micropulsations with periods between 3 and 6 sec may appear at any hour of the day at Charcot in Terre Adelie, a little south of the southern auroral zone. Heacock [1963] investigated telluric current micropulsations at five stations near the auroral zone. The diurnal variation data suggest a spiral pattern of occurrence in the auroral zone for aurorally associated micropulsations (period 3–20 sec). The pattern is visualized as being fixed in space, the Earth rotating beneath it. Such a spiral pattern may also exist at lower latitudes.

3. MICROPULSATIONS WITH PERIODS BETWEEN 0.1 AND 3 SEC

This section includes Benioff's Type A and Troitskaya's pulsations of pearl type (PP). Type A oscillations are essentially nocturnal in southern California, their occurrence increasing rapidly after sunset and falling rapidly after sunrise. The diurnal variation of occurrence frequency seems to be different in high latitudes, however. Sucksdorff [1936] found that micropulsations with periods around 2 to 3 sec are most likely to occur during daylight hours at Sodankyla. Harang [1936] observed that pulsations with periods around 1 sec or less appear most frequently at Tromsö between 0800–1000 LMT with a second maximum between 2000–2200 LMT. Benioff [1960] found the maximum occurrence frequency at Uppsala to be between 0700–1000 LMT.

Troitskaya [1961] also found that pearls in middle latitudes occurred mainly during the night hours, although in polar regions, they may appear at any time. Also in the polar regions short separate bursts are seen whereas in middle latitudes continuous series of pearls are more often observed. The predominant period is also different at middle and polar latitudes. Heacock and Hessler [1962] found that at College pearl-type telluric current pulsations occurred mainly in the daytime. Some diurnal variation in the pulse period was indicated. Thus from 1800 to 0600 UT (local daytime) the pulse periods average 2.4 sec while from 0600 to 1800 UT the periods average 1.9 sec. This may be explained by greater daytime attenuation of the shorter period pulses. The appearance of pearls usually coincides with times when other disturbances within the observed period range were at a low level, i.e. pearls as opposed to SIP do not represent simply the microstructure of some other form of macroscopic disturbance of the Earth's electromagnetic field. There also appears to be a rough inverse relationship to the solar sunspot cycle. Very likely the ionosphere is an opaque shield for waves of this frequency most of the time, their occasional appearances corresponding to intervals during which the ionosphere becomes transparent for oscillations in this period range. Benioff found that at times the correlation between recordings at two California stations, Isabella and Palomar, some 150 miles apart, was nearly perfect. Duffus *et al.* [1960a] have also reported occasions when pulsations of frequency about 1 c/s were recorded at two stations more than 500 miles apart (E–W) in Canada. Troitskaya [1961] often observed pearls (PP) over a very wide area, mainly during the time intervals 1600–2000 and 2200–0200 UT, although there is probably some local control. During great magnetic storms, pearls may be excited simultaneously in the Arctic, the Antarctic and in middle latitudes. Separate bursts may occur simultaneously over the same wide area on quiet days as well.

Jacobs and Jolley [1962] examined the records for pearls from a number of stations between October 1960 and February 1961. In many cases pearls were observed progressively earlier at eastern stations, their onset moving westward at a rate of approximately 14°/hour – i.e. their occurrence appears to be LMT dependent. On some occasions this linear trend extended right round the world, pearls reappearing at a station 24 hours after their first occurrence there. Using data taken during February 1962 at College and Macquarie Island, Dawson [1963] found a lack of agreement with regard to pearl events. College and Macquarie Island have conjugate latitudes but miss by 700 km in the east–west direction. He found a tendency for pearl events to occur on the same dates, but the beginning and terminal times were often different, and matching of individual beats was impossible.

The "pearl-beating" characteristic has been attributed to the superposition of two wave trains of slightly differing frequencies. However, the results indicate that the amplitude modulation envelope is usually associated with a far more complex superposition of waves than was previously realized. Tepley [1961a, b] has shown that hm emissions often display a fine structure, characterized by wave trains of increasing frequency. The "pearl-beating" characteristic observed in amplitude–time plots results from a superposition of a number of similar wave trains of relatively short duration and rapidly increasing frequency, each wave train being delayed in time by a comparable amount from the preceding train.

Vozoff *et al.* [1962] carried out a detailed analysis of one hour's recording of "impure" pearls. They found that most of the energy was concentrated in three bands – two, relatively narrow, centred at 0.53 c/s and 0.67 c/s and a much broader low frequency band. The 0.53 c/s band was somewhat smaller in amplitude and most of the character was due to structure within the 0.67 c/s band. When the records were re-analysed by thirds it became evident that there occurred drastic changes in the directional orientation and amplitudes of the 0.53 c/s components. Regardless of the picture one uses to explain the fields, it would appear that the sources of the 0.53 and 0.67 c/s peaks must be independent of one another, and they conclude that the changes, in time, of the relative amplitudes and orientations of the two major bands imply that the source oscillations can be excited independently.

Francis and Karplus [1960], and Francis *et al.* [1961] considered in some detail the transmission of hydromagnetic waves through the ionosphere. Hydromagnetic wave attenuation theory indicates an inverse relationship between the amplitude transmission of hydromagnetic waves and ionospheric ion density. Thus we may expect the signal amplitude to be relatively small during daylight hours and to become relatively large at night. This is in agreement with observation at middle latitude stations. Tepley [1961b] suggested that hm emissions are generated by the interaction during magnetically quiet conditions of solar proton streams with the geomagnetic field. (At such times there is a close correlation between the occurrence of hm emissions and polar cap absorption which is attributed to solar proton streams.) Troitskaya [1961] has reported a correlation between the occurrence of pearl oscillations (hm emissions) and solar-flare cosmic rays – the latter may also be closely correlated with polar-cap absorption events. It is interesting that the ratio of the frequencies typical of VLF emissions (near 5 kc/s) and hm emissions (0.5–5 c/s) is of the order of the mass ratio of protons to electrons. This observation leads to the suggestion that VLF and hm emissions may be generated by mechanisms which are at least qualitatively similar. As in the theory of VLF emissions, the wave frequency of the hm emission may be directly related to the geomagnetic field strength in the region where the emission is generated. Thus it is anticipated that proton streams moving in regions of greater geomagnetic field strength would generate hm emissions at higher frequencies. This is consistent with observations [Tepley, 1961b; Duffus *et al.*, 1958, 1960b; Troitskaya, 1961], which indicate that, although the higher oscillation frequencies (near 5 c/s) occur only rarely during quiet periods, they are relatively common during periods of unusual solar activity.

Tepley and Wentworth [1962] found that the highest observed emission frequency decreases with increasing geomagnetic latitude. They associate the hm-emission frequency with the bounce frequency of geomagnetically trapped electrons mirroring above the observation point. The highest observed hm-emission frequency corresponds closely with the maximum electron bounce frequency predicted by their model [Wentworth and Tepley, 1962]. Jacobs and Watanabe [1961] have tried to explain pearl type pulsations as hydromagnetic oscillations in the upper atmosphere as well as the exosphere below a height of about 2000 km. The height-distribution of the Alfvén velocity selects, from the complete spectrum of hydromagnetic waves which originated in outer space, those of particular frequencies with the result that their intensity is enhanced at the Earth's surface. The period of the enhanced wave is of the order of one to several secs depending on solar conditions. The enhancement is also of the correct order of magnitude for the intensity of pearls observed at the Earth's surface.

In addition to Tepley and Wentworth [1962] in America, Mainstone and McNicol [1962]in Australia, and Gendrin and Stefant [1962] in France have used frequency–time displays (sonagrams) to investigate micropulsations. They all found evidence of fine structure in the dynamic spectrum of short period pulsations with frequencies from fractions of one c/s to several c/s, which consists of trains of rapidly increasing frequency emissions repeated at intervals of about 2 min, the whole resembling a fan shaped structure. Gendrin and Stefant found that the product of the repetition period of the rising emissions and their mean frequency was fairly constant even though the mean frequency varied appreciably. Jacobs and Watanabe [1963] have interpreted the fan shaped structure in the sonagrams as caused by hydromagnetic oscillations in the lower exosphere excited by several bunches of charged particles trapped in the Earth's magnetic field. At the time of trapping a train of geomagnetic micropulsations will be observed in those regions where the trapping magnetic lines of force meet the Earth's surface. The charged particles in each bunch travel along the magnetic line of force towards the conjugate mirror point (in the southern hemisphere, say) giving rise to a train of similar pulsations there half a bouncing period later. After one bouncing period, from the beginning, the micropulsations reappear in the northern hemisphere, and after one and a half periods, they appear in the southern hemisphere again, and so forth. Correspondence of micropulsations between a pair of conjugate areas in the two hemispheres with a time-difference of half a bouncing period has actually been found in some cases by Yanagihara [1963] and Lokken *et al.* [1963]. The time-difference suggests that the velocity of the trapped particles is of the order of 10^8 cm/sec. Assuming that a secondary disturbance is emitted from each place of origin of the micropulsations so that pulsations observed at lower latitudes would consist of various frequencies each of which is determined by the local conditions of the lower exosphere and ionosphere, Jacobs and Watanabe show that the dynamic spectrum consists of several discrete frequencies with certain repeating periods which are shorter at the lower frequencies – which reflects the essential features of the experimental sonagrams.

Heacock and Hessler [1962] investigated "pearl type" telluric current micropulsations at College, Alaska. They found a number of occasions on which essentially only one pulse frequency was present in a pearl-type micropulsation sequence. On each such occasion there was a sequence of pearls nearly equally spaced several minutes apart. They call such a sequence of pearls formed by a nearly constant pulse frequency a necklace of pearls. Thus a pearl necklace is characterized by two constants, a pulse frequency and a pearl spacing. When two or more pearl necklaces are superimposed, "beads" are formed by the interactions of the different pulse frequencies. They use the names "pearl" and "bead" to distinguish the two observed types of amplitude enlargements, i.e. "pearls" are the equally spaced intervals of amplitude enlargements associated with a single pulse frequency, whereas "beads" are the beats produced by interacting frequencies.

There is the possibility of explaining pearl necklaces in terms of bunches of trapped protons oscillating between hemispheres with periods of 1–5 sec and drifting around the Earth in a few minutes. According to this idea, a pearl is formed as the proton bunch drifts over the recording station, each successive pearl representing a revolution about the Earth by the drifting protons. Tepley and Wentworth [1962] found correlations between hydromagnetic emissions (pearls) and X-ray events and for this reason suggested that the responsible particles are electrons rather than protons. It was pointed out by Jacobs and Jolley [1962] that the solar wind velocity is too low to account for trapped particles with bounce periods 1–5 sec. However Heacock [1963] has suggested the possibility that the particles are trapped in the solar plasma, thus arriving at the Earth with a higher velocity than the plasma front. In fact, it seems necessary to assume this trapping within solar plasma if trapped radiation is assumed to be the source of pearls, since Troitskaya and Mednikova [1961] found that pearl-type micropulsations frequently appear during the few minutes following a magnetic storm sudden commencement (ssc) and/or during the several hours preceding the ssc.

4. MICROPULSATIONS, MAGNETIC STORMS AND OTHER UPPER ATMOSPHERIC PHENOMENA

Troitskaya *et al.* [1962] considered the fine structure of magnetic storms with respect to micropulsations ($T < 20$ sec). Out of 30 storms investigated, 28 had PP excited during the interval 0–12 hours before the onset of the storm – usually some tens of minutes–2 hours before the beginning of the storm. The duration of the series of PP is generally 10 to 15 min and seldom exceeds 2 hours. Several cases were discovered where PP pulsations occurred simultaneously with different periods at different stations. Cecchini *et al.* [1960] have also observed PP excited before the onset of magnetic storms at Chambon-La-Forêt. The sudden commencement of the storm (ssc) consists (in the period range less than 20 sec) of a series of pulsations ($T \approx 8$–15 sec) diminishing in amplitude and lasting on the average 1.5–3 min. Short period PP are often superimposed on the ssc oscillations. (Out of 35 cases of ssc investigated by Troitskaya *et al.* [1962], 21 showed PP superimposed on the ssc pulsations.)

At the beginning of the initial phase of magnetic storms when the solar corpuscular stream is stopped by the Earth's magnetic field which becomes compressed, a sharp diminishing of PP periods is observed. The periods appear to decrease more at higher values of K_p. During great magnetic storms the appearance of pearls coincides with that of aurorae in middle latitudes, with a sharp drop in the critical frequency in the F2 layer, and sometimes with periods of complete absorption in the ionosphere.

Investigations of a connection between PP occurrence and phenomena in the high atmosphere has led to the discovery that very often PP are excited during periods of sharp increases in cosmic-ray intensity in the stratosphere when the magnetic field is quiet. When the magnetic field is disturbed, the times of such intensive cosmic-ray bursts in the stratosphere coincide with the excitation of SIP. An analysis of the microstructure of magnetic storms in middle latitudes by Troitskaya [1961] showed the existence of a peculiar sequence of pulsations (IPDP) during the development of the storm. It begins as SIP and contains pearl series which, as a rule, diminish in periods ($T \approx 10$–1 sec). Troitskaya and Mednikova [1961] believe that IPDP represent an important morphological element of magnetic storms, because the beginning of several types of disturbances in the atmosphere and the ionosphere coincides with the beginning of IPDP (a sharp fall in $foF2$, the propagation of red aurorae into low latitudes, bursts of X-rays in the stratosphere, and a sharp increase in cosmic noise absorption). IPDP also coincide with times of the deepest penetration of aurorae into low latitudes and the highest depression of the H component of the Earth's magnetic field. Heacock and Hessler [1963] found that there was a marked tendency for micropulsations at College to occur during the first and the last hours of the main phase of a magnetic storm. Auroral evidence suggests that a narrow (in latitude) band of micropulsation occurrence existed, and that this band moved southward during the maximum part of the main phase.

Campbell and Leinbach [1961] investigated ionospheric absorption at times of auroral and magnetic pulsations. High latitude cosmic noise absorption may be classified into two categories – auroral absorption and polar cap absorption. Auroral absorption is closely related to auroral coruscations and magnetic micropulsations [Campbell and Rees, 1961] indicating that the ionization producing this type of absorption does not effectively shield micropulsation activity and may imply that magnetic micropulsations are largest in the E region. On the other hand decreased micropulsation activity during polar cap absorption, considered to be a result of D-region ionization by high energy protons, seems to be an example of ionospheric shielding of magnetic pulsations.

Bomke [1962] also found that at Baxter State Park (geomagnetic latitude 57°N) magnetic micropulsations coincided with visually observed light fluctuations of flaming aurorae. Heacock [1963] on the other hand found no such correlation at College – in fact a negative correlation was obtained between night-time PP events at College and the occurrence of aurorae. Bomke also concluded that the 1 c/s oscillations are connected with the absorption of auroral particles in the lower ionosphere (≈ 100 km). This is also the height of flaming aurorae determined by Campbell and Rees [1961] by optical triangulation in Alaska.

Campbell and Matsushita [1962] carried out an investigation of auroral-zone geomagnetic micropulsations with periods from 5 to 30 sec using a year's data from College. Micropulsation storms (sudden increases in amplitude followed by higher than normal activity) in the auroral zones are related to auroral zone electron bremsstrahlung, ionospheric currents and absorption disturbance phenomena. The data strongly imply that the observed micropulsations result from ionospheric currents set up at the onset of a storm with the arrival of bombarding electrons.

Micropulsations in the frequency range under discussion have also been recorded following nuclear explosions above the ionosphere. In the case of the Argus experiments (1958) micropulsations with periods from about 1 to 3 sec were recorded nearly simultaneously at almost all the IGY French stations (Chambon-La-Forêt, Tamanrasset, Bangui, Kerguelen, Dumont d'Urville and Charcot) [Selzer, 1959] and have been described in detail by Eschenbrenner *et al.* [1960]. The characteristics of micropulsations observed on the records at Chambon-La-Forêt following the Starfish experiment (1962) have been analysed in detail by Roquet *et al.* [1962]. They appear as a microstructure of a bay-like disturbance and may be divided into four phases: A, lasting from 3 to 4 sec, B and C, both lasting about 1 min, and the final phase D. The phase A is an impulse with pulsations initially of period 1.5 sec, decreasing to 0.5 sec. The phases B and C consist of trains of irregular pulsations with a dominant period of about 2 sec for the B phase and about 4 to 8 sec for the C phase. Micropulsations in the D phase resemble pt's.

5. FINAL REMARKS

Vladimirov and Kleimenova [1962] analysed the structure of the Earth's electromagnetic field in the frequency range 0.5–100 c/s using data between 1959 and 1961 from stations in the U.S.S.R. Most of the observed disturbances in this range are associated with lightning discharges (atmospherics), although the microvariations observed during relatively prolonged intervals of time (trains, stable oscillations, and "pearls") cannot be thus explained. They concluded that the largest number of microvariations is found in the frequency range 8–10 c/s. Trains of these oscillations may be observed at all hours of the day. Oscillations in the interval 0.5–1.5 c/s are registered rather infrequently, usually before sunrise (0400–0600 LMT). They are generally stable oscillations with approximately constant amplitudes.

Microvariations in the range 3–5 c/s are registered least frequently—during the period of observation no trains were observed in this frequency interval. Oscillations of the "pearl" type are usually observed on quiet days, whereas stable oscillations are observed on both quiet and disturbed days. The orientation of the polarization axis is not constant but varies continuously even at the same place and at the same frequency, although it remains practically constant during a single pearl. In this respect Dawson [1963] found that pearl type micropulsations in the auroral zones are transverse waves propagated along magnetic field lines. Linear and both clockwise and counterclockwise elliptical polarizations are observed, but counterclockwise rotation predominates. In elliptical polarization the major axis shows a tendency to precess in the same direction as the rotation.

Lokken *et al.* [1963] investigated electromagnetic background signals in the vicinity of 1 c/s. They found that the natural background consisted of a comparatively steady, low-level "white" continuum relieved occasionally by the intrusion of either regular or impulsive geomagnetic signals, as well as by the normal occurrence of sferics. The amplitude and the frequency of the intrusions are latitude dependent. Characteristic regularly repeating signal reinforcement patterns are sometimes observed in the auroral zones. Such patterns are displaced in time at conjugate points by half their respective period [cf. Yanagihara, 1963].

Yanagihara [1963], using data obtained at Great Whale (GW) and Churchill (CH) in the Canadian Arctic and at Byrd (BY) in Antarctica by the Pacific Naval Laboratory and Stanford University during January 1961 [Lokken *et al.*, 1961] classified auroral zone micropulsations with periods from 0.3 to 10 sec into two main groups, viz. noise bursts and continuous type oscillations. Noise bursts include quite a wide range of frequencies and their waveforms are therefore irregular. They occur suddenly and die out after a short duration. Continuous type micropulsations on the other hand have regular waveforms in general, and Yanagihara divided them into three sub-classes. One of them is the pearl type of oscillation and the other two are defined by their period, either shorter or longer than 3 sec. A short account of this rather fundamental analysis will now be given.

Noise bursts are observed mainly during the hours 2100–0200 LMT at GW, their shortest period being 0.2–0.3 sec. The main part of a noise burst decreases abruptly away from the central area of activity. Thus Yanagihara found many cases where there was no evidence of a noise burst at CH whereas the GW-record clearly showed a noise burst, and vice versa. (The distance between CH and GW is about 1,100 km.) Generally speaking, there is a conjugate relationship between BY and GW (or CH) for noise bursts. A burst at BY corresponds to one at GW in some cases and to one at CH in others. The conjugacy is thus rather loose (in this sense). The charged particles responsible for noise bursts do not seem to be existing trapped particles, but new ones coming from outside the magnetosphere (because of their loose conjugacy). Their starting points are not necessarily symmetric with respect to auroral zone conjugate points.

The difference between PP and noise bursts is quite clear since PP has a simple or single band of frequencies compared to the broad band of noise bursts. During almost all of the active periods of PP in one auroral zone, similar activity can be traced in the other auroral zone, although the details of simultaneous correspondence are absent and the degree of activity on the whole is often different. On the other hand, there are some remarkable cases when pearls on a necklace occur alternately in the northern and southern auroral zones, the maximum activity at BY occurring midway between a pair of maxima at the northern stations. This fact suggests strongly a bouncing agent with a bounce time of 120 sec—the time between the appearance of consecutive pearls on a necklace. The mean velocity of the agent is thus of the order of 10^8 cm/sec, which is the same as the velocity of solar particles deduced from the time delay between a solar flare and the commencement of a magnetic storm. Solar protons trapped in the geomagnetic field thus appear to be the most probable agents responsible for PP, exciting resonant oscillations in the lower exosphere. The trapped protons do not necessarily form a single bunch—they may be distributed at random along a line of force. The details of the PP-variation would show in this case no apparent relationships between northern and southern auroral zone stations.

Continuous micropulsations with periods from 0.3 to 3 sec (CPsp*) are similar to PP. They differ only by the lack of bunching in the activity of the constituent micropulsations. The change from PP to CPsp is generally gradual, and these two classes are sometimes mixed on the record. Micropulsations with periods from 0.3 to 3 sec occur in PP type of activity generally during the period 0200–0600 LMT, and in the continuous type (CPsp) from 0600–1100 LMT. The generation mechanism is considered to be the same as that for PP, and similar conjugate relationships hold. Continuous micropulsations with periods from 3 to 10 sec (CPlp*) are observed conspicuously

---

* CPsp = continuous micropulsations (short period); CPlp = continuous micropulsations (long period).

from 1300–1800 LMT. Conjugate relationships are quite similar to those for PP, although details of such simultaneous correspondence are absent.

Yanagihara also studied in some detail the simultaneous correspondence of micropulsations with frequencies above several c/s between GW, CH and BY, and concluded that the existence of an outside agency is highly probable. The whistler mode of propagation is not a suitable explanation of the conjugacy—the travel time is too long for the frequency range under consideration to explain simultaneous occurrences, which at GW and BY agree within an uncertainty of the order of 1 sec. The diurnal variation is also very different from that of world-wide thunderstorm activity, although the diurnal variation of the background level is quite similar [Balser and Wagner, 1962]. High energy electrons trapped in the Earth's magnetic field are assumed tentatively to be the origin of these higher frequency (2–30 c/s) oscillations. When they reach the end of the field lines, they may excite a resonant oscillation or emit an electromagnetic field with the frequencies under consideration.

Ness *et al.* [1962] in a study of magnetic field fluctuations on the Earth and in space consider the observed micropulsations as the output of a system whose transfer function (frequency characteristic) is not constant. Thus although the input to the system (the sources) may be identical, differences associated with system changes are observed at the output. The resonance frequencies (eigen modes of oscillation) of the system are independent of the source characteristics and depend only on the distribution of physical parameters within the system. However, the relative amplitudes and phases of each eigen mode excited by a particular source is dependent on the source characteristics. It is possible that a detailed study and analysis of the frequency spectra of micropulsations with regard primarily to the existence and identification of distinct modes rather than concerned with relative amplitudes will allow a determination of the model which best represents the oscillating system.

REFERENCES

Alperovich, L. V., *Geomagnetism and Aeronomy* (Am. Geophys. Union translation), Vol. 1, 1961, p. 495.

Balser, M. and C. A. Wagner, *J. Geophys. Res.*, 67 (1962) 619.

Benioff, H., *J. Geophys. Res.*, 65 (1960) 1413.

Bomke, H. A., *J. Geophys. Res.*, 67 (1962) 177.

Campbell, W. H., *J. Res. Natl. Bur. Std.*, 64D (1960) 409.

Campbell, W. H. and H. Leinbach, *J. Geophys. Res.*, 66 (1961) 25.

Campbell, W. H. and M. H. Rees, *J. Geophys. Res.*, 66 (1961) 41.

Campbell, W. H. and S. Matsushita, *J. Geophys. Res.*, 67 (1962) 555.

Cecchini, A., G. Dupouy, J. Roquet and E. Selzer, *Compt. Rend.*, 250 (1960) 4023.

Dawson, J. A., *Trans. Am. Geophys. Union*, 44 (1963) 41.

Duffus, H. J., P. W. Nasmyth, J. A. Shand and C. S. Wright, *Nature*, 181 (1958) 1258.

Duffus, H. J., J. A. Shand and C. S. Wright, *Nature*, 186 (1960) 141 (a).

Duffus, H. J., J. A. Shand and C. S. Wright, *Pacif. Naval. Lab. Rept.* 60–6, Dept. Natl. Defence, Esquimalt, Brit. Columbia, 1960(b).

Ebert, E., *Terrest. Magnet. Atmos. Elec.*, 12 (1906) 1.

Eschenbrenner, S., L. Ferrieux, R. Godivier, R. Lachaux, H. Larzillière, A. Lebeaux, R. Schlich and E. Selzer, *Ann. Géophys.*, 16 (1960) 264.

Francis, W. E. and R. Karplus, *J. Geophys. Res.*, 65 (1960) 3593.

Francis, W. E., A. J. Dessler and A. J. Dragt, at: *URSI–IRE meeting*, Austin, Texas, Oct. 1961.

Gendrin, R. and R. Stefant, *Compt. Rend.*, 255 (1962) 752.

Harang, L., *Terrest. Magnet. Atmos. Elec.*, 41 (1936) 329.

Heacock, R. R., *J. Geophys. Res.*, 68 (1963) 1871.

Heacock, R. R. and V. P. Hessler, *J. Geophys. Res.*, 67 (1962) 3985.

Heacock, R. R. and V. P. Hessler, *Trans. Am. Geophys. Union*, 44 (1963) 42.

Holmberg, E. R. R., *Monthly Notices Roy. Astron. Soc., Geophys. Suppl.*, 6 (1953) 467.

Hutton, V. Rosemary S., *J. Phys. Soc. Japan*, 17 (1961) Suppl. A-II, p. 20.

Jacobs, J. A. and T. Watanabe, *J. Atmos. Terrest. Phys.*, 24 (1961) 413.

Jacobs, J. A. and E. J. Jolley, *Nature*, 194 (1962) 641.

Jacobs, J. A. and K. O. Westphal, in: *Physics and Chemistry of the Earth*, edited by L. H. Ahrens *et al.*, Pergamon, Oxford, Vol. 5, 1963, pp. 253–307.

Jacobs, J. A., J. E. Lokken and C. S. Wright, *J. Geophys. Res.*, 68 (1963) 4373.

Jacobs, J. A. and T. Watanabe, *Planet. Space Sci.*, 11 (1963) 869.

Kato, Y. and T. Saito, *J. Geomagnet. Geoelec.*, 10 (1959) 221.

König, H., *Z. Angew. Phys.*, 11 (1959) 264.

Lokken, J. E., J. A. Shand, C. S. Wright, L. H. Martin, N. M. Brice and R. A. Helliwell, *Nature*, 192 (1961) 319.

Lokken, J. E., J. A. Shand and C. S. Wright, *Can. J. Phys.*, 40 (1962) 1000.

Lokken, J. E., J. A. Shand and C. S. Wright, *J. Geophys. Res.*, 68 (1963) 789.

Mainstone, J. S. and R. W. G. McNicol, at: *Intern. Conf. Ionosphere, London, July 1962*, Inst. Phys. and Phys. Soc., London, 1963, p. 163.

Maple, E., *J. Geophys. Res.*, 64 (1959) 1395 (a).

Maple, E., *J. Geophys. Res.*, 64 (1959) 1405 (b).

Matsushita, S., *J. Geophys. Res.*, 68 (1963) 4369.

Ness, N. F., T. L. Skillman, C. S. Scearce and J. P. Heppner, *J. Phys. Soc. Japan*, 17 (1962) Suppl. A-II, p. 27.

Roquet, J., R. Schlich and E. Selzer, *Compt. Rend.*, 255 (1962) 549.

Schlich, R., *IAGA Bull.*, No. 16c (1961) 73.

Schumann, W. O., *Z. Naturforsch.*, 7a (1952) 149.

Selzer, E., *Compt. Rend.*, 249 (1959) 1133.

Selzer, E., *IAGA Bull.*, No. 16c (1961) 63.

Sucksdorff, E., *Terrest. Magnet. Atmos. Elec.*, 41 (1936) 337.

Tepley, L. R., *Lockheed Missiles and Space Div. Sci. Rept. 2* (LMSD-8948 14), Palo Alto, Calif., 1961(a).

Tepley, L. R., *J. Geophys. Res.*, 66 (1961) 1651 (b).

Tepley, L. R. and R. C. Wentworth, *J. Geophys. Res.*, 67 (1962) 3317.

Troitskaya, V. A., *Ann. IGY*, 4 (1957) 322.

Troitskaya, V. A., *J. Geophys. Res.*, 66 (1961) 5.
Troitskaya, V. A. and M. V. Mednikova, *IAGA Bull.*, No. 16c (1961) 135.
Troitskaya, V. A., L. A. Alperovich, M. V. Mednikova and G. A. Bulatova, *J. Phys. Soc. Japan,* 17 (1962) Suppl. A-II, p. 63.
Vladimirov, N. P. and N. G. Kleimenova, *Izv. Akad. Sci. USSR, Geophys. Ser.* (AGU transl.), (1962) 852.
Vozoff, K., R. M. Ellis and G. D. Garland, *Nature,* 194 (1962) 539.
Wentworth, R. C. and L. R. Tepley, *J. Geophys. Res.*, 67 (1962) 3335.
Yanagihara, K., *J. Geomagnet. Geoelec.*, 10 (1959) 172.
Yanagihara, K., *J. Geophys. Res.*, 68 (1963) 3383.

A REVIEW OF THEORETICAL STUDIES ON VLF EMISSIONS

I. KIMURA

Faculty of Engineering, Kyoto University (Japan)

Many investigators have been interested in the phenomena of VLF emissions, and several hypotheses have appeared for their interpretation. However, even at the present stage, it would be quite difficult to say which hypothesis is the most credible, because the phenomena seem to be much more complex than has been supposed hitherto, and many new facts are coming to light. However, almost all probable mechanisms have been already taken into consideration, and consequently the real mechanism of VLF emissions is likely to be one or two among those already proposed.

The possible mechanisms can be classified into two types, an emission type and an instability type. Examples of the first type are Čerenkov, cyclotron and synchrotron radiation by high energy particles. The second category includes longitudinal and transverse instabilities in charged particle beams. Ellis [1957] and later Ondoh [1961] adopted the Čerenkov mechanism, MacArthur [1959] and Murcray and Pope [1960] took the proton cyclotron radiation into account, and Dowden [1962a] proposed the electron cyclotron radiation mechanism. From the standpoint of instability, travelling wave tube (TWT) theory was proposed by Gallet and Helliwell [1959], a double-beam instability was considered by Unz [1962] and a proton cyclotron hypothesis by Kimura [1961] and Maeda and Kimura [1963]. The field has been reviewed by Ellis, but some additional comments will be added here.

Considering first the emission mechanisms, the radiation intensity from Čerenkov radiation by electrons and protons, and from cyclotron radiation by protons with a velocity of the order of 10^4 km/s are all weak compared with the cyclotron radiation of electrons with the same order of velocity. In this sense Dowden's hypothesis may be the best. He has emphasized that the mirror motion of the radiating electrons can produce repeated trains of discrete emissions, which are observed in practice. However, according to a detailed examination made by Helliwell [1962], such a repetition of emissions can be a kind of echo train of the whistler mode.

Next we will discuss mechanisms due to instabilities. In the TWT theory proposed by Gallet it was considered that a TWT-like mechanism would give rise to an amplification of a whistler-mode wave. However, I have concluded that the condition for amplification in the microwave TWT can not always apply in the magnetosphere. On the other hand if an electron beam is injected into the magnetosphere plasma, an instability of space charge waves is known to arise in a frequency region below the ambient plasma frequency. Consequently the space charge wave in the VLF region will grow as it propagates in the magnetosphere, but the amplification of a VLF radio wave is a different matter.

Although Bell and Helliwell [1959] and Adachi and Mushiaki [1962] have obtained a spatially-growing mode from the dispersion equation deduced from Maxwell's equations, the continuity equation of current and the equation of momentum transfer of charged particles, I believe this mode is the space charge mode which was previously mentioned and not the whistler mode. Therefore we can conclude that the TWT mechanism in an electron beam which Gallet considered does not, in its simplest form, apply to VLF emissions. However further attention should be paid to such a growing space charge wave because it may produce VLF emissions if the wave energy could be converted efficiently to radio wave energy at a boundary of the ambient plasma or by some irregularity in the magnetosphere or ionosphere. Such a possibility is only at the stage of qualitative discussion and needs much more theoretical examination. In any case such an instability will have a role in the production of longitudinal bunching in the beam.

Next we will consider a transverse instability or an interaction of the whistler mode wave with a cyclotron mode of a proton beam, as proposed by Maeda and myself. The cyclotron motion of the protons is anticlockwise if viewed in the direction of the magnetic field, and the whistler mode wave is right-handed (clockwise) polarized. Hence there can not be any interaction between them in the usual way, but if the protons travel faster than the phase velocity of the whistler-mode wave, one observes the whistler mode wave as having left handed (anti-clockwise) polarization and interaction may then arise. Such an interaction is usually called "Cyclotron resonance" and is believed usually to cause an acceleration of the charged particles through the energy of a radio wave, so that the cyclotron motion builds up and the radio wave is attenuated. However, in the present case, the interaction causes an amplification of both cyclotron wave and whistler-mode radio wave by means of the loss of energy of the longitudinal particle velocity. This result can be deduced by using a theoretical treatment similar to those made by Bell, and can be explained by a simple electro-dynamical relation as illustrated in Fig. 1.

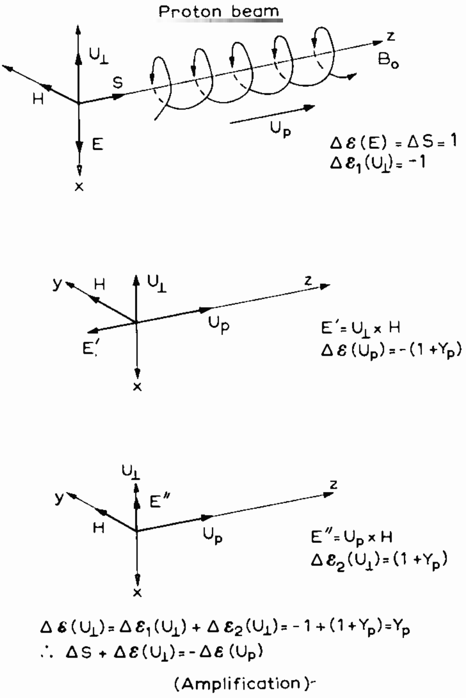

Fig. 1 Energy transfer between electromagnetic wave and proton stream in cyclotron resonance. $\Delta\varepsilon(\ )$ implies the energy change due to a change of the quantity in the bracket. E and H are electric and magnetic fields of the wave. S is the Poynting flux. $U_\perp$ and U_p are transverse and longitudinal velocities of the proton. $U_\perp \ll U_p$ is assumed. Y_p is the ratio of the proton gyrofrequency to the wave frequency. The change of energy is expressed in terms of the change in Poynting flux, ΔS (taken as unity in arbitrary units).

The condition for the amplification to arise is approximately the same as that used by Gallet and Helliwell at the start of their theory. That is,

$$\bar{V}_{\mathrm{p}} \cong v_{\mathrm{ph}} = \frac{c}{n} \tag{1}$$

where V_{p} is the velocity of the protons, v_{ph} is the phase velocity of the whistler-mode wave, and n is the refractive index given by

$$n^2 = f_0^2/f(f_H - f)\,. \tag{2}$$

As Gallet and Helliwell have deduced, the relation (1) in connection with refractive index (2) enables us to interpret the frequency–time characteristics of the discrete emissions. The amplification to be expected is given by

$$\Gamma = 6.33 \times 10^{-7}(N_{\mathrm{p}} f_{H\mathrm{e}}/f)^{\frac{1}{2}} \qquad \mathrm{dB/km} \tag{3}$$

where N_{p} represents the number density of the proton beam, and $f_{H\mathrm{e}}$ the gyrofrequency of electrons. A disadvantage of this mechanism in explaining VLF emissions is an insufficiency of this gain. In fact the gain to be expected in practice is about 20 dB per 1000 km of coupling if N_{p} is assumed to be 10^7 m^{-3} and $f_{H\mathrm{e}}/f$ is taken as 100.

If this is the mechanism, we have to look for a powerful noise source to be amplified. One possible source is atmospheric noise permeating throughout the magnetosphere, after having penetrated the ionosphere. In order to verify this hypothesis we need to know about VLF noise intensity in the ionosphere and magnetosphere in relation to the occurrence of VLF emissions. Fortunately statistics observed by Yoshida exist, indicating a good correlation between the occurrence of VLF emissions and whistlers for many stations. This result may imply that the VLF emissions are closely associated with the atmospherics which produce whistlers, although it might merely imply the interaction of the VLF emissions with the whistlers, as discussed later.

Here a transverse instability in longitudinal electron beam should be mentioned. A mutual interaction with a whistler-mode wave occurs when the electron beam travels in the opposite direction to the propagation of the whistler-mode wave. A mathematical treatment similar to that of the previous proton case shows that an evanescent type of instability arises in this electron whistler-mode interaction, so that there can be no amplification. This situation is illustrated in Fig. 2 by similar electro-dynamics to the proton case. The electrons gain transverse energy and the radio wave of the whistler mode is absorbed. As a result this effect seems to be unfavourable to Dowden's mechanism, because the radiated energy will be again absorbed by these emitting electrons.

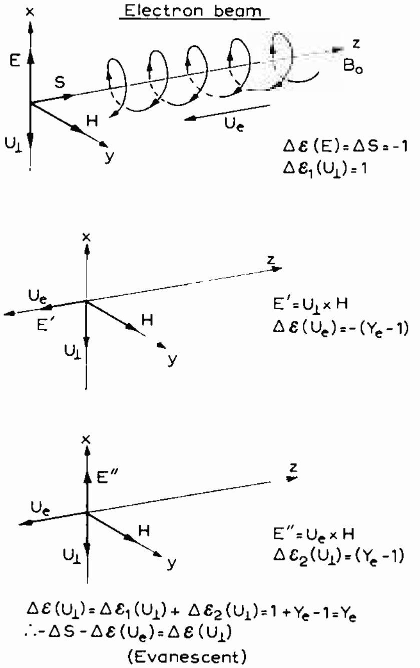

Fig. 2 Energy transfer between electromagnetic wave and electron stream in cyclotron resonance. $U_\perp$ and U_e are transverse and longitudinal velocities of the electron $U_\perp \ll U_e$ is assumed. Y_e is the ratio of the electron gyro-frequency to the wave frequency. The other notations are used as in Fig. 1.

Now we have to discuss hiss. Dowden [1962b] has reported that the TWT mechanism would be effective in producing hiss, because there is some narrow frequency region where a sufficient interaction over great distances is possible between the beam and the whistler-mode wave. An explanation of the hiss in terms of this frequency may be reasonable, provided that the TWT mechanism is replaced by another mechanism of amplification such as that described above.

Finally we add a few words on the interaction between whistlers and VLF emissions. It is clear that there will be no problem on this point as long as a mechanism of amplification is borne in mind as a main cause of the VLF emissions. On the other hand if a mechanism such as cyclotron radiation is concerned, another mechanism must be taken into account for the interaction. In this situation, we must recall that the electron beam can be energized by an transverse interaction with a whistler-mode wave, the latter wave being absorbed accordingly. If so, the energized electrons will emit cyclotron radiation. These processes are what Dowden is considering as the interaction mechanism. However it seems doubtful if such a process takes place efficiently.

In conclusion, much more knowledge about VLF emissions is needed in order to determine which hypothesis is really the most plausible. The following experiment, for instance, may provide a powerful clue to the solution. Whistler-mode echoes of a VLF transmitter may be observed, and a study made of whether a weakening of the echo is associated with an increase in VLF emissions.

REFERENCES

Adachi, S. and Y. Mushiaki, *IRE Trans.*, AP-10 (1962) 785.

Bell, T. F. and R. A. Helliwell, in: *Proc. Symp. Phys. Process in the Sun–Earth Environment*, Defence Research Board, Ottawa, Canada, DRTE 1025, 1960, p. 215.

Dowden, R. L., *J. Geophys. Res.*, 67 (1962) 1745 (a).

Dowden, R. L., *ibid.*, p. 2223 (b).

Ellis, G. R., *J. Atmos. Terrest. Phys.*, 10 (1957) 302.

Gallet, R. M., *Proc. IRE*, 47 (1959) 221.

Gallet, R. M. and R. A. Helliwell, *J. Res. Natl. Bur. Std.*, 63D (1959) 21.

Helliwell, R. A., *Nature*, 195 (1962) 64.

Kimura, I., *Rept. Ionosphere Space Res. Japan*, 15 (1961) 171.

MacArthur, J. W., *Phys. Rev. Letters*, 2 (1959) 491.

Maeda, K. and I. Kimura, in: *Space Research III*, Proc. Intern. Space Sci. Symp. COSPAR, Washington, D.C., 1962, edited by W. Priester, North-Holland Publ. Co., Amsterdam, 1963, p. 310.

Murcray, W. B. and J. H. Pope, *Phys. Rev. Letters*, 4 (1960) 5.

Ondoh, T., *J. Geomagnet. Geoelec.*, 12 (1961) 77.

Unz, H., *J. Atmos. Terrest. Phys.*, 24 (1962) 685.

Yoshida, S., (1963), *private communication.*

LES MICROPULSATIONS MAGNÉTIQUES DE FAIBLE PÉRIODE

R. GENDRIN
Centre National d'Études des Télécommunications, Issy-les-Moulineaux, Seine (France)

RÉSUMÉ

L'apparition d'émissions ELF dépend fondamentalement des conditions ionosphériques (jour–nuit, absorption aurorale, absorption dans la calotte polaire). Des émissions à pulsations rapides peuvent se présenter avec des maxima d'amplitude hors de phase, en des points conjugués magnétiquement. Il est nécessaire d'avoir une corrélation de ces phénomènes avec d'autres phénomènes géophysiques.

Une théorie pour la production de telles émissions ELF est basée sur une résonance de la cavité entre la basse ionosphère et la région dans laquelle la vitesse d'Alfvén est maximale. L'excitation peut se produire par ondes hydromagnétiques ou par électrons de faible vitesse. Un autre mécanisme possible pour la production des émissions consiste dans l'interaction des protons et du champ magnétique terrestre.

SUMMARY

The occurrence of ELF emissions depends fundamentally on ionospheric conditions (day–night, auroral and polar cap absorption). Noise with rapid pulsations ("necklace" appearance) can occur with maxima in amplitude out of phase at magnetically conjugate points. Correlation of these events with other geophysical phenomena is required.

One theory for the generation of such ELF noise is based on a resonance of the cavity between the lower ionosphere and the region where the Alfvén velocity is a maximum. The excitation may be by hydromagnetic waves

or low-velocity electrons. Another possible mechanism for noise generation involves the interaction between protons and the earth's magnetic field.

INTRODUCTION

Les principaux éléments du présent exposé sur les émissions ELF sont tirés de l'excellent rapport lu par le Prof. Jacobs, au congrès de Bad Homburg en août dernier, et qu'il n'a pas pu malheureusement présenter lui-même ici. Nous insistons cependant plus sur les théories proposées pour expliquer le phénomène des pulsations rapides structurées (PRS) consistant en des oscillations de fréquence croissante dont la période moyenne est t et répétées à des intervalles de temps T.

CLASSIFICATION

Reprennant l'excellente revue du Prof. Jacobs sur la question, on montre combien l'analyse en fréquence par le sonagraphe permet de simplifier une classification que les différents auteurs ayant étudié les enregistrements en amplitude en fonction du temps avaient rendu plutôt confuse.

ENREGISTREMENTS SIMULTANÉS

Les mêmes réserves s'imposent quant à l'observation simultanée des phénomènes en différents points. Notamment en ce qui concerne les enregistrements entre points conjugués dont les résultats sont si importants du point de vue théorique. Ainsi que Campbell l'a montré à Bad Homburg, le maximum de réponse en amplitude n'est pas une grandeur représentant réellement le phénomène dans le cas où plusieurs fréquences battent entre elles.

INFLUENCE DE L'IONOSPHÈRE

Compte-tenu de la variation rapide de l'absorption ionosphérique avec la fréquence au voisinage de 1 Hz, l'occurence des émissions ELF dépend fondamentalement des conditions ionosphériques (jour–nuit, absorption aurorale, absorption dans la calotte polaire). De nombreux travaux théoriques ont été effectués. Il n'empêche que nous n'avons aucune certitude sur la grandeur du champ électromagnétique réel au-dessus de l'ionosphère. Des mesures en satellite dans cette gamme de fréquence seraient du plus haut intérêt.

EFFETS AURORAUX

Les corrélations entre les phénomènes magnétiques et les différents évènements des zones aurorales (aurores visibles, absorption aurorale, évènements à rayons X) ont surtout été étudiées pour les micropulsations de période longue $t \approx 5$ à 10 sec. Il faudrait étudier les mêmes corrélations pour les PRS.

De même l'étude de leur corrélation avec les émissions VLF (surtout celles présentant une structure périodique) doit être entreprise.

THÉORIE ONDULATOIRE

Cette théorie est fondée sur la résonance de la cavité formée entre les basses couches de l'ionosphère ($\sim$70 km) et la région où la vitesse des ondes de Alfvén passe par un maximum ($\sim$2000 km). La fréquence de résonance d'une telle cavité conduit à des périodes $t \approx 2$ à 5 sec. L'excitation serait produite soit par des ondes hydromagnétiques soit par des électrons de faible vitesse ($\sim$500 km/s) dont le mouvement d'une hémisphère à l'autre s'effectuerait dans le temps $T/2$.

Conséquence: en deux points géomagnétiquement conjugués, des signaux n'ayant aucune cohérence entre eux et décalés dans le temps.

THÉORIE CORPUSCULAIRE

Des protons, au moment de leur passage au point miroir induisent au sol un champ magnétique variable dont la période t est celle de leur oscillation le long des lignes de force. Leur dérivé longitudinale de période T est la cause de la répétition des signaux en un même endroit.

La corrélation expérimentale observée entre t et T est expliquée en admettant l'existence de protons d'énergie E comprise entre 5 et 40 MeV piégés sur des coquilles magnétiques de L compris entre 1.5 et 4. Les domaines observés de variation des grandeurs t et T entraînent dans le plan E, L, un domaine d'existence des particules. Ce domaine s'explique compte-tenu de nos connaissances d'une part sur l'origine probable de ces particules, d'autre part sur la rupture des conditions d'invariance adiabatique. Enfin les flux requis sont bien inférieurs à ceux que l'on sait exister pour des particules de cette énergie dans la première zône de Van Allen.

Conséquence: En deux points géomagnétiquement conjugués, les signaux ont une cohérence de phase (π) et leur enveloppe n'est pas décalée dans le temps.

CONCLUSION

L'étude des émissions ELF est un outil puissant pour atteindre les instabilités transitoires des particules qui existent dans la magnétosphère. Mais d'autres résultats expérimentaux sont nécessaires, notamment en ce qui concerne les enregistrements en des points conjugués et les corrélations spécifiques des PRS avec les autres phénomènes géophysiques.

DISCUSSION

(a) VLF and ELF Emissions

Experiments in France have shown that chorus and hiss have different diurnal variations. Chorus attains its maximum at 6 a.m., except when dawn is earlier, in which case D-region absorption during daylight leads to an earlier maximum. Hiss is often associated with magnetic storms, showing a maximum some 18–20 hours after a sudden commencement. Both chorus and hiss are related to the K_p magnetic index *(R. Rivault)*. In Japan, however, hiss has been found to increase at the time of a sudden commencement, but both hiss and chorus increase during the storm recovery phase *(Miss K. Yoshida)*. Correlations between bursts of VLF hiss at 4–6 kc/s and K_p index have also been noticed in Japan at geomagnetic latitude 34°. Bursts of hiss lasted about 2 hours and during these periods the K_p index reached a value of 5. No chorus has yet been observed *(A. Iwai)*. The diurnal variations in noise in Japan imply that continuous noise in the range 5–30 c/s results from terrestrial atmospherics in the earth–ionosphere cavity but that bursts are received from in or above the ionosphere *(K. Yanagihara)*.

VLF noise observed in the Alouette satellite has been shown to occur in bands of geomagnetic latitude with particular L-values [*1*]. Regular noise bands existed at L-values greater than 9, erratic noise occurred from $L=9$ to $L=4$ and noise at steadily rising frequencies was observed as L decreased from 3.6 to 2.5. The noise was more nearly constant at still lower values. Similar behaviour occurred in the two hemispheres, but no correlation was found with observations on the ground *(J. H. Chapman)*.

The noise has a possible relationship with the precipitation of high-energy electrons as evidenced by cosmic noise absorption, auroral luminosity and electron bremsstrahlung. Precipitation is local in latitude but less so in longitude. Hiss and cosmic noise absorption can start simultaneously, but

References p. 97

time differences can occur because the emission is related to the peak precipitation, while the absorption is a cumulative effect. Occasional anti-correlation between hiss and riometer records may be caused by D-region absorption of the hiss *(R. M. Gallet)*. The extent of auroral-zone precipitation can sometimes be deduced from magnetic data; precipitation observed by using a balloon has been related to an electrojet line current located by triangulation from magnetograms. Whether the correlation between noise and precipitation is positive or negative can depend on whether the ionospheric effects are localised or extensive *(W. H. Campbell)*.

The observation of emissions at frequencies of the order of 1 c/s, by observing the waveform, requires considerable caution. Rising frequency components in the noise structure can lead to beat phenomena which can confuse the identification of the true nature of the noise *(W. H. Campbell)*.

In considering the theories of VLF emission based on plasma instabilities it is necessary to take into account the velocity distributions of particle streams. Where a stream approaches its mirror point in the geomagnetic field, longitudinal energy will be converted into gyratory transverse energy. According to recent calculations by T. F. Bell, such gyratory stream motion introduces an additional term into the plasma stream dispersion formula. As a result, an enhancement of the whistler mode is obtained for streaming electrons rather than for ions. The growth rate is adequate for explaining VLF emission data, but less than that for electrostatic longitudinal instability of the same system. The latter mechanism is, however, more susceptible than the whistler mode to suppression by Landau damping, and gyrating electrons could therefore account, both qualitatively and quantitatively, for the growth and emission of whistlers *(O. Buneman)*.

(b) Earth–Ionosphere Cavity Resonances

Resonances in the earth–ionosphere cavity at frequencies of a few c/s have now been observed by several workers. In Japan, waveforms of atmospherics with components of this order of frequency have been recorded simultaneously at two or more stations. The waveforms were sometimes similar and sometimes not, but it was concluded that energy was being received from lightning discharges at frequencies below 20 c/s *(K. Sao)*.

It has been observed that the frequency of the resonance can vary [*2*, *3*]. However the most probable frequency observed may depend on the bandwidth of the amplifier used, if this is selective, and the best recording technique is to record in a wide bandwidth, and derive the spectrum subsequently *(R. Gendrin)*.

It has been observed, in Brisbane, that the second resonance, at about 14 c/s, can have greater amplitude than the first, at 8 c/s. Simultaneous observations at several stations might indicate the reasons for this phenomenon *(H. C. Webster)*. A similar observation has been made in the United States [*4*] and interpreted by assuming that the sources were at a distance subtending an arc of 90° at the centre of the earth. The field distribution, according to the theory of the cavity resonance, may then be favourable to the reception of energy at 14 c/s but not at 8 c/s *(R. Gendrin)*.

REFERENCES

1. R. E. Barrington, J. S. Belrose and D. A. Keeley, *J. Geophys. Res.*, 68 (1963) 6539.
2. H. König, *Z. Angew. Phys.*, 11 (1959) 264.
3. C. Polk and F. Fitchen, *J. Res. Natl. Bur. Std.*, 66D (1962) 313.
4. M. Balser and C. A. Wagner, *J. Geophys. Res.*, 67 (1962) 619.

SESSION ON GUIDED WAVES IN THE TROPOSPHERE AND THE IONOSPHERE

GUIDED WAVES IN THE EARTH-IONOSPHERE CAVITY

JAMES R. WAIT
Central Radio Propagation Laboratory, National Bureau of Standards,
Boulder, Colorado (U.S.A.)

SUMMARY

This paper is devoted to the theory of the mode propagation with special emphasis on VLF radio waves. The effective waveguide is the space formed by the earth's surface and the lower edge of the ionosphere. The mode solution is developed as a natural generalization of the classical airless-earth theory following an earlier analysis by the author. It is shown, for frequencies less than about 10 kc/s, that the field may be described in terms of flat-earth modes which are analogous to those in a straight rectangular microwave guide. However, at higher frequencies the earth curvature plays a major role and the character and excitation of the modes are changed drastically. Complications resulting from the anisotropy of the ionosphere are also considered. A critical discussion of the recent work on the subject is given.

RÉSUMÉ

Cette communication est consacrée à la théorie de la propagation et particulièrement pour les ondes radioélectriques de très basse fréquence (VLF). Le guide d'ondes agissant est l'espace formé par la surface terrestre et la limite inférieure de l'ionosphère. La solution du mode est développée comme une généralisation de la théorie classique vide-terre après une analyse faite par l'auteur. Il montre que, pour des fréquences inférieures à environ 10 kHz, le champ peut être décrit en fonction de modes pour terre unie analogues à ceux se développant dans un guide d'ondes rectangulaire et en ligne droite. Toutefois, pour des fréquences plus élevées, la courbure de la terre joue un

rôle prépondérant et le caractère et l'excitation des modes subissent des changements considérables. L'auteur examine aussi les complications provenant de l'anisotropie de l'ionosphère. La communication se termine par une discussion critique des récents travaux sur le sujet.

INTRODUCTION

The literature on the theory of VLF propagation is now very extensive. For a general introduction to the field, one might first turn to the special issue of the Proceedings of the Institute of Radio Engineers (June, 1957) which was devoted to VLF radio waves. Quite recently, several texts have been published which contain theoretical developments of mode theory [Al'pert, 1960; Brekhovskikh, 1960; Budden, 1962a; Wait, 1962a]. Despite the similarity of the motivation, the authors of these texts treat the subject from quite different viewpoints. Nevertheless, the basic theoretical concepts are the same.

It is our intention to outline the development of VLF mode theory. It is recommended that the reader consult the above texts for details. In the present review we shall emphasize the underlying unity between the different approaches. At the same time, we shall call attention to a number of works which have been published only very recently.

DEVELOPMENT OF MODE THEORY

A convenient starting point for VLF mode theory is the ground wave solution for an airless earth [van der Pol and Bremmer, 1937–1939; Fock. 1945]. For example, if the source is a vertical electric dipole located on the surface of a smooth spherical earth of surface impedance Z_g and radius a, the radial electric field at (r, θ, ϕ) can be written [Wait, 1962a]

$$E_r = \frac{e^{-ika\theta}}{a(\theta \sin\theta)^{\frac{1}{2}}} V_0 , \tag{1}$$

where

$$V_0 \cong 2(\pi x)^{\frac{1}{2}} e^{-i\pi/4} \sum_{s=1}^{\infty} \frac{e^{-ixt_s}}{t_s - q^2} \frac{w_1(t_s - y)}{w_1(t_s)} , \tag{2}$$

where

$$w_1(t) = \exp(-2\pi i/3)(-\pi t/3)^{\frac{1}{2}} H_{\frac{1}{3}}^{(2)}\left[\tfrac{2}{3}(-t)^{\frac{3}{2}}\right], \tag{3}$$

t_s is a solution of

$$w_1'(t) = q w_1(t), \tag{4}$$

and finally $q = -i(ka/2)^{\frac{1}{3}} Z_g/\eta_0$, and $\eta_0 = 120\pi$.

For the purposes of the subsequent analysis, V_0 is written as a contour integral in the manner

$$V_0 = e^{i\pi/4}(x/\pi)^{\frac{1}{2}} \oint \frac{e^{-ixt} w_1(t-y)}{w_1'(t) - q w_1(t)} \, dt. \tag{5}$$

The contour encloses the poles at $t = t_s$ in a clockwise sense.

We will now assume that the ionosphere can be represented by some sort of a concentric reflecting shell at height h. Thus, at $r = a + h$, the fields are to be related by the radial surface impedance Z_i. Most generally, Z_i is a function of t but within a good approximation it may be considered as a constant.

Using the boundary condition at $r = a + h$, along with the usual boundary condition at the ground, one finds, after some analysis, the representation [Wait, 1961]

$$V = e^{i\pi/4}\left(\frac{x}{\pi}\right)^{\frac{1}{2}} \oint \frac{e^{-ixt}\left[w_1(t-y) + A(t) w_2(t-y)\right]}{\left[w_1'(t) - q w_1(t)\right]\left[1 - A(t) B(t)\right]} \, dt, \tag{6}$$

which is a suitable generalization of Eq. (5). The symbols are defined by

$$A(t) = -\left[\frac{w_1'(t-y_0) + q_i w_1(t-y_0)}{w_2'(t-y_0) + q_i w_2(t-y_0)}\right], \tag{7}$$

$$B(t) = -\left[\frac{w_2'(t) - q w_2(t)}{w_1'(t) - q w_1(t)}\right], \tag{8}$$

$$q_i = -i(ka/2)^{\frac{1}{3}}(Z_i/\eta_0), \quad y_0 = \left(\frac{2}{ka}\right)^{\frac{1}{3}} kh,$$

$$w_2(t) = \exp(2\pi i/3)(-\pi t/3)^{\frac{1}{2}} H_{\frac{1}{3}}^{(1)}\left[\tfrac{2}{3}(-t)^{\frac{3}{2}}\right]. \tag{9}$$

The result is valid for $ka \gg 1$ and $h \ll a$ which are not very stringent.

The poles of the integrand now occur only at $t=t_n$, where

$$1 - A(t)B(t) = 0, \qquad (10)$$

as it may be shown that the integrand is finite at $t=t_s$, the ground wave poles. The residue series representation is obtained by deforming the original contour to enclose the poles t_n. Provided that q and q_i can be regarded as constants (independent of t), one finds that [Wait, 1961, 1962a]

$$V \cong (4/y_0)(\pi x)^{\frac{1}{2}} e^{-i\pi/4} \sum_n \exp(-ixt_n) G_n(y) \Lambda_n, \qquad (11)$$

where

$$\Lambda_n = \frac{y_0}{2}\left\{(t_n - q)^2 - \frac{(t_n - y_0 - q_i)^2 [w_2'(t_n) - q w_2(t_n)]^2}{[w_2'(t_n - y_0) + q_i w_2(t_n - y_0)]^2}\right\}^{-1}, \qquad (12)$$

and

$$G_n(y) = \frac{w_1(t_n - y) + A(t_n) w_2(t_n - y)}{w_1(t_n) + A(t_n) w_2(t_n)}. \qquad (13)$$

The quantity Λ_n can be regarded as an excitation factor since it is a measure of how well a mode of order n is excited. On the other hand, $G_n(y)$ is a height-gain function as it is equal to the ratio of the field E_r at height y to the field at zero height. The formula for V may be generalized to a finite source height z_0 by replacing $G_n(y)$ by $G_n(y)G_n(y')$ where

$$y' = \left(\frac{2}{ka}\right)^{\frac{1}{3}} kz_0 .$$

A more familiar form of the mode series is obtained by replacing x, t_n and y_0 by their definitions. Thus

$$V = 2\frac{(d/\lambda)^{\frac{1}{2}}}{h/\lambda} e^{-i\pi/4} \sum_{n=0}^{\infty} \exp[ikdC_n^2/2]\, G_n(y) G_n(y') \Lambda_n, \qquad (14)$$

where $d=a\theta$ is the great circle distance, λ is the wavelength, h is the height of the upper boundary, and $C_n=(2/ka)^{\frac{1}{3}}(-t_n)^{\frac{1}{2}}$.

THE RESONANCE CONDITION

The modal equation

$$A(t_n)B(t_n) - 1 = 0, \qquad (15)$$

must be solved in order to obtain t_n. In general, this is a messy business and some approximation is warranted. As it turns out, $(y_0 - t)$ is sufficiently large that the Airy functions having this argument may be replaced by the first term of their asymptotic expansions. Then, it is found that Eq. (15) takes the form

$$R_g R_i F_g \mathrm{e}^{-i\tilde{I}} = \mathrm{e}^{-i2\pi n}, \tag{16}$$

where

$$\tilde{I} = \tfrac{2}{3}ka\left[(C')^3 - C^3\right], \quad C' = \left(C^2 + \frac{2h}{a}\right)^{\frac{1}{2}},$$

$$R_g = \frac{C - \Delta_g}{C + \Delta_g}, \quad R_i = \frac{C' - \Delta_i}{C' + \Delta_i},$$

and

$$F_g = \frac{\dfrac{w_2'(t) - qw_2(t)}{w_1'(t) - qw_1(t)}}{i\exp\left[i\frac{4}{3}(-t)^{\frac{3}{2}}\right]\left[\dfrac{-i(-t)^{\frac{1}{2}} - q}{i(-t)^{\frac{1}{2}} - q}\right]}. \tag{17}$$

The denominator of the latter expression is the asymptotic approximation (for large negative t) of the numerator. Thus, if $(ka/2)^{\frac{1}{3}} C_n \gg 1$, F_g can be replaced by unity. Under this restriction, the modal equation has a clear geometrical-optical significance: R_g is the Fresnel coefficient at the ground for an angle of incidence whose cosine is C, while R_i is the Fresnel reflection coefficient at the ionosphere for an angle of incidence whose cosine is C'. The quantity $\tilde{I}$ can be regarded as the (complex) phase suffered by a wave which propagates from the ground ($z=0$) to the reflecting level $z=h$ and back again. The latter statement is confirmed by noting that

$$\tilde{I} = 2k\int_0^h \left(C_n^2 + \frac{2z}{a}\right)^{\frac{1}{2}} \mathrm{d}z = 2\int_0^{y_0} (y - t_n)^{\frac{1}{2}}\,\mathrm{d}y, \tag{18}$$

which has the characteristic phase integral form.

Unfortunately, the condition requiring the largeness of $(ka/2)^{\frac{1}{3}} C_n$ is not met for the important modes at VLF. In fact, the real part of C_n may be zero for certain modes [Wait, 1962a]. Thus, one must use the form of the mode equation which involves the complicated correction factor F_g. Extensive numerical works are now available for the mode characteristics for this general case [Spies and Wait, 1961]. Most workers in the field have attempted to avoid this situation by making further approximations which appear to render the results invalid.

SOME SPECIAL CASES

An important limiting case arises in the course of the detailed analysis of the mode equation. At sufficiently low frequencies, $(ka/2)^{\frac{1}{3}} C_n$ has a magnitude somewhat greater than unity, while at the same time $|C_n^2| \gg 2h/a$. The modal equation then reduces to

$$R_{\mathrm{g}}(C_n) R_{\mathrm{i}}(C_n) \exp(-i 2khC_n) = \mathrm{e}^{-i2\pi n}, \tag{19}$$

which corresponds to propagation in a flat-earth system. In this situation, the modes always have a phase velocity greater than c. Actually, this is a fairly good approximation for frequencies less than about 10 kc/s, although it may be used for a qualitative description for frequencies up to 20 kc/s. It is also important to note that, for this low frequency range, the excitation factor Λ_n is near unity and thus the modes are effectively launched by a vertical dipole located on the ground.

Another limiting case occurs for the higher frequencies (i.e., of the order of 30 kc/s) where the phase velocity is becoming appreciably less than c. In this case, t_n may have a real part somewhat greater than one, while at the same time $(y_0 - t)$ has a real part greater than one. For this case, the modal equation reduces to

$$i \exp\left[-i \tfrac{4}{3} (y_0 - t_n)^{\frac{3}{2}}\right] R_{\mathrm{i}}(C'_n) \cong \exp\left[-i 2\pi n\right], \tag{20}$$

which can be written

$$2k \int_{\hat{z}}^{h} \left(C_n^2 + \frac{2z}{a} \right)^{\frac{1}{2}} \mathrm{d}z + i \log R_{\mathrm{i}}(C'_n) - \frac{\pi}{2} = 2\pi n, \tag{21}$$

where $\hat{z} = -aC_n^2/2$. It can be noted that, within this approximation, the modal characteristics are independent of the electrical properties of the ground. For this reason, such a mode may be described as "earth detached". They are closely related to the (acoustic) whispering gallery modes first investigated by J. W. Strutt (Lord Rayleigh) [1910, 1914].

The phase integral form of the mode equation given above has an interesting physical significance. The total (complex) phase consists of a "to-and-fro" path from h to the reflection at the caustic $\hat{z}$. The phase shift at the caustic accounts for the $-\pi/2$ on the left-hand side of equation (21). In the region between 0 and $\hat{z}$ the field is evanescent. Consequently, excitation of these modes by a ground-based transmitter is very weak. This fact is borne out by the behavior of Λ_n when computed from the general theory.

NATURE OF THE BOUNDARY

In this rather sketchy outline of VLF mode theory we have said very little about the nature of the reflecting boundary. In the simplest case, the ionosphere is regarded as a homogeneous medium with a sharp lower boundary at $z=h$. Then the surface impedance parameter Δ_i is given (exactly) by

$$\Delta_i = \frac{1}{N_i}\left(1 - \frac{S_n^2}{N_i^2}\right)^{\frac{1}{2}} \quad \text{where} \quad S_n^2 = 1 - C_n^2$$

Because S_n is near unity for the important modes it is permissible to regard Δ_i as a constant defined by

$$\Delta_i \cong \frac{1}{N_i}\left(1 - \frac{1}{N_i^2}\right)^{\frac{1}{2}},$$

where N_i is the refractive index of the medium. Furthermore, since $|C_n| \ll \Delta_i$ the ionospheric reflection coefficient may be approximated by

$$R_i(C) = \frac{C' - \Delta_i}{C' + \Delta_i} \cong -e^{\alpha C'}, \quad \text{where} \quad \alpha = -\frac{2N_i^2}{(N_i^2 - 1)^{\frac{1}{2}}}. \tag{22}$$

The mode equation may now be written in the convenient form

$$\tfrac{2}{3}ka\left(C_n^2 + \frac{2h}{a}\right)^{\frac{3}{2}} + i\alpha\left(C_n^2 + \frac{2h}{a}\right)^{\frac{1}{2}} + i\log\left[\frac{w_2'(t_n) - qw_2(t_n)}{w_1'(t_n) - qw_1(t_n)}\right] - (4n-1)\frac{\pi}{2} = 0. \tag{23}$$

It has been shown elsewhere [Wait, 1962a; Wait and Walters, 1963] that other ionosphere models lead to a reflection coefficient which is also approximated by $-\exp(\alpha C')$ where α is almost a constant for grazing angles. Thus, the modal equation (23) has wide applicability [Wait, 1963a].

INFLUENCE OF EARTH'S MAGNETIC FIELD

To take full account of the earth's magnetic field, in VLF mode theory, leads to many additional complications. Using a flat-earth model, Budden [1952] obtained an interesting solution under the stated assumption that azimuthal symmetry prevailed about the source dipole. Unfortunately, this important paper contains some mathematical errors which are the subject of subsequent discussion [Wait, 1957; Budden, 1957]. A revised treatment was given by Wait [1960] which was free of negative-order modes. A similar treatment was given by Crombie [1960] who restricted the solution to the case of a purely transverse terrestrial magnetic field and a flat earth. A somewhat heuristic treatment [Wait and Spies, 1960] gave a solution for mode propagation in a curved waveguide with one wall having anisotropic properties.

A very thorough development of mode propagation for a curved earth with a vertical terrestrial magnetic field has been considered by Krasnushkin [1962]. His development is based on the theory of singular and non-self-adjoint operators. The final results appear to be in agreement with a recent analysis of Wait [1963b] for the same problem, using a much simpler approach. In later work [Wait, 1963c] it is not necessary to assume that the terrestrial magnetic field is vertical. Related developments and discussions of the influence of the magnetic field in mode propagation are given in papers by Schumann [1956], Budden [1962b], Wait [1962a, 1963c], and also Johler and Berry [1962]. A recent analysis for a purely transverse magnetic field has been carried out by Galejs and Row [1963] which is applicable to ELF mode propagation. Some closely related work on reflection coefficients for an anisotropic ionosphere should also be noted [Crombie, 1961; Field and Tamarkin, 1961; Johler, 1961; Johler and Harper, 1962; Poeverlein, 1958; Swift, 1962; and Westcott, 1962].

The prime influence of the terrestrial magnetic field is to couple the TE and TM modes in the earth–ionosphere waveguide. For example, in the case of a plane wave incident on the ionosphere, the reflection coefficient is described by a 2 × 2 matrix. This has the form

$$\begin{bmatrix} {}_{\parallel}R_{\parallel} & {}_{\perp}R_{\parallel} \\ {}_{\parallel}R_{\perp} & {}_{\perp}R_{\perp} \end{bmatrix},$$

where the elements are scalar reflection coefficients. The first subscript is chosen to indicate that the electric vector is either parallel (i.e., $\parallel$) or perpendicular (i.e., $\perp$) to the plane of incidence. The second subscript is chosen to indicate that the electric vector, of the reflected wave, is either parallel or perpendicular to the plane of incidence. When the medium is isotropic, the cross-polarized components ${}_{\perp}R_{\parallel}$ and ${}_{\parallel}R_{\perp}$ vanish.

The theory for mode propagation in a waveguide formed by the earth and an anisotropic ionosphere can be treated as a generalization of the earlier results. Using this approach [Wait, 1963c], the radial field components can be written in the form of a column matrix. Thus, for vertical dipole excitation,

$$\begin{bmatrix} E_r \\ \eta_0 H_r \end{bmatrix} \cong \frac{e^{-ika\theta}}{a(\theta \sin\theta)^{\frac{1}{2}}} \begin{bmatrix} F_e \\ F_h \end{bmatrix}, \tag{24}$$

where F_e and F_h are dimensionless field functions. The residue series representation for these functions takes the form

$$\begin{bmatrix} F_e \\ F_h \end{bmatrix} \cong -2(\pi x)^{\frac{1}{2}} e^{-i\pi/4} \sum_n e^{-ixt_n} \frac{[w_1(t_n - y) + [A(t_n)]\, w_2(t_n - y)]}{[\Omega'(t_n)]\,[w_1'(t_n) - q w_1(t_n)]} \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \tag{25}$$

where t_n are solutions of

$$\det[\Omega(t)] = 0, \tag{26}$$

$$[\Omega(t)] = [A(t)]\,[B(t)] - \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \tag{27}$$

and

$$[\Omega'(t_n)] = \left\{ \frac{\partial/\partial t \det[\Omega(t)]}{\det[\Omega(t)]} \times [\Omega(t)] \right\}_{t=t_n}. \tag{28}$$

Also, in analogy with the isotropic solution

$$[A(t)] \cong \begin{bmatrix} {}_{\parallel}R_{\parallel}(C') & {}_{\perp}R_{\parallel}(C') \\ {}_{\parallel}R_{\perp}(C') & {}_{\perp}R_{\perp}(C') \end{bmatrix} \exp\left[-i\tfrac{4}{3}(y_0 - t)^{\frac{3}{2}} - i\pi/2\right], \tag{29}$$

and

$$[B(t)] \cong \begin{bmatrix} -\left[\dfrac{w_2'(t) - q w_2(t)}{w_1'(t) - q w_1(t)}\right] & 0 \\ 0 & -\left[\dfrac{w_2'(t) - \hat{q} w_2(t)}{w_1'(t) - \hat{q} w_1(t)}\right] \end{bmatrix}, \tag{30}$$

where

$$q = -i(ka/2)^{\frac{1}{3}}(Z_g/\eta_0),$$
$$\hat{q} = -i(ka/2)^{\frac{1}{3}}(\eta_0/Z_g).$$

Here the matrix reflection coefficient involving ${}_{\parallel}R_{\parallel}$, ${}_{\perp}R_{\parallel}$, . . . , is to be evaluated at an angle of incidence whose cosine is C_n', where $(ka/2)^{\frac{1}{3}}C_n'=(y_0-t_n)^{\frac{1}{2}}$. The matrix $[A(t_n)]$ is the reflection coefficient at the ionospheric reflecting layer whereas $[B(t_n)]$ is the reflection coefficient at the ground.

The expression quoted above for F_e and F_h is valid provided that $|(ka/2)^{\frac{1}{3}}C_n'|$ is greater than about 2. This encompasses cases of practical interest in the VLF range.

The modal equation (27) may be written more explicitly in the form [Wait and Spies, 1960]

$$[1-{}_{\parallel}R_{\parallel}\,R_\mathrm{g}F_\mathrm{g}\exp(-i\tilde{I})][1-{}_{\perp}R_{\perp}\,\hat{R}_\mathrm{g}\hat{F}_\mathrm{g}\exp(-i\tilde{I})] \\ -{}_{\parallel}R_{\perp}\,{}_{\perp}R_{\parallel}\,R_\mathrm{g}F_\mathrm{g}\hat{R}_\mathrm{g}\hat{F}_\mathrm{g}\exp(-2i\tilde{I})=0, \qquad (31)$$

where

$$R_\mathrm{g}=\frac{C_n-\Delta_\mathrm{g}}{C_n+\Delta_\mathrm{g}}, \qquad \hat{R}_\mathrm{g}=\frac{\Delta_\mathrm{g}C_n-1}{\Delta_\mathrm{g}C_n+1}\cong-1,$$

$$\tilde{I}=\frac{2ka}{3}[(C_n')^3-C_n^3].$$

F_g is defined by Eq. (17) and $\hat{F}_\mathrm{g}$ has the same form with q replaced by $\hat{q}$. As a practical matter, since $\hat{q}$ is very large

$$\hat{F}_\mathrm{g}\cong\frac{w_2(t_n)}{w_1(t_n)}\exp\left[-i\left(\frac{\pi}{2}+\tfrac{4}{3}(-t_n)^{\frac{3}{2}}\right)\right]. \qquad (32)$$

Eq. (31) illustrates the coupling between TE and TM modes. This takes place as a result of the term proportional to ${}_{\parallel}R_{\perp}\,{}_{\perp}R_{\parallel}$. For highly grazing modes this term is often negligible and then the mode equation splits into two uncoupled ones:

$$1-{}_{\parallel}R_{\parallel}\,R_\mathrm{g}F_\mathrm{g}\exp(-i\tilde{I})\cong0 \qquad (33a)$$

and

$$1-{}_{\perp}R_{\perp}\,\hat{R}_\mathrm{g}\hat{F}_\mathrm{g}\exp(-i\tilde{I})\cong0. \qquad (33b)$$

Solutions of these lead to pure TM- and TE-type modes, respectively. When coupling is appreciable, the modes may still be divided into two groups which are described conveniently as quasi TM and quasi TE modes.

In a quantitive discussion of VLF mode theory, it is really necessary to consider the physical properties of the ionosphere and to specify the form of the profile. This aspect of the subject is outside the scope of this survey.

A related question, which should be mentioned, concerns the influence of non-uniform width of the waveguide. To fix ideas, we will assume that the problem may be treated as a two-dimensional one. That is, between the transmitter and receiver the effective height $h(s)$ of the reflecting layer is a function of s, the great circle distance from the transmitter. Therefore, after some consideration, the generalized form of Eq. (14) may be written

$$V \cong \frac{(d\lambda)^{\frac{1}{2}}}{[h(0)\,h(d)]^{\frac{1}{2}}} \mathrm{e}^{-i\pi/4} \sum_{n=0}^{\infty} \exp\left[ik\int_{0}^{d} C_n^2(s)\,\mathrm{d}s\right] \bar{\Lambda}_n G_n^{(0)}(y')\,G_n^{(d)}(y), \quad (34)$$

where $\bar{\Lambda}_n = [\Lambda_o^{(0)} \Lambda_n^{(d)}]^{\frac{1}{2}}$.

Here, the superscript (0) indicates that the quantity is to be calculated as if the waveguide were of constant height $h(0)$, whereas the superscript (d) indicates that the quantity is to be calculated as if the waveguide were of constant height $h(d)$. Furthermore, $C_n(s)$, which is assumed to be slowly varying, is a solution of the modal equation (15) where the height h is to be replaced by $h(s)$. Obviously, such a representation is valid only if the function $h(s)$ is slowly varying. Under more general conditions, it is necessary to consider conversion of modes from one order to another [Wait, 1962b].

THE CONTINUOUS SPECTRUM

In discussing mode propagation in the spherical earth–ionosphere waveguide, it is most often convenient to expand the field in terms of radial eigenmodes. These are characterized by a radial (or height) field pattern which is a form of a standing wave [Wait and Spies, 1963]. The attenuation and phase velocity of these modes are determined principally by the surface impedance at the ground and at the effective lower boundary of the ionosphere. For this reason, they may be called the principal modes and their totality is the "mode sum". As we have seen, such representations are highly convergent expansions for the total field of a specified source. It is important to know that this mode sum may not be a complete representation for the field.

When the ionosphere is stratified, additional modes can exist which are weakly coupled to the main earth–ionosphere waveguide. For example, it is possible that lowly attenuated modes at VLF may propagate between the E and F layers. This would appear to be an important subject for future study.

In the case of a planar model, there may exist a continuous spectrum, in addition to the discrete modes, which is present because of the open region or free space at the top of the waveguide. In a detailed analysis using function theoretic methods [Brekhovskikh, 1960; Wait, 1960, 1962a], it may be shown that the continuous spectrum in terrestrial waveguides is related to highly attenuating waves which vary approximately as $1/\rho^2$ where ρ is the distance from the source. Sometimes these waves are called lateral waves; they do not appear to play any significant role in terrestrial radio propagation. A numerical study of these waves, for a planar model, has been carried out by Anderson [1962]. However, it has recently been pointed out [Berry, 1963] that for the spherical model, with a homogeneous ionosphere, no lateral ionospheric wave is present.

The role of the continuous spectrum in ground wave propagation was actually considered by van der Pol and Bremmer [1937] in their study of diffraction of electromagnetic waves by a sphere. The contributions which they describe as the "rainbow terms" are really part of the continuous spectrum. When the conductivity at the sphere is sufficiently large, they show that the rainbow terms do not play a role in the diffraction process. A similar conclusion is arrived at when the ground is replaced by a surface impedance [Wait, 1956] which has the virtue of being valid also for a stratified ground.

Another aspect of terrestrial waveguides which might warrant consideration is antipodal focussing. In dealing with very long-range propagation, the angular distance may not always be small compared with unity. Thus, in general, one should employ a model representation which has the form

$$E_r = \sum_{n=0}^{\infty} \delta_n \frac{\nu(\nu+1)}{\sin \nu\pi} P_\nu(-\cos\theta), \tag{35}$$

where δ_n is some excitation factor and

$$\nu(\nu+1) \cong (\nu+1/2)^2 \cong kaS_n^2 \cong ka(1-C_n^2),$$

and a is the radius of the earth. The complex coefficient S_n or C_n must be found from a transverse resonance relation as indicated in the earlier sections.

If θ is not near 0 or π, the Legendre function may be replaced by the first term of its asymptotic expansion. Thus, the modes are individually proportional to

$$\left(\frac{1}{\sin\theta}\right)^{\frac{1}{2}} \cos\left[kaS_n(\pi-\theta) - \frac{\pi}{4}\right],$$

provided $1/|\nu| \ll (\pi-\theta)$ and $1/|\nu| \ll \theta$. In this case, the field is simply the linear combination of two peripheral waves of the form

$$\left(\frac{1}{\sin\theta}\right)^{\frac{1}{2}} \exp(-ikaS_n\theta)$$

and

$$\left(\frac{1}{\sin\theta}\right)^{\frac{1}{2}} \exp(-ikaS_n(2\pi-\theta))\exp(i\pi/2),$$

when $\theta<\pi$. These waves are travelling in opposite directions along the two respective great-circle paths $a\theta$ and $a(2\pi-\theta)$ from the source to the observer. It is noticed that there is a $\pi/2$ phase advance which the wave, travelling on the long great-circle path, picked up as it went through the pole $\theta=\pi$. The linear combination of these two travelling waves is to form a standing wave pattern whose distance Δ_{m} between minima is approximately given by

$$k\Delta_{\mathrm{m}}\operatorname{Re}S_n=\pi \quad \text{or} \quad \Delta_{\mathrm{m}}=\lambda/(2\operatorname{Re}S_n),$$

subject to $(-\operatorname{Im}S_n)\ll\operatorname{Re}S_n$.

As one approaches the pole (i.e., $\theta\rightarrow\pi$), asymptotic representations for $P_\nu(-\cos\theta)$ break down and it is desirable to employ the approximation

$$P_\nu(-\cos\theta)\cong J_0\left[kaS_n(\pi-\theta)\right]. \tag{36}$$

The range of validity and other extensions of these formulae are given elsewhere [Wait, 1962a].

THE SCHUMANN RESONANCES

A very interesting situation occurs at extremely low frequency when the earth's circumference becomes comparable with the wavelength. The importance of this type of resonance was pointed out by Schumann [1957]. The existence of this resonance may be demonstrated by employing the expansion

$$\frac{P_\nu(-\cos\theta)}{\sin\nu\pi}=-\frac{1}{\pi}\sum_{m=0}^{\infty}P_m(\cos\theta)\frac{2m+1}{m(m+1)-\nu(\nu+1)}, \tag{37}$$

where the summation is over integral values of m and is valid when ν is non-integral. The Schumann or cavity-type resonances occur when the magnitude of $\nu(\nu+1)$ or $(kaS_n)^2$ is near $m(m+1)$ for some integral value of m.

The lowest order resonance occurs for the radial mode $n=0$ when $m=1$ and the frequency is approximately 10.6 c/s. The next two cavity modes correspond to $m=2$ and 3 and the resonance frequencies are approximately 18.3 c/s and 25.9 c/s, respectively. The finite conductivity of the ionospheric shell can be shown to modify these resonance frequencies to some extent [Wait, 1962a]. The geophysical significance of these cavity modes is the subject of a review paper now being prepared by Madden.

RELATED TOPICS

There are many other aspects of terrestrial waveguides which would warrant further discussion. For example, the coupling of VLF energy from the earth ionosphere into the exosphere is an important subject which has not been discussed in this outline at all. Crary [1961], Helliwell [1962], and Maeda and Oya [1962] have studied this problem recently using ray methods. A closely related problem, treated by Pitteway [1962], is the calculation of the fields within the ionosphere for a ground-based transmitter. The practical significance of these theoretical calculations is evident from the recent observations of Barrington and Belrose [1963] which were made from the Alouette satellite.

Another interesting topic not considered in this outline is the subsurface terrestrial waveguide. There is some evidence that regions of the earth's crust may serve as a waveguide for propagation of radio waves between underground terminals. Some of the theoretical developments in VLF ionospheric propagation may be taken over, with only minor modifications, for application to sub-surface propagation. The interested reader may consult the May 1963 issue of the *IEEE Transactions* (on Antennas and Propagation) which is devoted entirely to this topic.

REFERENCES

Al'pert, Ya. L., *Radio Wave Propagation in the Ionosphere,* Izd. AN SSSR, Moscow, 1960, transl. by Consultants Bureau, New York.

Anderson, W. L., *J. Res. Natl. Bur. Std.,* 66D (1962) 63–72. (Correction in 67D (1963) 63–65).

Barrington, R. G. and J. S. Belrose, *Nature,* 198 (1963) 651–656.

Berry, L. A., private communication (1963).

Brekhovskikh, L. M., *Waves in Layered Media,* Academic Press, New York, 1960.

Budden, K. G., *Phil. Mag.,* [7] 43 (346) (1952) 1179–1188.

Budden, K. G., *Proc. IRE*, 45 (1957) 772–774.

Budden, K. G., *The Wave-guide Mode Theory of Wave Propagation*, Prentice-Hall, Englewood Cliffs, N.J., 1962(a).

Budden, K. G., *Proc. Roy. Soc. (London)*, A265 (1962) 538–553(b).

Crary, J. H., *Stanford Electronics Labs., Rept.* No. 9, Stanford, Calif., July 1961.

Crombie, D. D., *J. Res. Natl. Bur. Std.*, 64D (1960) 265–268.

Crombie, D. D., *J. Res. Natl. Bur. Std.*, 65D (1961) 455–464.

Field, E. C. and P. Tamarkin, *J. Geophys. Res.*, 66 (1961) 2737–2750.

Fock, V. A., *J. Phys. U.S.S.R.* 9 (1945) 256–266.

Galejs, J. and R. V. Row, *Sylvania Res. Lab. Res. Rept.* No. 334, Waltham, Mass., April 1963.

Helliwell, R. A., *Proc. Intern. Conf. on the Ionosphere, London, 1962* (Inst. Phys–Phys. Soc.), Chapman and Hall, London, 1963, pp. 452–460.

Johler, J. R., *J. Res. Natl. Bur. Std.*, 65D (1961) 53–65.

Johler, J. R. and L. A. Berry, *J. Res. Natl. Bur Std.*, 66D (1962) 737–762.

Johler, J. R. and J. D. Harper, Jr., *J. Res. Natl. Bur. Std.*, 66D (1962) 81–99.

Krasnushkin, P. E., *Nuovo Cimento Suppl.*, [10] 26, No. 1 (1962) 50–112.

Madden, T., *Reviews of Geophysics* (to appear in a future issue).

Maeda, K. and H. Oya, *Proc. Intern. Conf. on the Ionosphere, London, 1962* (Inst. Phys.–Phys. Soc.), Chapman and Hall, London, 1963, pp. 461-466.

Pitteway, M. L. V., *Proc. Intern. Conf. on the Ionosphere, London, 1962* (Inst. Phys.–Phys. Soc.), Chapman and Hall, London, 1963, p. 435.

Poeverlein, H., *J. Atmos. Terrest. Phys.*, 12 (1958) 236–247.

Rayleigh, Lord, *Phil. Mag.* 20 (1910) 1001–1004.

Rayleigh, Lord, *Phil. Mag.* 27 (1914) 100–109.

Schumann, W. O., *Z. Angew. Phys.*, 8 (1956) 126–127.

Schumann, W. O., *Z. Angew. Phys.*, 6 (1957) 225.

Spies, K. P. and J. R. Wait, *NBS Tech. Note* No. 114, Government Printing Office, Washington, D.C., July 17, 1961 (PB-161615).

Swift, D. W., *J. Res. Natl. Bur. Std.*, 66D (1962) 663–680.

van der Pol, B. and H. Bremmer, *Phil. Mag.*, [7] 24 (1937) (159) 141–176; [7] 24 (1937) (164) 825–864; [7] 25 (1938) (171) 817–834; [7] 27 (1939) (182) 261–275.

Wait, J. R., *J. Res. Natl. Bur. Std.*, 56 (1956) 237–244.

Wait, J. R., *Proc. IRE*, 45 (1957) 760–767.

Wait, J. R., *J. Res. Natl. Bur. Std.*, 64D (1960) 153–204. Also appears in Russian in: Foreign Radioelectronics (Moscow) (Sept. 1960) 50–83.

Wait, J. R., *J. Res. Natl. Bur. Std.*, 65D (1961) 37–46.

Wait, J. R., *Electromagnetic Waves in Stratified Media*, Pergamon, Oxford, 1962(a).

Wait, J. R., *Proc. Intern. Conf. on the Ionosphere, London, 1962* (Inst. Phys.–Phys. Soc.), Chapman and Hall, London, 1963, pp. 446–451(b).

Wait, J. R., *J. Res. Natl. Bur. Std.*, 67D (1963) 375–382(a).

Wait, J. R., *J. Res. Natl. Bur. Std.*, 67D (1963) 297–301(b).

Wait, J. R., *Can. J. Phys.*, 41 (1963) 299–315(c).

Wait, J. R. and K. P. Spies, *J. Geophys. Res.*, 65 (1960) 2325–2331.

Wait, J. R. and K. P. Spies, *J. Res. Natl. Bur. Std.*, 67D (1963) 183–187.

Wait, J. R. and L. C. Walters, *J. Res. Natl. Bur. Std.*, 67D (1963) 361–367.

Westcott, B. S., *J. Atmos. Terrest. Phys.*, 24 (1962) 921–936.

GUIDANCE AND BEAMING IN THE MAGNETOSPHERE AT HYDROMAGNETIC, AUDIO AND RADIO FREQUENCIES

H. G. BOOKER

Stanford Research Institute, California (U.S.A.)

SUMMARY

Guidance in a magneto-plasma such as the magnetosphere is examined from the viewpoints of (a) Alfvén "plucking" of tubes of flux, and (b) waveguide action induced by field-aligned irregularities of ionization density. It is concluded that:

(1) The concept of resonant "plucking" of a tube of flux of the earth's magnetic field is probably applicable over about two decades of frequency in the hydromagnetic range. The logarithmic mid-frequency decreases from about 1 c/s at low latitudes to about 10^{-2} c/s at high latitudes. The minimum transverse radius of such a tube at the surface of the earth is a few thousand kilometres.

(2) At whistler frequencies guidance in the absence of field-aligned structure extends only a wavelength or two in the medium and is quite unable to explain the whistler phenomena.

(3) The minimum strength of field-aligned irregularities required for guidance at whistler frequencies is of the order of one percent. The corresponding minimum transverse scale of the irregularities is a few tens of kilometres.

(4) Guidance by field-aligned irregularities is possible for comparatively small fractional changes of ionization density over about five decades of frequency. This frequency range slides down in frequency by about three decades as one moves from low to high latitude lines. Guidance disappears at sufficiently high radio frequencies because the magnetosphere then behaves substantially like free space. Guidance of this type disappears at sufficiently low hydro-magnetic frequencies because the transverse scale of the guiding

structure required is too large to be accommodated in the magnetosphere. Guiding by field-aligned irregularities is unlikely much above 10 Mc/s or much below 1 c/s.

(5) At frequencies between the ionic plasma frequency and one-half the electronic gyro frequency anisotropy of the medium permits guidance by field-aligned irregularities of modes in which the waves zig-zag at a large angle to the earth's magnetic field. For these modes the phase and group velocity over much of the frequency range are independent of frequency and equal to one-half the electronic Alfvén velocity.

RÉSUMÉ

La dirigibilité dans un magnétoplasma tel que la magnétosphère est étudiée aux points de vue (a) du "plumage" (plucking) d'Alfvén des tubes de flux, et (b) de l'action de guide d'ondes induite par des irrégularités de la densité d'ionisation distribuées le long du champ.

On conclut que:

(1) Le concept du "plumage" résonant d'un tube de flux du champ magnétique terrestre est probablement applicable pour environ deux décades de fréquence dans la gamme hydromagnétique. La mi-fréquence logarithmique diminue d'environ 1 Hz aux basses latitudes à environ 10^{-2} Hz aux hautes latitudes. Le rayon minimal transversal d'un tel tube à la surface terrestre est de quelques milliers de kilomètres.

(2) Aux fréquences des sifflements la dirigibilité en l'absence d'une structure alignée le long du champ ne s'étend qu'à une ou deux longueurs d'onde dans le milieu et ne peut expliquer les phénomènes des sifflements.

(3) L'intensité minimale d'irrégularités distribuées le long du champ exigée pour la dirigibilité aux fréquences des sifflements est de l'ordre d'un pour cent. L'échelle transversale minimale correspondante des irrégularités est de quelques dizaines de kilomètres.

(4) La dirigibilité par irrégularités distribuées le long du champ est possible pour des changements fractionnaires relativement petits de la densité d'ionisation pour environ cinq décades de fréquence. Cette gamme de fréquence glisse vers le bas d'environ trois décades au fur et à mesure qu'on se déplace des lignes de basse latitude à celles de haute latitude. La dirigibilité disparaît aux fréquences radioélectriques élevées car la magnétosphère se comporte alors comme l'espace libre. La dirigibilité de cette espèce disparaît

aux fréquences hydromagnétiques suffisamment basses parce que l'échelle transversale de la structure de guidage nécessaire est trop grande pour trouver place dans la magnétosphère. Le guidage par irrégularités distribuées le long du champ ne semble pas être beaucoup au dessus de 10 MHz ou beaucoup en dessous de 1 Hz.

(5) Aux fréquences situées entre la fréquence de plasma ionique et la moitié de la gyro fréquence électronique, l'anisotropie du milieu permet la dirigibilité par irrégularités distribuées le long du champ de modes pour lesquels les ondes zigzaguent suivant de grands angles avec le champ magnétique terrestre. Pour ces modes la phase et la vélocité de groupe sur la plus grande partie de la gamme de fréquence sont indépendantes de la fréquence et égales à la moitié de la vélocité électronique d'Alfvén.

1. INTRODUCTION

The possibility of guidance of waves by a magnetic field in a plasma is of considerable interest in astrophysics. In the earth's magnetosphere the possibility of guidance of Alfvén waves [*1*] round the tubes of flux of the earth's magnetic field is of interest in connection with pulsations of the earth's magnetic field [*2–6*]. Likewise the possibility of guidance at audio frequencies by field-aligned structure in the magnetosphere is important in connection with whistlers and other audio frequency phenomena [*7*, *8*, *9*]. Moreover, it would be of great interest if such guidance were feasible in the magnetosphere at frequencies above the penetration frequency of the ionosphere [*10*]. It is the objective of this paper to examine what is currently known about the theoretical possibilities of these aspects of guidance in the magnetosphere.

It should be noticed that there is some confusion in the literature between the concepts of guidance and beaming in a magneto-plasma. If the magneto-plasma possesses field-aligned irregularities, it is clear that the possibility exists of guidance qualitatively similar to that existing in a laboratory wave-guide. But is guidance feasible in a homogeneous magneto-plasma? A wave-source of limited physical dimensions in general has a near field associated primarily with storage of energy, and a far field associated primarily with radiation of energy to large distances. It is from the far field that we derive the radiation pattern of the source and judge to what extent the source constitutes a beam antenna. In the far field the radiated power-density in general decreases inversely as the square of the distance from the source. For any beam antenna there exists between the storage field and the radiation field an intermediate field of great interest. This is the field that gives the parallel beam behavior in optical and microwave devices. In optics it is known as the Fresnel region, whereas the radiation field is known as the Fraunhofer region. For an end-fire antenna the field in the Fresnel region is directly controlled by the guiding structure of the antenna. In the Fresnel region divergence is relatively unimportant. In the Fresnel region the field has guidance characteristics whether or not the form of the antenna involves an end-fire guidance structure. We must therefore think of any source that leads to beam characteristics in the radiation field as having an intermediate field with guidance features. From the storage field close to the source there emerges a guidance field in the direction of the beam, and after a certain distance the guidance field breaks out into the diverging beam. Guidance in a homogeneous magneto-plasma depends on being sufficiently close to the source to be in the guidance field rather than in the diverging radiation field.

For a source in a magneto-plasma no complete analytical solution is yet available describing the transition from the storage field to the radiation field through the guidance field. However, the behaviour in the radiation field is reasonably well known. Moreover, it is unlikely that, for this type of beam antenna, the broad dimensional relationships between the radiation field and the guidance field differ radically from those applicable for all other beam antennas. On this assumption we may estimate the extent of the guidance field for a source in a magneto-plasma.

In a wide range of circumstances encountered in the magnetosphere we shall find that the guidance field extends no great distance from the source. In these circumstances field-aligned irregularities are required to produce guiding of practical importance. Using an adaptation of the wave-guide theory of duct propagation in the troposphere, we may estimate the minimum strength of field-aligned irregularities required to produce guiding, and the minimum transverse scale of the irregularities required to make the guiding effective.

2. THE MAGNETO-IONIC THEORY AT RADIO, AUDIO AND HYDROMAGNETIC FREQUENCIES

We shall be interested in discussing the propagation of waves in a magneto-plasma above and below the following frequencies: the electronic-plasma frequency f_{Ne}, the electronic gyro frequency f_{Me}, the ionic-plasma frequency f_{Ni}, and the ionic gyro frequency f_{Mi}. At hydromagnetic frequencies (frequencies of the order of f_{Mi} and below) it is convenient to express velocities in terms of the ionic Alfvén velocity $cf_{\mathrm{Mi}}/f_{\mathrm{Ni}}$, where c is the velocity in free space. At whistler frequencies it is convenient to compare velocities with the electronic Alfvén velocity $cf_{\mathrm{Me}}/f_{\mathrm{Ne}}$.

We shall neglect the effect of all collisions. Thus neutral molecules, if present, play no part. We shall also neglect the pressure terms in the vibrational equations of motion of the charged particles. The possibility of sonic waves in the plasma is thus eliminated. This requires the assumption that the velocity of ion-acoustic waves in the plasma is small compared with the ionic Alfvén velocity, an assumption well satisfied in the magnetosphere. We are therefore concerned with the waves in the plasma that are referred to in radio literature as the ordinary and extraordinary waves, and in the hydromagnetic literature as the transverse and fast waves. It should be noted that, for an arbitrary direction of propagation relative to the imposed magnetic field, these waves involve corrugations of density even though the associated gradients of pressure are neglected.*

The propagation of waves of this type in a magneto-plasma constitutes what is known as the magneto-ionic theory [*12*, *13*]. However, to cover hydromagnetic frequencies as well as radio frequencies, we require the form of the magneto-ionic theory that incorporates ionic motion. The magneto-ionic theory in this form has been investigated by Åström [*14*] and others [*15*, *16*, *17*], and is described in some detail in a book by Denisse and Delcroix [*18*]. In the present paper use will be made of two approximations to the general theory. In both of these approximations it is assumed that the ratio of the ionic mass to the electronic mass may be taken as infinite. In the radio approximation this is achieved by correctly allowing for the inertia of the electrons but taking the mass of the ions as infinite. In the hydromagnetic approximation the infinite ratio of ionic mass to electronic mass is achieved by correctly allowing for the inertia of the ions but taking the mass of the electrons as zero. The radio approximation is applicable at frequencies large compared with f_{Mi} and f_{Ni}. The hydromagnetic approximation is applicable at frequencies small compared with f_{Me} and f_{Ne}. The radio approximation gives the well-known Appleton–Hartree [*19*, *20*]

---

* Thus Eq. (101) of Lighthill [*11*] is incorrect, thereby making the corresponding section of his paper inapplicable.

formula for the refractive index n of a wave of frequency f whose direction of phase propagation makes an angle θ with the direction of the imposed magnetic field. This formula is:

$$n^2 = 1 - \frac{f_{\mathrm{Ne}}^2/f^2}{1 - \dfrac{f_{\mathrm{Ne}}^2}{f^2 - f_{\mathrm{Ne}}^2}\left[\tfrac{1}{2}\sin^2\theta \pm \sqrt{\tfrac{1}{4}\sin^4\theta + \cos^2\theta\left(\dfrac{f^2 - f_{\mathrm{Ne}}^2}{ff_{\mathrm{Me}}}\right)^2}\,\right]}. \quad (1)$$

The hydromagnetic approximation has been derived by Booker [*21*] and yields the formula:

$$n^2 = 1 + \frac{f_{\mathrm{Ni}}^2}{f_{\mathrm{Mi}}^2 - f^2}\left[1 + \frac{1}{\cos\theta}\left\{\tfrac{1}{2}\sin^2\theta\left(1 + \frac{f_{\mathrm{Mi}}^2 - f^2}{f_{\mathrm{Ni}}^2}\right) \pm \sqrt{\tfrac{1}{4}\sin^4\theta\left(1 + \frac{f_{\mathrm{Mi}}^2 - f^2}{f_{\mathrm{Ni}}^2}\right)^2 + \cos^2\theta\,\frac{f^2}{f_{\mathrm{Mi}}^2}}\right\}\right]. \quad (2)$$

Propagation is predominantly quasi-longitudinal or quasi-transverse according as the $\cos^2\theta$ term under the radical is large or small compared with the $\sin^4\theta$ term. With the hydromagnetic approximation, propagation is predominantly quasi-transverse below the ionic gyro frequency and predominantly quasi-longitudinal above the ionic gyro frequency. With the radio approximation, propagation is predominantly quasi-longitudinal except near the electronic-plasma frequency. Thus, propagation is predominantly quasi-longitudinal except below the ionic gyro frequency and in the neighborhood of the electronic-plasma frequency.

Under quasi-longitudinal conditions at frequencies small compared with the electronic gyro frequency the radio approximation becomes:

$$n^2 = 1 \pm \frac{f_{\mathrm{Ne}}^2}{ff_{\mathrm{Me}}\cos^2\theta} \quad (3)$$

and it is upon this equation that the Eckersley law for whistlers is based [*22*]. Under quasi-longitudinal conditions at frequencies large compared with the ionic gyro frequency, the hydromagnetic approximation becomes:

$$n^2 = 1 \pm \frac{f_{\mathrm{Ni}}^2}{ff_{\mathrm{Mi}}\cos\theta} \quad (4)$$

However, this equation is identical with Eq. (3) because the ratio of the square of the plasma frequency to the gyro frequency is independent of particle mass. We thus see that, while the Eckersley law for whistlers is usually thought of as based on the low frequency behavior of the radio approximation, it may also be thought of as based on the high frequency behavior of the hydromagnetic approximation. If there is a range of frequencies where the Eckersley law is applicable, both the radio and the hydromagnetic approximations are valid in this frequency range. We therefore see that, under a wide range of conditions encountered in the magnetosphere, the high frequency behavior of the hydromagnetic approximation fits on to the low frequency behavior of the radio approximation, the overlap occurring in the frequency range where the Eckersley law for whistlers is applicable.

3. THE LEFT-HAND WAVE ($f < f_{Mi} < f_{Ni}$)

Let us first consider the wave for which the electromagnetic vectors rotate in the left-hand sense round the direction of the imposed magnetic field. This is the ordinary wave for $f < f_{Ni}$, that is, the wave for which propagation becomes independent of the imposed magnetic field when the direction of the imposed magnetic field is rotated so as to be transverse to the direction of phase propagation.* The left-hand wave has an attenuation band from the ionic gyro frequency to the electronic plasma frequency. In the pass band below the ionic gyro frequency we may apply the hydromagnetic approximation. A standard calculation of group propagation based upon Eq. (2) leads to the behavior depicted in Fig. 1.

Each of the four diagrams in Fig. 1 represents the far-field behavior of a pulse radiated from the origin. The radiated pulse is confined within a cone round the direction of the imposed magnetic field. Within the cone, two pulses are radiated with somewhat different velocities. Outside the cone the wave is evanescent. The arrows shown in the diagram indicate the directions in which individual wave-crests move within the pulse. On the axis of the cone, the individual wave-crests move within the slower pulse in the radial direction; for the faster pulse, however, the direction of phase propagation would be transverse to the radial direction if the phase velocity at this position were not zero. As the frequency increases to the edge of the pass band at the ionic gyro frequency, the group velocity tends to zero. On the

---

* Note that Åström [*14*] reverses the names "ordinary" and "extraordinary" at hydromagnetic frequencies.

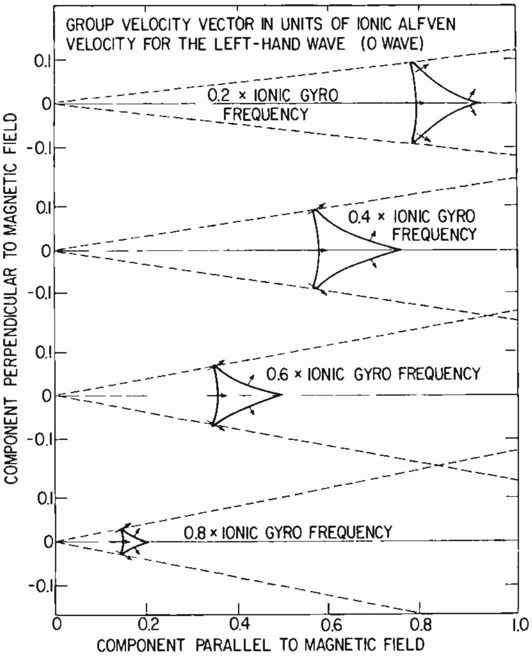

Fig. 1. Far field behavior at hydromagnetic frequencies of a pulse radiated from a source generating the magneto-ionic component for which the electromagnetic vectors rotate left-handed about the imposed magnetic field. The arrows indicate the directions in which individual wave-crests move within the pulse.

other hand, as the frequency tends to zero, the triangular pulse pattern shrinks to a point that moves along the direction of the imposed magnetic field with the ionic Alfvén velocity. The semi-vertical angle of the cone to which radiation is confined is equal to about

$$\frac{1}{4}\left(\frac{f}{f_{\mathrm{Mi}}}\right)^{\frac{1}{2}}. \tag{5}$$

We thus see that an ordinary wave source in a magneto-plasma at frequencies less than the ionic gyro frequency is a species of beam antenna pointing both ways along the imposed magnetic field with a semi-beam angle given by expression (5).

Let us now assume that the guidance field associated with the radiation field illustrated in Fig. 1 is roughly the same as that for any end-fire antenna having a semi-beam angle given by expression (5). To do this, we combine

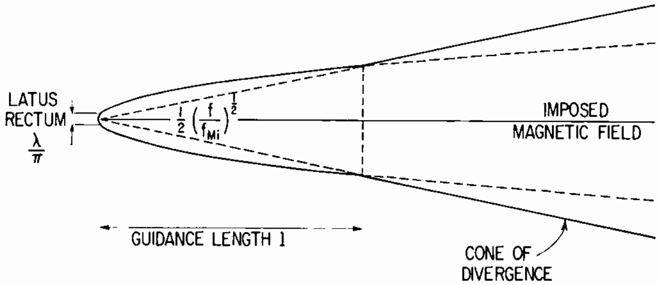

Fig. 2. Illustrating the relation between the radiation-beam angle $\frac{1}{2}\,(f/f_{\mathrm{Mi}})^{\frac{1}{2}}$, the guidance length l, and the wavelength λ in the medium.

the radiation cone with a paraboloid of revolution as shown in Fig. 2. The paraboloid has its focus at the source and its axis along the imposed magnetic field. The *semi latus rectum* of the paraboloid is $\lambda/2\pi$, where λ is the wavelength in the medium. At frequencies small compared with the ionic gyro frequency, λ is derived from f using, not the free space velocity, but the ionic Alfvén velocity. We assume that the wave is guided along the magnetic field for the distance l illustrated in Fig. 2, after which it diverges in the cone as shown in Fig. 1. The length l is then the usual length of an end-fire antenna producing a semi-beam angle given by expression (5). From Fig. 2 we easily deduce that

$$l = \frac{4}{\pi}\frac{f_{\mathrm{Mi}}}{f}\lambda\,. \tag{6}$$

To apply these concepts to the magnetosphere we need to compare the guidance length l given by Eq. (6) with the length of a particular tube flux of the earth's magnetic field in the magnetosphere. We assume without investigation that the bent nature of the earth's magnetic field and the decrease of plasma density with height in the magnetosphere are not of vital importance, and we evaluate the guidance length l given by Eq. (6) for the point where the tube of magnetic flux crosses the equatorial plane. We use a model of the magnetosphere in which the ions are protons and the electronic-plasma frequency decreases inversely proportional to the square of geocentric distance, starting from a value of 1 Mc/s at low levels in the magnetosphere. In this way we derive Fig. 3, in which the various diagrams refer to tubes of flux with different mean latitudes Λ. The double arrow indicates the range of frequencies over which the length of the tube is less

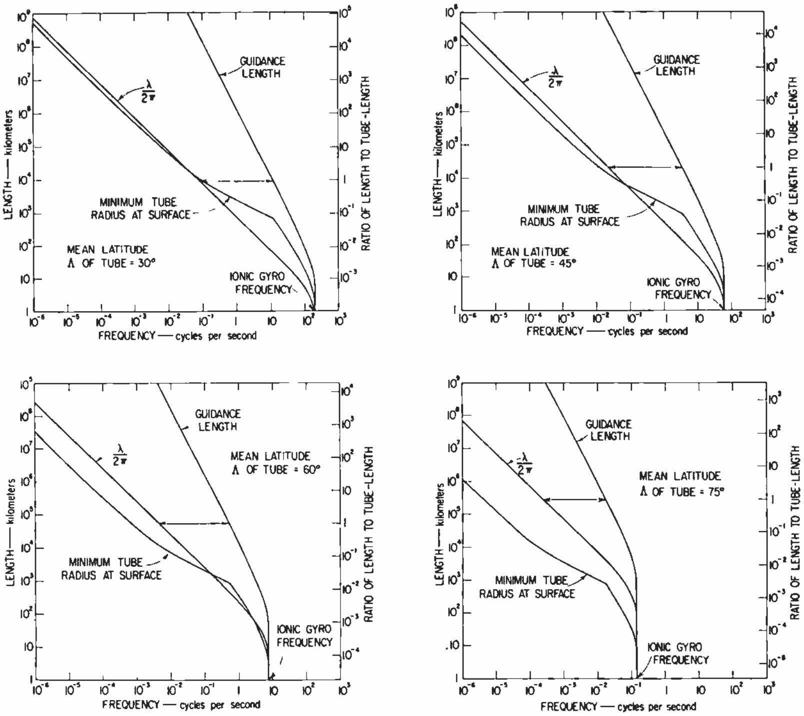

Fig. 3. Illustrating, as functions of latitude and frequency, the guidance length *l*, the value of $\lambda/2\pi$, and the minimum tube-radius for which Alfvén guidance is applicable.

than the guidance length *l* but greater than $\lambda/2\pi$. This is the range of frequencies in which the concept of resonant "plucking" of tubes of flux is probably appropriate. We see that the concept is applicable over about two decades of frequency, and that the logarithmic mid-frequency decreases from about 1 c/s at low latitudes to about 10^{-3} c/s at high latitudes. Also shown in Fig. 3 is the minimum radius of tube for which the guidance concept is applicable. This is deduced from the maximum relevant radius of the paraboloid indicated in Fig. 2, and has been corrected from the equatorial crossing point of the tube to the surface of the earth. For resonant "plucking", radii are of the order of a few thousand kilometers.

4. THE RIGHT-HAND WAVE ($f < f_{Me} < f_{Ne}$)

Let us now turn our attention to the wave for which the electromagnetic vectors rotate right-handed about the direction of the imposed magnetic field. This wave is the extraordinary wave for $f < f_{Ni}$, and the ordinary wave for $f_{Ni} < f < f_{Ne}$. The switch in terminology at the ionic-plasma frequency arises from a behavior close to transverse propagation-conditions similar to that occurring at the electronic-plasma frequency close to longitudinal propagation-conditions [*23*]. For the right-hand wave the far-field behavior of a pulse emanating from a source is illustrated in Fig. 4 for frequencies less than the electronic gyro frequency. The right-hand half of Fig. 4 is based on the radio approximation using the form appropriate for whistler frequencies [*24*], namely,

$$n^2 = \frac{f_{Ne}^2}{f\,(f_{Me}\cos\theta - f)} \tag{7}$$

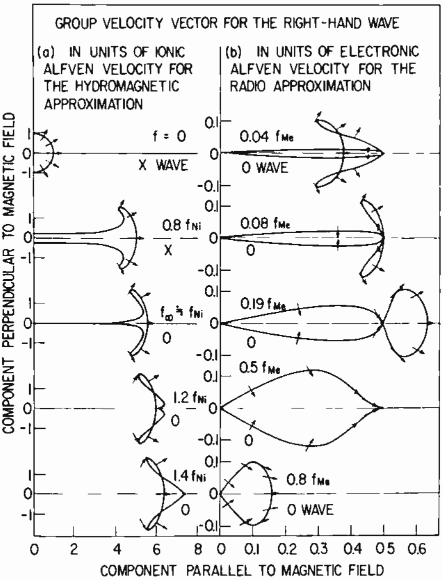

Fig. 4. Far field behavior of a pulse radiated from a source generating the magneto-ionic component for which the electromagnetic vectors rotate right-handed about the imposed magnetic field. The arrows indicate the direction in which individual wave-crests move within the pulse.

and velocity is expressed in units of the electronic Alfvén velocity. The left-hand half of Fig. 4 is based on the hydromagnetic approximation using the complete formula given in equation (2), and velocity is expressed in units of ionic Alfvén velocity. For the left-hand half of Fig. 4 it has been assumed that f_{Ni}/f_{Mi} equals 10.7, corresponding to a value of f_{Ne}/f_{Me} of 1 for atomic oxygen, $\frac{1}{2}$ for helium, and $\frac{1}{4}$ for hydrogen. The arrows indicate the directions in which individual wave-crests move within the pulse.

Each wave-packet into which the pulse in Fig. 4 may be dissected moves radially away from the source. Hence the portions of the pulse in the right-hand half of Fig. 4 that trail back to the source are subject to strong divergence and are relatively unimportant. Likewise, in the left-hand half of Fig. 4, the portions of the pulse that are nearly parallel to the imposed magnetic field (see the pulse patterns for $f = 0.8\, f_{Ni}$ and f_{Ni}) are subject to strong divergence and are relatively unimportant. Notice how the high frequency behavior of the hydromagnetic approximation fits onto the low frequency behavior of the radio approximation. Fig. 4 thus gives a picture of how the omni-directional hydromagnetic wave at frequencies small compared with the ionic gyro frequency becomes gradually transformed into the whistler mode.

Fig. 4 illustrates the fact that, from the ionic gyro frequency to the electronic gyro frequency, the right-hand wave exhibits some degree of beaming in the direction of the imposed magnetic field and in the reverse direction. As has been shown by Smith [*24*], the strongest beaming occurs at a frequency of about $0.19\, f_{Me}$ and the minimum value of the semi-beam angle is about 11°. For the right-hand wave, therefore, the imposed magnetic field produces about as much beaming as that involved in typical Yagi antennas. The guidance field consequently extends from the source along the magnetic field about as many wavelengths in the medium as are involved in the length of a typical Yagi antenna. It is clear, therefore, that, in the absence of field-aligned irregularities, guidance of the whistler mode in the magnetosphere by the earth's magnetic field is hopelessly inadequate to explain non-divergent propagation of whistlers round tubes of magnetic flux between opposite hemispheres.

5. GUIDANCE BY FIELD-ALIGNED IRREGULARITIES

From the previous section it is clear that guidance of whistlers round the tubes of flux of the earth's magnetic field from one hemisphere to the other requires field-aligned irregularities of plasma density. Using ray theory, investigations of this wave-guide action have been made by Smith, Helliwell, and Yabroff [*25*], by Yabroff [*26*], and by Smith [*27*]. Using the mode theory of wave-guides [*28*], investigations have been made by Voge [*29*, *30*], and by Booker [*31*]. For weak magnetospheric ducts in which only one or two modes are trapped, or in which even the lowest mode is only partially guided, the mode theory is the more appropriate. For strong magnetospheric ducts in which many modes are trapped, the ray theory is appropriate. For estimating the minimum strength of field-aligned irregularities required to produce guiding, and the minimum scale transverse to the magnetic field for which the guiding is effective, the mode theory is the more appropriate.

The simplest kind of field-aligned irregularity that has been studied involves a discontinuity of ionization density at a surface in the magnetosphere formed by rotating a line of flux of the earth's magnetic field round the magnetic axis. Such a surface of discontinuity can form what in acoustics is known as a whispering gallery. A wave can be guided around the surface from one hemisphere to the other by a succession of total internal reflections at the interface. Another example of an electromagnetic whispering gallery occurs at the surface of the earth under conditions of tropospheric duct propagation [*32*]. One way of describing what is happening in a tropospheric duct is to say that the equivalent radius of the earth is negative, so that the earth's surface is concave outwards, and propagation proceeds in rectilinear segments by successive reflections from the concave surface. Thus the theory of tropospheric duct propagation [*33*, *34*] is directly adaptable to magnetospheric duct propagation. In particular, the tropospheric concept of modified refractive index is applicable to magnetospheric duct propagation. The tubes of flux of the earth's magnetic field may be straightened out provided that an appropriate transverse gradient of refractive index is introduced. The modifying transverse gradient required at any point is equal to the curvature of the lines of magnetic flux of the earth's magnetic field at that point and is easily calculated.*

For a field-aligned irregularity of ionization density consisting of a single axially-symmetrical surface of discontinuity let N be the ionization

---

* The formulae for field curvature given by both Booker [*31*] and Voge [*29*] are, however, incorrect. In Booker's Eq. (11) the power $\frac{1}{2}$ in the denominator should be replaced by $\frac{3}{2}$; this is only a misprint and does not affect subsequent statements. In Voge's Eq. (22) the factor $1 + 3 \sin^2 \theta$ should be raised to the power $\frac{3}{2}$; this modifies the statement that immediately follows, but does not upset the main results given in Table 1.

density just below the interface and $N+\Delta N$ the ionization density just above the interface. Let n be the refractive index just below the interface and λ the corresponding local wavelength. Let the gradient of ionization density in the part of the magnetosphere under consideration be such that the corresponding ray curvature exceeds the local curvature of the earth's magnetic field by κ; κ is then the local curvature of rays in the modified problem in which the lines of flux of the earth's magnetic field have been straightened. A mode on the underside of the interface consists of crossing waves each of which converts into the other by reflection at the interface on the top-side and by refraction in the medium of the underside. The distance between these two surfaces is the track-width w of the mode. The angle of incidence of the waves at the interface is calculated by application of the phase-integral rule, allowing for the $\frac{1}{2}\pi$ phase-change at the lower edge of the track and the appropriate Fresnel phase-change at the interface. For guidance of the mode the field on the top-side of the interface must be substantially evanescent, so that the waves on the underside of the interface must be incident at a more glancing angle than is required for total internal reflection. By equating this angle to the critical angle for total internal reflection we may estimate the minimum discontinuity of ionization density required to guide the mode. In this way we obtain for the minimum fractional change of ionization density required to guide the lowest mode

$$\frac{\Delta N}{N} = \frac{n^2}{1-n^2}\left(\tfrac{3}{8}\kappa\lambda\right)^{\frac{2}{3}} \tag{8}$$

and for the corresponding track-width

$$w = \frac{1}{2\kappa}\left(\tfrac{3}{8}\kappa\lambda\right)^{\frac{2}{3}} \tag{9}$$

Booker [31] has applied Eqs. (8) and (9) to a model of the magnetosphere in which the electronic-plasma frequency decreases inversely proportional to the square of geocentric distance from a value of 1 Mc/s low in the magnetosphere. He calculated expressions (8) and (9) as functions of position round a number of lines of magnetic flux over a wide range of frequencies. at a particular frequency the variations of $\Delta N/N$ and w around a particular line of flux usually remain within the same power of ten and so may be roughly identified with the values at equatorial transit. These values are shown as functions of frequency in Fig. 5 for both the left-hand and right-hand waves; the various diagrams refer to field-aligned irregularities in different latitudes Λ.

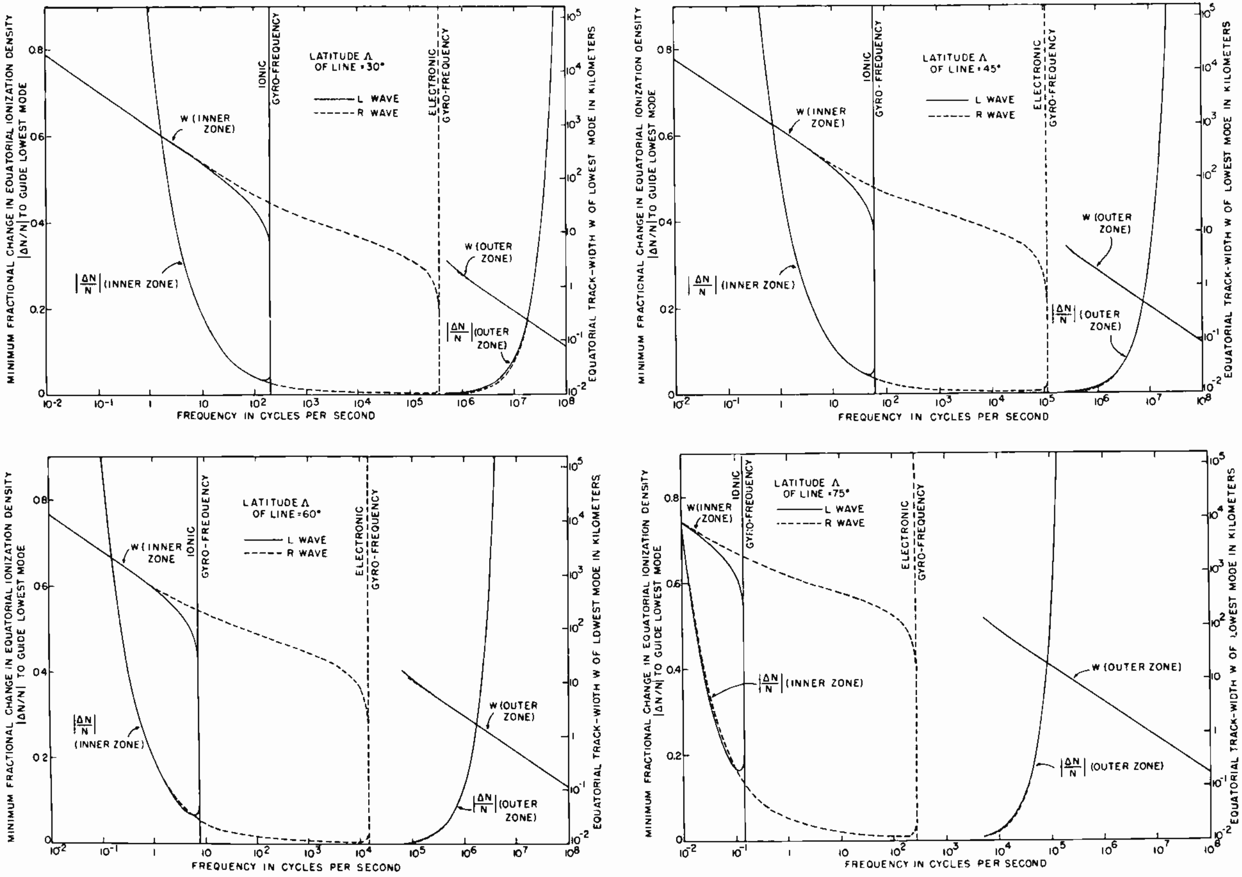

Fig. 5. Illustrating, as functions of latitude and frequency, the minimum fractional variation of ionization density required for field-aligned guiding and the minimum transverse scale for which the minimum fractional deviation is effective.

More elaborate field-aligned structures than a single discontinuity have been considered by Voge [*29*, *30*] with results not essentially different from those given in Fig. 5. The value of $\Delta N/N$ shown in Fig. 5 may be interpreted as the minimum fractional deviation of ionization density required for field-aligned guiding in a practical magnetosphere. The value of w shown in Fig. 5 may be interpreted as the minimum transverse scale for which the minimum fractional deviation is effective.

From Fig. 5 we see that, for the right-hand wave at whistler frequencies, guidance is produced by field-aligned irregularities involving a fractional variation of ionization density of only one percent. This is almost certainly the explanation of the ease with which whistlers are guided round the lines of flux of the earth's magnetic field. We also notice from Fig. 5 that, for a given line of flux, there are about five decades of frequency over which guidance is possible for comparatively small fractional changes of ionization density. This frequency range slides down in frequency by about three decades as one moves from low to high latitude lines. Guidance disappears at sufficiently high radio frequencies because the magnetosphere then behaves substantially like free space. Guidance of this type disappears at sufficiently low hydromagnetic frequencies because the transverse scale of the guiding structure required is too large to be accomodated in the magnetosphere. Field-aligned guiding is unlikely much above 10 Mc/s or much below 1 c/s.

The calculations shown in Fig. 5 were based on the assumption that, for the small angles of propagation to the magnetic field involved, the refractive index could be taken as identical with the value for strictly longitudinal propagation. The validity of this assumption has been investigated by Voge [*30*] who shows that the values of $\Delta N/N$ and w given in Fig. 5 should be multiplied by

$$\left(1 - 2\frac{f}{f_{\mathrm{Me}}}\right)^{\frac{1}{3}}, \qquad f \leqq \tfrac{1}{2} f_{\mathrm{Me}} \tag{10}$$

$$-\left(2\frac{f}{f_{\mathrm{Me}}} - 1\right)^{\frac{1}{3}}, \qquad \tfrac{1}{2} f_{\mathrm{Me}} \leqq f < f_{\mathrm{Me}} \tag{11}$$

The effect of this correction is to make it even easier to obtain guiding in the neighborhood of one half the electronic gyro frequency. However, it should be noted that, if one moves along a line of flux that crosses the surface where $\frac{1}{2} f_{\mathrm{Me}}$ is equal to the frequency f of the wave under consideration, the sign of $\Delta N/N$ changes. This would have an important effect if one were considering a field-aligned irregularity consisting of a single axially-symmetric surface of discontinuity for which the sign of ΔN were everywhere the same. Trapping of the mode would then be replaced by leakage, or *vice versa*, as one crossed the surface where $f=\frac{1}{2}f_{\mathrm{Me}}$. However, in practice, one is more likely to have a series of field-aligned irregularities. All that happens then as one crosses the surface where $f=\frac{1}{2}f_{\mathrm{Me}}$ is that, whereas the mode has previously been hugging one side of the duct, it now crosses over and hugs the other side. The upshot is that the dependence of refractive index on direction of propagation relative to the magnetic field has no major effect on Fig. 5.

Voge [*30*] points out however that, when the dependence of refractive index on direction of propagation relative to the magnetic field is taken into account, modes are possible in which the direction of phase propagation differs radically from the direction of the magnetic field. These modes correspond in Fig. 4 to the alternative intersection of the pulse with the magnetic axis. The alternative intersection exists for frequencies above the ionic-plasma frequency and below one half the electronic gyro frequency. Furthermore, as pointed out by Gendrin [*35*], propagation of this type is non-dispersive for the frequency range $f_{\mathrm{Ni}} \ll f < \frac{1}{2}f_{\mathrm{Me}}$; as shown in the right-hand half of Fig. 4, the velocity of propagation in these circumstances is equal to one half the electronic Alfvén velocity.

REFERENCES

1. H. Alfvén, *Nature*, 150 (1942) 405.
2. H. Benioff, *J. Geophys. Res.*, 65 (1960) 1413.
3. W. H. Campbell and S. Matsushita, *J. Geophys. Res.*, 67 (1962) 555.
4. R. R. Heacock and V. P. Hessler, *J. Geophys. Res.*, 67 (1962) 3985.
5. J. A. Jacobs and T. Watanabe, *J. Atmos. Terrest. Phys.*, 24 (1962) 413.
6. J. E. Lokken, J. A. Shand and C. S. Wright, *J. Geophys. Res.*, 68 (1963) 789.
7. L. R. O. Storey, *Phil. Trans. Roy. Soc. London*, A246 (1954) 113.
8. R. A. Helliwell and M. G. Morgan, *Proc. IRE*, 47 (1959) 200.
9. R. A. Helliwell, J. H. Crary, J. H. Pope and R. L. Smith, *J. Geophys. Res.*, 61 (1956) 139.
10. R. M. Gallet and W. F. Utlaut, *Phys. Rev. Letters*, 6 (1961) 591.
11. M. J. Lighthill, *Phil. Trans. Roy. Soc. London*, A252 (1960) 49.
12. J. A. Ratcliffe, *The magneto-ionic theory and its applications to the ionosphere*, Cambridge University Press, London, 1959.
13. K. G. Budden, *Radio waves in the ionosphere*, Cambridge University Press, London, 1961.
14. E. Åström, *Arkiv Fysik*, 2 (1950) 443.
15. J. W. Dungey, *Cosmic electrodynamics*, Cambridge University Press, London, 1958.
16. C. O. Hines, *J. Atmos. Terrest. Phys.*, 11 (1957) 36.

17. B. S. Tannenbaum and D. Mintzer, *Phys. Fluids,* 5 (1962) 1226.
18. J. F. Denisse and J. L. Delcrois, *Théorie des ondes dans les plasmas,* Dunod, Paris, 1961.
19. E. V. Appleton, *J. Inst. Elec. Engrs. (London),* 71 (1932) 642.
20. D. R. Hartree, *Proc. Cambridge Phil. Soc.,* 27 (1931) 143.
21. H. G. Booker, at: *Natl. URSI comm. meeting,* Washington, D.C., 1963.
22. T. L. Eckersley, *Nature,* 135 (1935) 104.
23. H. G. Booker, *Proc. Roy. Soc. (London),* A147 (1934) 352.
24. R. L. Smith, *J. Res. Natl. Bur. Std.,* 64D (1960) 505.
25. R. L. Smith, R. A. Helliwell and I. W. Yabroff, *J. Geophys. Res.,* 65 (1960) 815.
26. I. Yabroff, *J. Res. Natl. Bur. Std.,* 65D (1961) 485.
27. R. L. Smith, *J. Geophys. Res.,* 66 (1961) 3699.
28. K. G. Budden, *The wave-guide mode theory of wave propagation,* Logos Press, London, 1961 (Prentice-Hall).
29. J. Voge, *Ann. Télécommun.,* 16 (1961) 288.
30. J. Voge, *Ann. Télécommun.,* 17 (1962) 34.
31. H. G. Booker, *J. Geophys. Res.,* 67 (1962) 4135.
32. H. G. Booker, *J. Inst. Elec. Engrs. (London),* 93 (1946) 69.
33. H. G. Booker and W. Walkinshaw, *Meteorological factors in radio wave propagation,* Phys. Soc., London, 1946, p. 80.
34. J. Voge, *Onde Élec.,* 28 (1948) 99.
35. R. Gendrin, *Compt. Rend.,* 251 (1960) 1085.

DISCUSSION

(a) Guidance in the Troposphere

The magnitude and frequency of occurrence of tropospheric ducting are, at some locations, greater than would be expected from climatological data. Results of experiments in the "trade winds" include a six-week period in summer with ducts extending for 1000 nautical miles westward from California for more than 90 per cent of the time. Both the intensity and frequency of occurrence of the duct decreased in the westward direction and from summer to winter. Refractive index measurements in winter suggest the presence of a duct for 40 per cent of the time between Brazil and Ascension Island. Height-gain measurements show maximum signal at the altitude of an abrupt change in refractive index ($\Delta N = 50$). With an antenna well below a strong duct, a loss of 10–30 dB in duct excitation is observed at the horizon range. It has been suggested that the loss may be calculated by adopting ray-tracing below the duct, Booker–Gordon scattering in the volume bounded by the antenna beam and the duct, and the assumption that the power intercepted by the duct is determined by its acceptance angle as deduced by ray-tracing methods. The required assumptions regarding turbulence fall between reasonable limits, but available meteorological data are not adequate to verify the mode of excitation *(F. Macdonald)*.

(b) Guidance below the Ionosphere

The wave-guide mode-theory has been verified by recording spectra of atmospherics at a distance [*1*]. Maximum energy occurs at 10 kc/s and there is a sharp cut-off at 3–4 kc/s. Other maxima in the spectra occur at frequencies above 10 kc/s. The cut-off frequency has a marked diurnal variation consistent with a lowering of the ionosphere by day. The sudden raising of the cut-off frequency when a solar flare occurs can be explained by the formation of enhanced ionisation in the height-range 60–80 km *(T. Obayashi).*

One suggested explanation of the observation of maxima in the spectra well above 10 kc/s is non-linearity in the ionospheric conductivity; for weak electric fields the forced motion of electrons is not linearly proportional to field strength *(K. Maeda).* However the spectra could also be explained in terms of interference between two or more waveguide modes *(J. R. Wait).*

(c) Guidance in the Magnetosphere

The possibility of guidance of high frequency waves along magnetic field lines was raised at the General Assembly of 1960, and is still a contentious topic. An experiment was carried out in the summer of 1962 near Paris (magnetic latitude 50°). Ten echoes were received from distances between 21,500 and 22,500 km. Ducting may have occurred in magnetic shells which have been detected by the Ariel and Alouette satellites *(F. du Castel).* However propagation round the earth, followed by backscatter to the receiver, is another possible mechanism *(R. A. Helliwell).* No echoes have been detected in experiments on 16 Mc/s at Brisbane (magnetic latitude 37°) using sensitive receivers with directional aerials. Rough calculations in agreement with the more refined treatment of Booker, suggest that beamwidths of the order of 1° would have been necessary to detect an echo. The sizes of small-scale transverse irregularities, as derived from spread-F and scintillation observations, are of the right order of magnitude for the Booker analysis *(J. A. Thomas).* In Japan, HF backscatter echoes have been received from ranges of 6000–8000 km, which coincides with the length of the geomagnetic field line through the transmitter, and it has been suggested tentatively that a whispering-gallery type of phenomenon occurs along field-aligned irregularities [2] *(T. Obayashi).* It has been concluded, from the lack of attenuation of ducted echoes observed at very low frequencies in the Alouette satellite, and from the symmetry of ducts observed by use of a rocket, that the irregularities consist of deficiencies in ionization in volumes of cylindrical form *(T. E. Van Zandt).*

REFERENCES

1. T. Obayashi, *J. Res. Natl. Bur. Std.*, 64D (1960) 41.
2. T. Obayashi, *J. Radio Res. Lab. Japan*, 6 (1959) 603.

AUTHOR INDEX*

---

* Italic numbers pertain to authors' actual contributions.