REPORT 262-7

ELF, VLF AND LF PROPAGATION IN AND THROUGH THE IONOSPHERE

(Question 25/6)

(1963-1966-1970-1974-1978-1982-1986-1990)

1. Introduction

Transmitted radio frequencies in the range from 30 Hz to 300 kHz, which are typically reflected from the lowest ionospheric layers, are useful for a wide range of applications in addition to radiocommunication. In particular, the stability of propagation of frequencies in the VLF range (3-30 kHz) makes them useful for navigation and time comparison purposes. (For terrestrial paths, a discussion of the propagation characteristics of frequencies below about 30 kHz is found in Report 895, and Report 265 contains circuit performance information for the frequency range from 30 to 500 kHz.) However, it has been known for many years that very low frequencies can be propagated through the ionosphere by a mode which for historical reasons has been called the "whistler mode". Signals originating in lightning flashes were observed at frequencies within the audio range and were termed "musical atmospherics" [Eckersley, 1925; Barkhausen, 1919]. These frequencies are subject to dispersion such that the velocity of propagation decreases with frequency. The received signal therefore has a characteristic whistle of decreasing frequency over a period of a second or more. They also consist of a series of well-separated echoes with increasing frequency dispersions. These remarkable properties have been explained theoretically in terms of propagation, by an extraordinary mode of low velocity and small attenuation, along a path closely confined around a line of the Earth's magnetic field, the signals travelling to and fro between conjugate points on the surface of the Earth [Storey, 1953; Morgan *et al.*, 1956; Helliwell and Morgan, 1959]. A comprehensive survey of the history of whistler research has been published [Helliwell, 1965].

The whistler mode is classified into a ducted mode propagating along field aligned irregularities of enhanced ionization [Smith, 1961; Cerisier, 1974] and a non-ducted mode with large wave normal angles to geomagnetic field lines [Kimura, 1966; Smith and Angerami, 1968; Aikyo *et al.*, 1972]. Ray-tracing results of VLF waves in model magnetospheres [Aikyo and Ondoh, 1971; Walter and Scarabucci, 1974] have suggested a density gradient wave trapping in the plasmapause and a VLF wave trapping of non-ducted modes in the plasmasphere or plasma trough as observed by satellites [Burtis and Helliwell, 1969; McPherson and Koons, 1970; Gurnett and Shaw, 1973]. The whistler duct width increases with corrected geomagnetic latitude in the plasmasphere [Ondoh, 1976].

2. Use of VLF and LF transmitters

The whistler mode of propagation has been studied by using high-power VLF and LF transmitters. With the increasing interest being shown in the problem of transmission on various frequencies for terminal points on the surface of the Earth and in or above the ionosphere, it is now preferable to think of ELF, VLF and LF propagation in general and to restrict the term "whistler" to transmissions covering a frequency spectrum such as is originated by a lightning flash for which the frequency dispersion characteristic of whistlers can be observed.

It is interesting to note that the times when relatively strong signals have been obtained between conjugate points with VLF transmitters have shown only poor correlation with the times when whistlers were prevalent. Thus, although experiments using natural sources are of great scientific interest in unravelling some of the complexities of VLF propagation through the ionosphere, they must be supplemented with experiments directly related to propagation on given frequencies from chosen transmitting points.

3. Frequency limits and intensity considerations

It has been found that when both terminals are on the surface of the Earth, the whistler mode is effective at frequencies as low as 400 Hz and as high as 35 kHz. There is a well-defined cut-off frequency which is approximately 0.6 of the minimum gyro-frequency for electrons along the path. Satellite-borne receivers, which extend the observations to non-ducted signals, show the presence of whistler-mode signals at frequencies as high as 0.9 of the local electron gyro-frequency [Dunckel and Helliwell, 1977]. Whistler-mode propagation has been observed at most locations between geomagnetic latitudes 20° and 80°, and during the winter night even at Okinawa and Varanasi where the geomagnetic latitude is as low as 15° [Ondoh *et al.*, 1979; Singh and Singh, 1977]. Observations at middle latitudes show that, at night, signals by a single traverse between conjugate points can be obtained by the whistler mode for more than half the time and can approach in strength on occasion to within 10 dB of the conventional waveguide signal between the Earth and the ionosphere. Little is known about the intensity of daytime whistler-mode signals, but it appears that they are severely attenuated in the D region of the ionosphere.

Factors important in the calculation of intensity are:

- the polarization and directivity of the radiator,
- the properties of the path between the end-points of the duct in the ionosphere and the terminal points on the ground,
- the transmission coefficient for the propagation through the lower regions of the ionosphere,
- the spatial divergence in the duct,
- multipath effects resulting from the presence of more than one duct,
- the amplification, or absorption, of signal energy through interaction with charged particles in the plasma.

4. Propagation analysis

A full-wave computer program has been developed for studying the fields in a horizontally stratified ionosphere for waves incident from above or below for a wide range of the relevant parameters [Pitteway, 1965; Pitteway and Jesperson, 1966]. In some models studied, the effects of sporadic-E layers have been included. Sporadic E can give very high internal reflection coefficients for waves incident from above. This is important when only the distant end of the guiding magnetic field line is in daylight, since very efficient two-hop whistler-propagation may then be possible. It has also been shown that a large part of the whistler wave energy can be reflected in the absence of sporadic E provided the wave-normal direction is outside the acceptance cone for penetration to the Earth's surface [Thomas and Smeathers, 1971]. This is important in the interpretation of rocket measurements of whistlers.

Near 14 kHz the transmission coefficient for upgoing waves varies only slowly with angles of incidence between ± 85° at middle latitudes, whereas at 100 kHz efficient transmission is possible only at angles within a cone having its axis along the direction of the magnetic field; this influence of the magnetic field is more noticeable at all frequencies at lower latitudes [Thomas and Horowitz, 1971]. Both by day and night, the transmission coefficient is mainly determined by losses in the ionosphere, provided that steep gradients of electron density, similar to those in a sporadic-E layer, are absent. The whistler-wave absorption, which occurs chiefly in the lower ionosphere, increases with frequency and with decrease in latitude [Thomas and Horowitz, 1971; Wieder, 1967].

In the auroral zone, the whistler wave absorption is considerably influenced by particle precipitation, that is, several tens of dB for polar black-out events, and 10 to 20 dB at a sunlit noon or auroral night, whereas it is only a few dB in the quiet ionosphere during a winter night [Ondoh, 1963; Harang, 1968].

At the lower ELF frequencies Galejs [1972] and Pappert [1973] found that excessive dipole moments were required for effective excitation of the terrestrial waveguide mode by satellite-borne sources. De Witt *et al.*, [1976] calculated the propagation characteristics of ELF/VLF waves through the ionosphere from a source in the magnetosphere. Expressions were developed which gave the ratio of the power transmitted to the Earth's surface to the power incident on the top of the ionosphere, as a function of the number of wave-hops in the earth-ionosphere waveguide. The wave polarization was calculated as a function of the number of hops. In addition, in calculating the signal power budget for a magnetospheric source of ELF or VLF waves, it was necessary to calculate the geometric spreading factor of the waves as they propagated from the source to a receiver at the Earth's surface [Kelly *et al.*, 1976a]. In all low altitude transmitter cases (below about 2200 km) the spreading factor decreased rapidly in magnitude as distance from the maximum point of the hot spot power pattern increased. The spreading factor was shown to be smaller and less sensitive to receiver location for a fixed high-altitude transmitter location. The satellite power required to provide a S/N ratio in excess of 0 dB in a 1 Hz bandwidth at a ground range of 1000 km from the ionospheric exit point of the waves was evaluated for several cases [Kelly *et al.*, 1976b]. The power requirement (in the megawatt range) exceeds that available on current spacecraft missions, but it is within the realm considered possible for future space electric power systems.

5. Satellite observations

The study of VLF propagation in and through the ionosphere has been considerably advanced by using satellites. For a terminal point within the ionosphere, the effect of a highly anisotropic medium on the antenna characteristics and thus on the transmission loss must be considered. A useful review of satellite observations of VLF phenomena in the magnetosphere has been published [Rycroft, 1967].

An interesting series of experiments has been undertaken in the Lofti satellite programme. Lofti-I indicated that useful amounts of VLF radio energy can penetrate the atmosphere/ionosphere interface and, in particular, that 18 kHz signals from ground-based transmitters were detected as far as 16 000 km away in the ionosphere with substantially less attenuation at night than by day, as expected. The observed time delays ranged from 10 to 200 ms, indicating that the VLF propagation velocity in the ionosphere is much lower than in free space [Leiphart *et al.*, 1962]. In the Lofti-II experiment, in addition to signal strength, measurements were made of dipole impedance in the ionosphere. The measured impedance was found to be radically different from that in free space. This is also in accordance with theoretical analyses.

Alouette-1 contained a receiver covering the frequency range 0.4 to 10 kHz using an electric dipole. The VLF signals received at the satellite were very strong. Short fractional hop (SFH) whistlers, i.e. those which have been propagated from a lightning flash only once through the ionosphere often overloaded the receiver. Transmissions were received from high-power ground-based transmitters and even from low-power transmitters (100 W) at 10 kHz, but no study has yet been made of these signals. Long fractional hop (LFH) whistlers, i.e. those thought to be propagating down the line of force from the opposite hemisphere, were often observed having the same dispersion characteristics during a full ten-minute telemeter recording. This implied that a particular duct was active throughout this period in propagating the whistlers which, after leaving the duct, travelled some thousands of kilometres transversely to reach the satellite receiver. Horizontal propagation of SFH whistlers can lead to reflection of these signals near the height of the satellite [Barrington and Belrose, 1963; Carpenter *et al.*, 1964; Smith, 1964].

However, simultaneous ground and satellite reception of whistlers [Thomson and Dowden, 1977a] show that most whistlers are received in satellites after reflection near the base of the ionosphere. Since downgoing whistlers usually exit from ducts at altitudes well above 1000 km [Thomson and Dowden, 1977b], whistlers from a given duct can be received on satellites over a wide range along the path of a satellite (up to 2000 km for ISIS-2 at an altitude of 1400 km). Even wider reception ranges, without change in dispersion characteristics, occur for non-ducted "pro-longitudinal" whistlers [Thomson and Dowden, 1977c]. While in both cases those effects are due to deviation ($\approx 20°$) from strictly field-aligned propagation, transverse propagation is not involved.

While theoretically one would expect ions to strongly influence ELF propagation, the effects of ions were not directly observed prior to the satellite experiments. The importance of ions is demonstrated by the identification of ioncyclotron whistlers [Smith *et al.*, 1964; Barrington *et al.*, 1966a and b], which have been studied to provide a measure of mean ionic mass at the height of the satellite [Gurnett *et al.*, 1965; Barrington and McEwen, 1967]. Moreover, a VLF plasma reasonance, the lower hybrid resonance for the transverse mode of propagation, was identified in Alouette VLF data as a cut-off frequency for VLF noise [Brice *et al.*, 1964]. This identification also provided information on the mean ionic mass at the height of the satellite [Barrington *et al.*, 1965]. Solar cycle variations of the occurrence rate of trans-equatorial proton and deuteron ion whistlers were obtained from ISIS observations [Watanabe and Ondoh, 1984].

6. Conclusions

The study of ELF, VLF and LF propagation in and through the ionosphere began with ground based observations of whistlers, which are dominantly influenced by their long propagation path through the magnetosphere. Satellite-borne observations have greatly advanced our knowledge about propagation within the ionosphere – these observations have revealed the importance (at the lowest frequencies) both of propagation transverse to the direction of the Earth's magnetic field and of ions on propagation. As might be expected, the ionosphere strongly affects the propagation of ELF, VLF and LF radio waves, which can penetrate it by the whistler mode of propagation. This propagation is possible for Earth-space and space-Earth systems. The propagation is characterized by large group delays, highly variable attenuations, very indirect transmission paths, and also by a complicated interaction between the propagated waves and energetic particles present in the ionosphere. Because of this latter observation, proposals have been made for employing high-power VLF and LF transmitters in satellites. While such transmissions may give rise to significant amounts of noise and interference, they are likely to be limited by the difficulty in providing high power for satellite-borne transmitters.

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