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RESEARCH REPORT

DUCTED PROPAGATION OF VLF WHISTLER-MODE SIGNALS AT L=1.93 AS DEDUCED FROM MEASUREMENTS OF GROUP TRAVEL TIMES AND ARRIVAL DIRECTIONS

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Abstract

Group travel times and arrival directions of the whistler-mode signals from VLF transmitter in Eastern USSR were measured at the geomagnetic conjugate point (geomag. lat. 40.2°S; L = 1.93) in South Australia. The dispersion values obtained by the group travel times were almost the same around sunset at the two frequencies of 14.881 kHz and 11.905 kHz. The arrival directions of the 14.881 kHz whistler-mode signals were mainly distributed around the magnetic field line intersecting the receiver. These results indicate that the mid-latitude whistler-mode waves propagate in a field-aligned duct and penetrate through the low-latitude ionosphere of the receiver. A comparison between the group travel times around sunset on two geomagnetically quiet days is discussed based on the measurements of arrival directions and intensities of the whistler-mode signals.

1. Introduction

Whistler ducts are produced by field-aligned plasma density irregularities. Ducted propagation of daytime whistlers at low-latitudes ($20-35°$ geomagnetic lat-

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itude) has been established experimentally by measuring wave normal directions aboard a rocket (Iwai *et al.*, 1974), by the simultaneous observations at multiple stations (Hayakawa and Ohtsu, 1973), by direction finding (DF) and polarization measurements at Moshiri (geomagnetic latitude, 34.5°N) (Hayakawa *et al.*, 1981) and at Yamaoka (Ohta *et al.*, 1984) and theoretically by means of computations of ray tracing and wave absorption (Tanaka and Hayakawa, 1985).

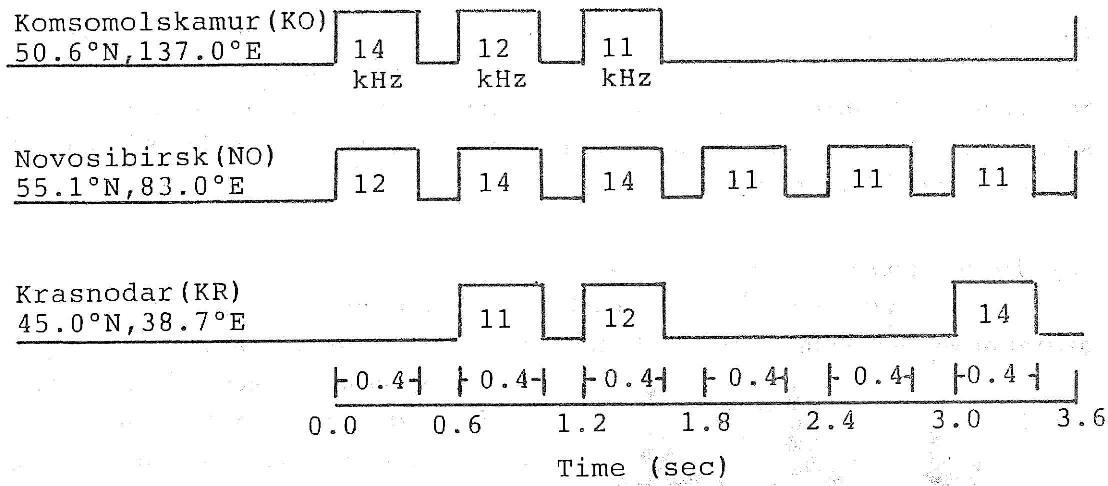
The occurrence of whistlers is controlled by propagation conditions as well as thunderstorm activities around the conjugate zone of the receiver. Conjugate measurements of whistler-mode signals from VLF transmitter are powerful means to clarify the propagation effect on the occurrence of whistlers. From conjugate measurements of whistler-mode signals from VLF transmitter in Eastern USSR at Ceduna ($L = 1.93$) in South Australia in 1984, it was found that intensities of whistler-mode signals increased usually at sunset compared with those during the night. This result has been inferred as a mechanism of spatially coherent propagation in a field-aligned duct and transmission out of the duct onto the ground at sunset by means of the calculation of the wave attenuation in the lower ionosphere (Tanaka *et al.*, 1987). The purpose of the present paper is to elucidate experimentally the above inference from the measurements of group travel times and arrival directions of VLF whistler-mode signals carried out at Ceduna in 1986.

2. Measurements of group travel times and arrival directions

Three Soviet VLF transmitter stations, as shown in Fig. 1, organized as the "Alpha" navigation system, transmit VLF signals at 14 .881 kHz, 12.649 kHz and 11.905 kHz, each for a duration of 0.4 sec, according to the transmission format indicated in Table 1. Conjugate measurements of the whistler-mode signals from Komsomolskamur (KO) station (geographic coordinates, 137.0°E, 50.6°N) in Eastern USSR were carried out during July to August in 1986 at Ceduna (geographic coordinates, 133.7°*E*, 31.1°*S*), South Australia.

Wideband (10 – 20 kHz) "NS" and "EW" components of magnetic fields and a vertical component of electric fields were received by crossed loop antennas (10 m high, 16 m base, 1 turn, triangular type) with their planes oriented in the geomagnetic NS and EW directions and by a vertical monopole, respectively. Narrowband (bandwidth, ±50 Hz) receivers of the three components were also equipped at a specific frequency of 14.881 kHz for the direction finding of the whistler-mode signals. The three wide- and narrow-band signals were modulated by carrier signals at multiple frequencies, and were recorded through a 2 ch PCM-processor in a VTR recorder (0 – 20 kHz bandwidth) for one minute every 10 minutes from 16 h to 08 h JST (135°E.M.T.).

Table 1. Transmission format normally used for Soviet "Alpha" navigation system from three VLF transmission stations.



Station	KO	NO	KR
Distance (km) from Ceduna	9,190	10,820	12,810
Direction (°) from North	-2.2	26.5	51.1

Distance from each station to Ceduna, and direction angle measured clockwise from geographic north for the waveguide-mode signal propagating along the long circle from each transmitter to Ceduna.

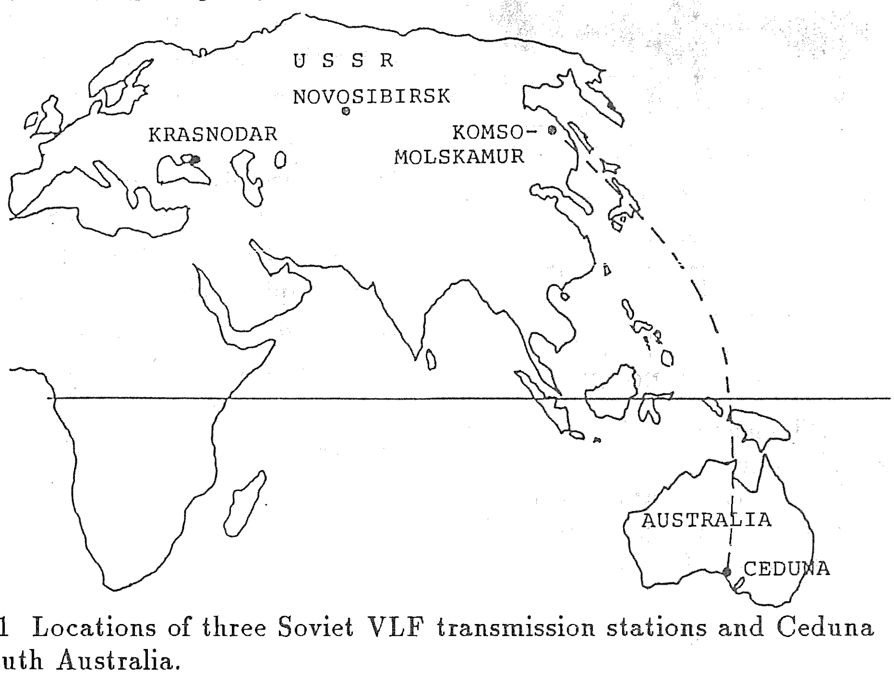


Fig. 1 Locations of three Soviet VLF transmission stations and Ceduna in South Australia.

Fig. 2 shows a typical example of amplitude variations on NS, EW and vertical components at 14.881 kHz received at Ceduna. The transmitting format at 14.881 kHz from the three stations (KR, KO and NO) is also represented in the lower panel. Superimposed partially on the NO waveguide-mode signals, enhanced signals were received on the three components with a time delay of about 0.5 sec. from the KO waveguide-mode signals. These enhanced signals were identified as whistler-mode signals by means of polarization measurements of waveforms of the NS and EW components (Nishino *et al.*, 1987).

(a) Measurement of group travel times

Group travel times of whistler-mode waves can be measured by delay times from arrival of waveguide-mode signals to that of whistler-mode ones, as shown in Fig. 2.

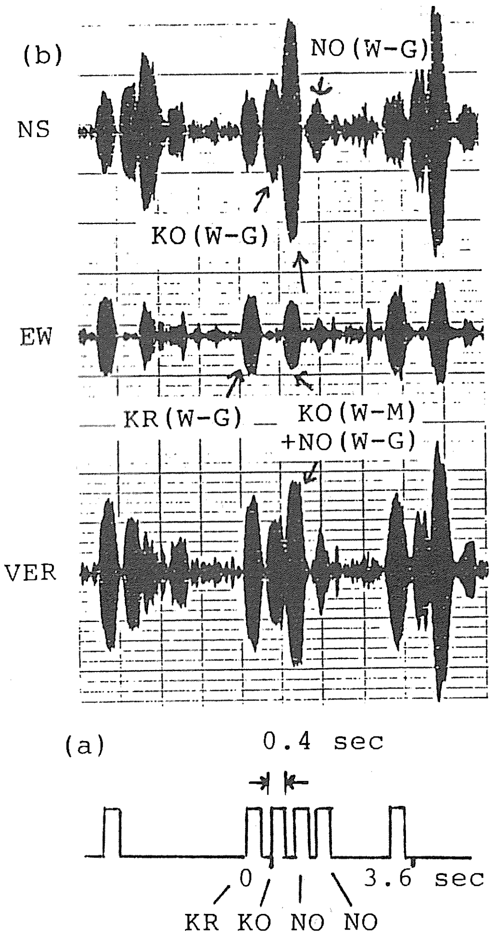


Fig. 2 (a)Transmission format of the 14.881 kHz signals.
(b)Amplitude variations in NS, EW and vertical components of the received signals at Ceduna.

A trigger pulse is generated by the multiplier of the NS and EW components of the KR waveguide-mode signal appearing at the first sequence of 3.6 sec. repetition during one minute data. The KO waveguide-mode and KO whistler-mode signals are extracted from NS and EW components in the subsequent format, respectively. Thereafter, they are led to the respective envelope detectors. Two channel outputs are fed to an A/D converter of Waveform Analyzer (HP9000, series 300), and the delay times between them are measured by cross-correlation analyses with a time resolution of 10 msec. The delay times are measured from the points of the cross-correlated peak between the two detector outputs, so it seems difficult to discriminate the delay times of the whistler-mode waves propagating in different ducts of closely- spaced elements of a complex multiduct structure. Group travel times are obtained as the sum of the delay times and the propagation time (30 msec.) of the KO waveguide-mode signals.

(b) Measurements of arrival directions

Whistler-mode waves penetrating through the lower ionosphere are, in general, elliptically polarized. We adopted a DF method based on the field analysis from two horizontal magnetic fields and a vertical electric field of the arrival waves (Okada *et al.*, 1977; Ohta, 1984). As the detailed derivation of the DF was described by the above authors, we show only the reduction of azimuthal (θ) and incident (i) angles of the arrival waves, as follows.

$$\theta = \tan^{-1} \frac{M_{NS-V} \sin \phi_{NS-V}}{-M_{EW-V} \sin \phi_{EW-V}}$$

$$i = \sin^{-1} \frac{1}{M_{NS-V} \cos \phi_{NS-V} \cos \theta + M_{EW-V} \cos \phi_{EW-V} \sin \theta}$$

where M_{NS-V} and M_{EW-V} are amplitude ratios of NS component to the vertical one and EW to the vertical, respectively, and ϕ_{NS-V} and ϕ_{EW-V} are phase differences of NS to the vertical and EW to the vertical, respectively. As described above, since the KO whistler-mode signals are superimposed on the NO waveguide-mode signals, the DF has errors, depending on the relative intensity ratios and phase differences between the two signals. We estimate briefly the DF errors in terms of the whistler-mode signals arriving from the directions of $-30° < \theta < 30°$ and $i = 30°$, which are dominant directions, as shown in Fig. 7 of the next section. Assuming the intensity ratio (NO/KO) of 0.2, DF errors are estimated roughly within ±5 degrees on the azimuthal and ±6 degrees on the incident angles in the range of the phase difference of ±180° between the two signals. On the DF analyses by the Computer (ACOS–650), we selected relatively strong whistler-mode signals with the intensity ratio (NO/KO) less than 0.2.

3. Ducted propagation of whistler-mode signals

Fig. 3 shows a typical example of temporal variations in group travel times of the whistler-mode signals measured at 11.905 kHz and 14.881 kHz. Both variations connected by broken lines fluctuate mainly due to a technical problem in which timing of the trigger pulse described at the previous section is disturbed by irregular atmospherics. Then they are smoothed out by taking the running average, as shown by solid lines. A similar trend in the variations between the two frequencies enables us to estimate that the whistler-mode waves propagate in the same set of ducts on the two frequencies. Using the relation of $D = t \times \sqrt{f}$ (D, dispersion; t, travel time; and f, frequency), dispersion values of the whistler-mode waves are calculated from the measured group travel times, as shown in Fig. 4. The standard deviation of the fluc-

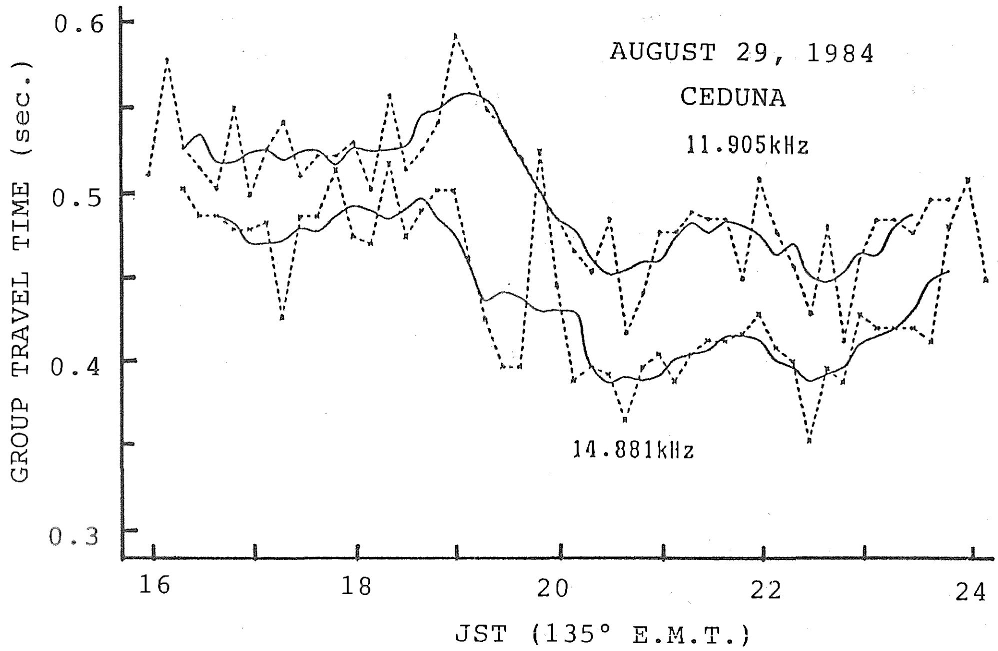


Fig. 3 Temporal variations of the group travel times at 11.905 kHz and 14.881 kHz from daytime to midnight on August 29, 1984.

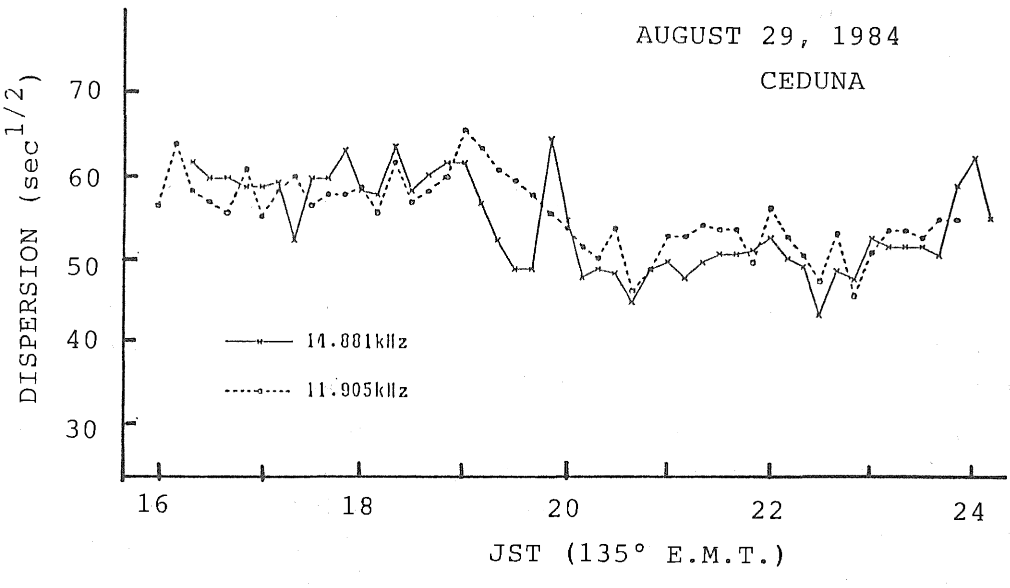


Fig. 4 Temporal variations of the dispersion values at 11.905 kHz and 14.881 kHz from daytime to midnight on August 29, 1984.

tuating values from the running average of Fig. 3 are group travel times of about 24 ms and 18 ms for 14.881 kHz and 11.905 kHz, respectively, which correspond to errors of the dispersion values of about 3 $sec^{1/2}$ and 2 $sec^{1/2}$ for 14.881 kHz and 11.905 kHz, respectively. Therefore, the group travel times of Fig. 4 are recognized to be almost the same on the two frequencies, which evidently indicates that the whistler-mode waves propagate in the same set of field-aligned ducts on the two frequencies.

Fig. 5 shows an occurrence histogram of the measured group travel times of the 14.881 kHz whistler-mode waves, in which the occurrence is definitely confined in the limited range of 0.35–0.6 sec. A group travel time depends on total electron contents in a ducted tube and path length of the duct (path latitude) (Andrews *et al.*, 1978). The propagation path in the magnetosphere between the transmitter and the conjugate receiver is definitely dominant in the magnetic meridian plane. In order to evaluate the measured group travel times, we calculate group travel times along the ray path between 300 km altitudes of the conjugate ionospheres, assuming 50 % duct enhancement and 50 km duct width (Ondoh, 1976) superposed on the background electron density determined by a diffusive equilibrium model (Tanaka and Hayakawa, 1985). The electron density in the evening at 500 km reference altitude is given by 1×10^5 and 2×10^5 $/cm^3$. Fig. 6 shows group travel times calculated as a function of L-shell at 300 km altitude. The measured group travel times of 0.35–0.6 sec. correspond to the path latitudes of $L = 1.7 - 2.3$ and $L = 1.5 - 2$ in terms of the above two values of the electron density, respectively.

Direction finding is essential to determine the ionospheric exit points of transmission out of the duct onto the ground. Fig. 7 shows a statistical distribution of arrival directions of the 14.881 kHz whistler-mode signals with relatively strong intensities received around sunset. The distribution is depicted by occurrence rates in 36 segments divided by every 30° in the azimuthal and incident angles. It is clearly found that arrival directions are mainly distributed around the magnetic field line ($\theta = 0°$, $i = 30°$) intersecting the receiver. This result evidently supports the measurement that the 14.881 kHz whistler-mode waves received at Ceduna are nearly circular polarization (Nishino *et al.*, 1987). It is concluded from the measurements of group travel times and arrival directions that the whistler-mode waves from the KO transmitter propagate in the field-aligned ducts and penetrate through the low-latitude ionospheres of the receiver.

4. Temporal variations of group travel times on geomagnetically quiet days

Fig. 8 shows temporal variations in group travel times around sunset on two

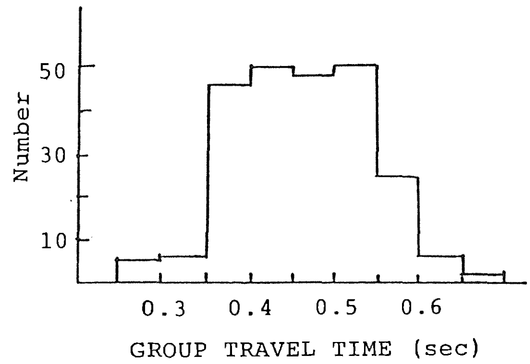


Fig. 5 Occurrence histogram of the measured group travel times for the 14.881 kHz whistler-mode waves.

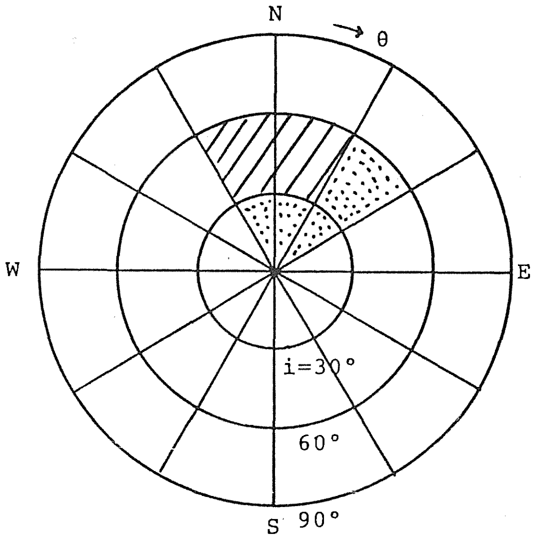


Fig. 7 Distribution of the arrival directions of the 14.881 kHz whistler-mode waves. The distribution is depicted by occurrence rates in 36 segments divided by every 30° in azimuthal and incident angles.

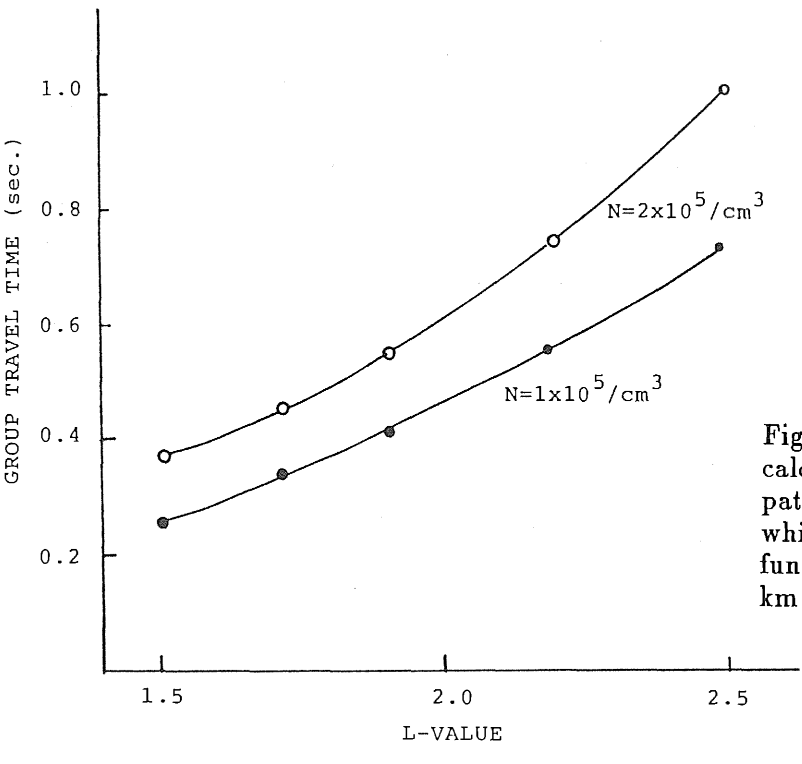


Fig. 6 Group travel times calculated along the ray path for the 14.881 kHz whistler-mode signals as a function of L-value at 300 km altitude.

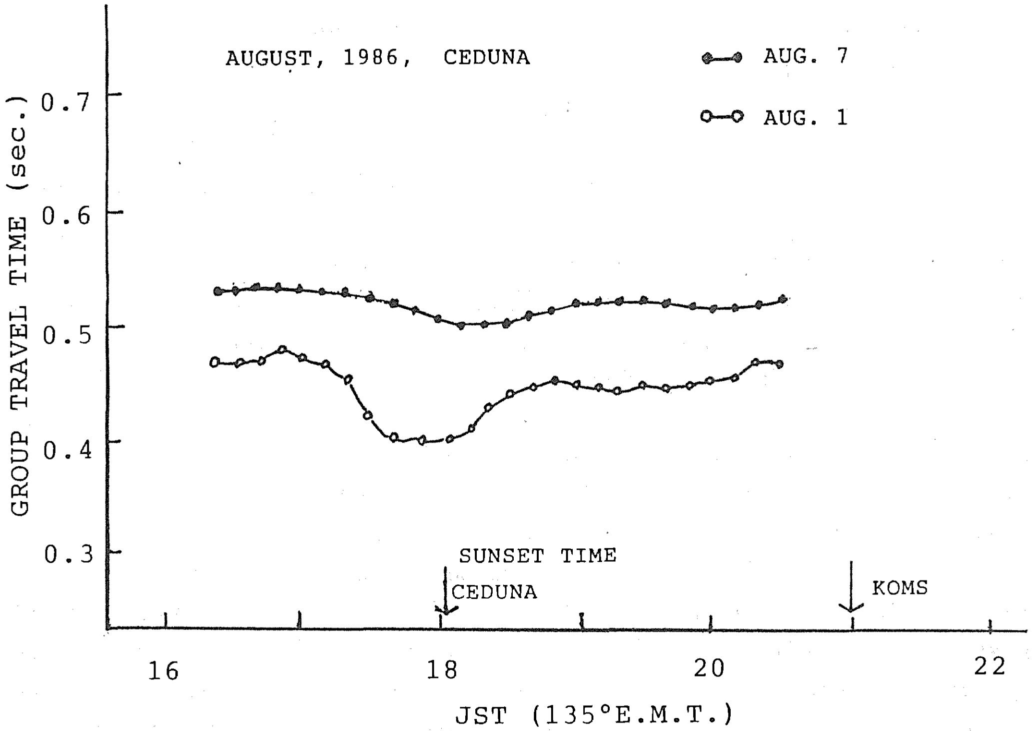


Fig. 8 Temporal variations of the group travel times around sunset on two geomagnetically quiet days; Aug. 7 and Aug. 1, 1986.

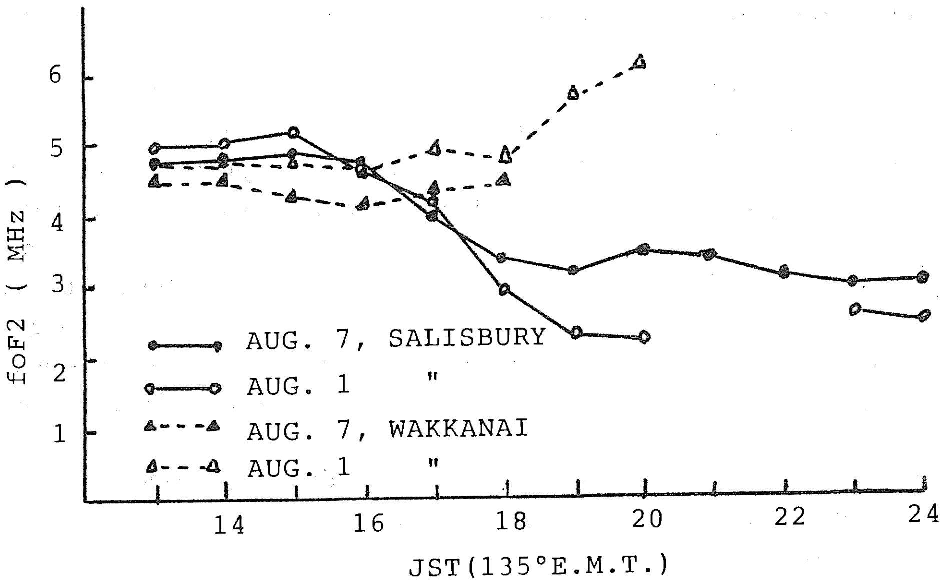


Fig. 9 Temporal variations of the ionspheric f_oF_2 values observed at Wakkanai, Japan and Salisbury, South Australia on Aug. 7 and Aug. 1, 1986.

geomagnetically quiet days, Aug. 7 and Aug. 1 ($K_p < 2$ throughout the day), 1986. Both group travel times decrease from the daytime to the sunset time of the receiver, and thereafter increase toward the sunset time of the transmitter station. However, it is found that the variation on Aug. 1 shows a relatively sharp decrease during 17 h to 18 h JST. Group travel times of whistler-mode waves depend on the total electron contents in the ducted tube and the path latitude of the duct, as described above. In order to discuss a difference between the both temporal variations, we first show temporal variations of the ionospheric f_oF_2 values in the zones close to the transmitter and the conjugate one in Fig. 9. Wakkanai (geographic lat., 45.4°N, long., 141.7°E), of Japan and Salisbury (lat., 35.0°S, long. 138.8°E) of South Australia are about 700 km southeast from the transmitter and about 450 km southeast from the receiver, respectively. Both the sunset times in Wakkanai and Salisbury advance the transmitter and receiver by about a half-hour. It is found that the F–region over the transmitter is still sunlit between 17 and 18 h JST, while it is around sunset at the ionospheric level over the receiver. Then a decrease of the group travel times between 17 to 18 h JST in Fig. 8 seems to be caused by the decrease of total electron contents in the ducted tube (coupling fluxes of plasma between the plasmasphere and the ionosphere) around the sunset time of the receiver. The relatively sharp decrease of the group travel times on Aug. 1 seems to correspond to the relatively sharp one of the f_oF_2 values. The decrease of the group travel times around the sunset time may be also caused by a movement of a path latitude due to an inward drift of a duct inferred from Doppler shift measurements of VLF whistler-mode signals (McNeill and Andrews, 1975) and of LF whistler-mode signals (Nishino *et al.* 1989). Moreover, Andrews (1980) explained that the coupling fluxes contribute less than 20 % to the measured Doppler shifts at $L = 2.3$, most of which is therefore produced by cross-L drifts.

Figs. 10(a) and 10(b) show temporal variations of arrival directions of the 14.881 kHz whistler-mode waves around sunset on Aug. 7 and Aug. 1, respectively. On Aug. 7, exits of the whistler-mode waves penetrating through the ionosphere lie steadily around the magnetic field intersecting Ceduna, while the ones on Aug. 1 vary actively with time; particularly from 18:00 to 18:10 JST the exits move drastically from the field-aligned direction to the eastern high-latitude side of Ceduna. The exit movements to the high-latitude side may imply the effect of the drift of the magnetospheric duct if the lower ends of the duct extend down to the lower ionosphere. However, the relatively sharp decrease of the group travel times on Aug. 1 is not consistent with the movement to the high-latitude side of the path.

Tixer and Charcosset (1978) indicated the partly ducted propagation in the equatorial plane during magnetic quiet conditions in the middle latitude range between $L = 1.4$ to 4 from natural whistler observations aboard satellite. Also, Cerisier (1974) indicated the possibilities of partly ducted propagation of artificial VLF waves (16.8 kHz) through the magnetosphere by the satellite at 750 km altitude, both in

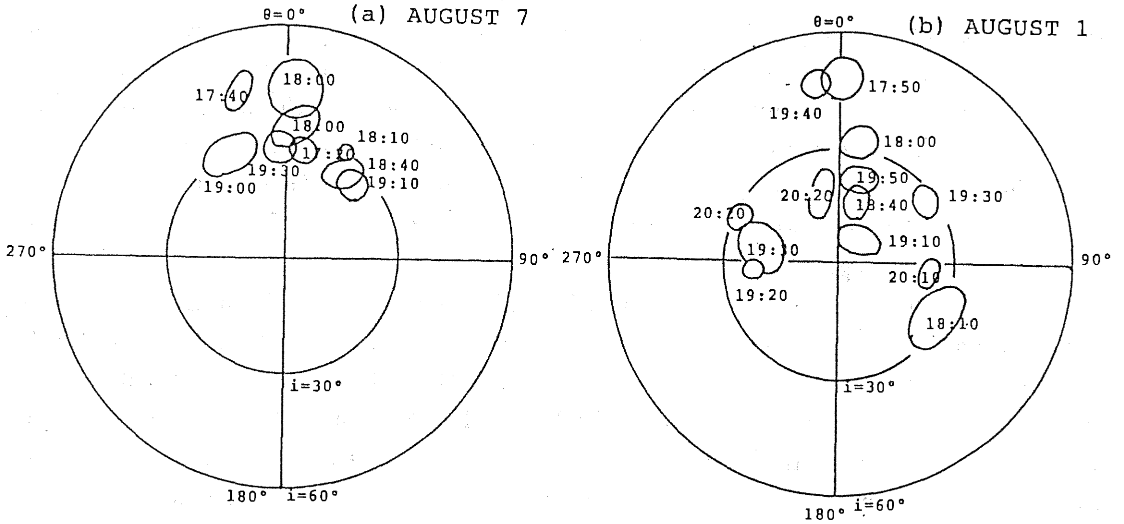


Fig. 10 Temporal variations of the arrival directions of the 14.881 kHz whistler-mode waves around sunset on (a) Aug. 7 and (b) Aug. 1, 1986.

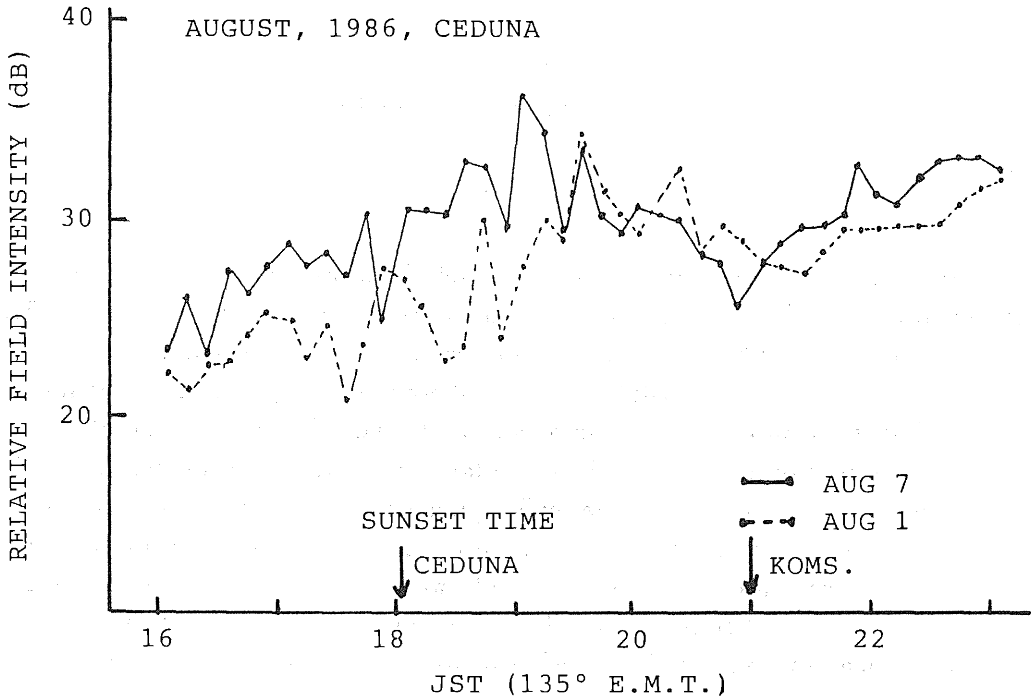


Fig. 11 Temporal variations of the field intensities of the 14.881 kHz whistler-mode signals around sunset on Aug. 7 and Aug. 1, 1986.

the zone close to the transmitter (L = 2.1) and in the conjugate zone, and found that generally the lower ends of the ducts are situated above the satellite. Moreover, Hayakawa et al. (1981) indicated from the DFs of mid-latitude whistlers that the small apparent movements of the exit regions may be due to a temporal fluctuation of the propagation conditions between the duct endpoint and the lower boundary of the ionosphere. From these observations it is reasonable that the exit movements to the high-latitude side on Aug. 1 in Fig. 10(b) are probably attributable to temporal fluctuation of the propagation conditions due to irregularities of electron density in the ionospheric F region.

Fig. 11 shows temporal variations of field intensities of the whistlermode signals around sunset on Aug. 7 and Aug. 1. The intensities are r.m.s. values of NS and EW components. The intensities on Aug. 1 are weaker than those on Aug. 7 until around 19:20, and are markedly weaker from 18:00 to 19:20 JST while the exits move to the high-latitude side or near the zenith of Ceduna. Weak intensities on Aug. 1 may be caused by scattering loss of the whistler-mode waves when they propagate into and out to field-aligned ducts and by the relatively large transmission loss in the lower ionosphere on the high-latitude side of Ceduna. They may be also caused by the transient effect on the duct formation due to the drastic drift of the ducted tube in the magnetosphere. In this case, electron densities in the ducted tube decrease temporarily, and as a result it may be possible that the group travel times decrease.

5. Concluding remarks

From the measurements of group travel times and arrival directions of the whistler-mode signals radiated from VLF transmitter in Eastern USSR, it is confirmed that the mid-latitude whistler-mode waves (L = 1.93) propagate in a field-aligned duct and penetrate through the low-latitude ionosphere of the magnetic field line intersecting the receiver. However, it is found as an event study that the exit points from the lower ionosphere moved from the field line latitude to the high-latitude ionospheres over the receiver even on geomagnetically quiet days. The exit movements may be attributed to temporary fluctuation of the propagation conditions in the ionospheric F–region. Propagation of VLF whistler-mode waves in the ionosphere and magnetosphere at the middle-latitudes will be clarified by further analyses of voluminous data, and a theoretical approach will be needed in which ray tracing is used from the duct endpoints to the lower ionosphere employing realistic models of the magnetosphere and ionosphere.

Acknowledgements

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