Research Letter

Waveguide Parameters of 19.8 kHz Signal Propagating over a Long Path

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The amplitude and phase of 19.8 kHz signal from navigational transmitter located in North West Cape, Australia, recorded at Suva, Fiji, have been utilized to determine the waveguide mode parameters. The propagation path is mixed over land and sea having Transmitter-Receiver Great Circle Path distance 6.7 Mm. The experimental values of the parameters were found to be consistent with the theoretical values calculated using the mode theory of VLF wave propagation in the waveguide.

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1. Introduction

Extremely Low Frequency (ELF: 3–3000 Hz) and Very Low Frequency (VLF: 3–30 kHz) signals propagate to great distances in the waveguide bounded by the Earth’s surface (ground or sea) and the lower ionosphere (~60–140 km), consisting of the D and E-regions. This atmospheric waveguide is known as the Earth-Ionosphere Waveguide (EIWG). The D and E-regions are too high for balloons and too low for the satellite measurements. Radio sounding does not work, particularly at night, since electron densities in this region are low to reflect high frequency radio waves with ionosondes and incoherent radars. Therefore, the lower ionosphere remains the least studied region of the Earth’s atmosphere [1]. The conductivity of the D-region increases exponentially with height which may also vary with latitude and longitude along the propagation path. At ELF/VLF, the Earth’s surface and the lower ionosphere act as good electrical conductors. Electromagnetic waves reflect when incident upon conducting boundaries and are guided along the conducting structures.

The EIWG offers very little attenuation hence the guided ELF-VLF signals can be received literally around the world [2] and have long been used for long-distance communication, positioning and timings. Communications with submarines immersed in the conducting sea necessitated the use of VLF waves and later ELF waves, with their comparatively large skin depths in sea water [3]. Yokoyama and Tanimura [4] first observed diurnal variation of the amplitude of VLF (17.7 kHz and 22.9 kHz) signals propagated over long distances (>5000 km). Diurnal variations of VLF transmitter signals show amplitude minima associated with phase steps during sunrise and sunset transitions between transmitter and receiver [4–6] which could not be explained by single mode propagation theory. Wait [2] suggested that multiple modes are needed to explain VLF propagation in the EIWG. Crombie [5] proposed a model based on two modes being present in the nighttime portion of the propagation path and only one mode in the daytime portion of the propagation path in the EIWG. Clilverd et al. [6] have presented some interesting long-term (1990–1995) studies of VLF propagation over a long North-South path from Cutler (USA), Marine (NAA transmitter, 24 kHz) to Faraday, Antarctica. They found the timings of the minima in the received signal strength to be remarkably consistent from year to year. They also found that the timings of minima were consistent with modal conversion taking place as the day-night boundary (terminator) crossed the propagation path, at specific, consistent locations. The stability and reproducibility of the received amplitude and phase of VLF navigational transmitter signals make VLF propagation a useful tool for long-range communication and navigation system.
Purpose of this paper is to estimate the waveguide parameters from the observations of 19.8 kHz during December 2006, at Suva (18.1°S, 178.5°E), Fiji. This signal is transmitted by North West Cape, NWC (21.8°S, 114.1°E, 1 MW radiated power) VLF transmitter and propagates mostly in the West-East direction to Suva. The 1-minute averaged amplitude and phase data recorded at 0.1 second have been used for analysis.

2. Theoretical Background

When a VLF wave is transmitted from a vertical antenna, a number of modes are excited in the EIWG. The electric field strength of the signal propagating in the waveguide can be represented by a superposition of discrete waveguide modes [2, 7] expressed as:

\[ E = \frac{E_o}{h} \sum_{m=1}^{\infty} |A_m| \exp(-\alpha_m d) \exp \left[ i \omega \left( t - \frac{d}{v_m} \right) + i \arg A_m \right], \]

(1)

where \( E_o \) is a constant depending on radiated power and frequency of operation \( \omega \), \( h \) is the height of EIWG, \( A_m \) is the excitation factor of the \( m^{th} \) mode, \( \alpha_m \) is the attenuation rate of the \( m^{th} \) mode, \( d \) is the distance between transmitter and receiver, \( t \) is the time, and \( v_m \) is the phase velocity of the \( m^{th} \) mode.

The EIWG attenuation during day is higher than during the night and higher order waveguide modes have a larger spatial attenuation rate and are less efficiently radiated. The waveguide parameters can be estimated involving two modes in the night and one mode in the day. At large distances from transmitter (>5000 km), the mode 1 with lowest attenuation is dominant in the intensity. The diurnal change of the signal amplitude \( E_{DN} \) is defined as the ratio of nighttime to daytime signal strengths due to first mode. Using the expression of modal superposition (1), the value of \( E_{DN} \) in terms of dB can be obtained as:

\[ E_{DN}(dB) = \frac{h_0}{h_N} \left[ (|A_{N1}(dB)| - |A_{D1}(dB)|) - (\alpha_{D1} - \alpha_{N1}) d \right], \]

(2)

where \( N \) and \( D \) refer to night and day. \( A_{N}(dB) \) and \( A_{D}(dB) \) are the excitation factors in dB given by \( A_{N}(dB) = 20 \log_{10}(A_N) \) and \( A_{D}(dB) = 20 \log_{10}(A_D) \) respectively.

The diurnal phase shift normalized over 1 Mm (= 1000 km) represented by \( \phi_{DN} (\mu s \text{ Mm}^{-1}) \) is expressed as [7]:

\[ \phi_{DN} = \frac{10^4}{3} \left( \frac{c}{\nu_{N1}} - \frac{c}{\nu_{D1}} \right), \]

(3)

where \( c \) is the speed of light in free space and \( \nu \) is the phase velocity of VLF waves with mode 1 in the EIWG given by \( \nu = c (1 - (\lambda_2/2 h)^2)^{1/2} \), where \( \lambda_2 \) is free space wavelength of the transmitter signal.

The modal interference spacing \( D_{MS} \) between the successive signal minima (fades) at receiver can be simply defined by considering the interference of two modes [5]:

\[ D_{MS} = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1}, \]

(4)

where \( \lambda_1 \) and \( \lambda_2 \) are the waveguide wavelengths of the first and second order modes, respectively. The Equation (4) can be simplified to as given by Crombie [5]:

\[ D_{MS} = \frac{4 h^2}{\lambda_o^2}. \]

(5)

3. Observational Data and Results

Experimental set-up consists of a short (1.5 m) whip antenna, pre-amplifier, VLF service unit coupled with pre-amplifier, and Software based Phase and Amplitude Logger termed “SoftPAL”. The whip antenna receives the vertical electric field component of transverse magnetic (TM) mode of the VLF propagation. SoftPAL is a state of art data acquisition system recently (2006) developed by AD Instruments, New Zealand, which can log amplitudes (in dB above 1 \( \mu V/\text{m} \)) and phases (in degrees) of seven MSK (minimum shift key) VLF transmitter signals continuously with the time resolutions ranging from 10 milliseconds to 10 seconds, using a GPS based timing. Transmitter Receiver Great Circle Path (TRGCP) for NWC-Suva is 6.696 Mm. Typical diurnal variation of amplitude and phase of the signal on 10 December 2006, as recorded by SoftPAL, is presented in Figure 1. The daytime signal strength is larger than the nighttime which could be mostly due to the higher attenuation of EIWG for the daytime VLF propagation [8]. However, the received intensity of the signal depends on a number of factors including the excitation of modes, path attenuation, surface conductivity, ionosphere height, and the direction of propagation. The attenuation of VLF signals for the east-to-west propagation is greater than for the west-east propagation and the difference in the attenuation decreases as the frequency increases which probably disappears above about 20 kHz [9]. Three amplitude minima labeled as SR1, SR2, SR3 and SS1, SS2, SS3, respectively, are observed during sunrise and sunset transition along the TRGCP. As seen from Figure 1, the phase retards during the night and the rapid change of phase takes place at the time of the amplitude minima. Since D-region ionization is controlled by solar radiation, the reflection height of VLF waves, that is, height
of the EIWG, at night, increases by about 10–15 km from its daytime value. As a consequence of the increase in the reflection heights, the phase velocity of the wave decreases and the signal is delayed (retarded) at the receiver. The amplitude data for selected 15 days in December 2006 are overplotted in Figure 2 to indicate the reproducibility of the amplitude values over a 24 hour period. The phase values are not plotted as the phase builds up over the day and deviates from reproducing similar values over the days. However, the stepwise phase advances coincides very well with the amplitude minima over any day and form of variation is almost the same. The signal variability is larger during the night than during the day indicating that propagation path is more stable in the day. The generation of successive minima at the receiver during sunrise and sunset transitions is generally accepted due to the destructive interference in the superposition of propagating modes with each other which may involve more than two modes in the night and dominant day mode at the terminator converted into a series of nighttime modes [6]. It can be seen from Figure 2 that the depth of fading varies from 20–22 dB during sunrise and 3–4 dB during sunset transitions along the TRGCP and fading is better shaped during sunrise transition. This could be due to the less attenuation of waves propagating in the nighttime portion of the EIWG from transmitter to receiver, the shape of the lower ionospheric boundary and resulting scattering patterns, and the destructive interference of different number of modes at receiver during sunrise and sunset transitions. Also over the course of the propagation path, energy couples between modes which may result in the variation of depths of minima with the movement of the terminator between receiver and transmitter. Considering three different models for conductivity of the lower ionosphere, Devi et al. [10] carried out a waveguide mode analysis of 16 kHz VLF wave travelling great distances, to study its propagation parameters. They showed that for waveguide height less than 70 km, the change in phase due to changes in the phase velocity is smaller when ionosphere is assumed to have finite conductivity than when it is infinitely conducting. Using the data from Figure 2, the values of $E_{DN}$ in dB and diurnal phase change in degrees are estimated 7.5 dB and 375°, respectively. At 19.8 kHz, the value of the nighttime EIWG height ($h_N$) = 90 km and the daytime EIWG height ($h_D$) = 75 km, is a reasonable approximation. The height of the EIWG changes during day and night due to photoionization of the upper boundary of the EIWG (ionosphere) in the day. At 19.8 kHz, the value of first order mode differential excitation factor ($|A_{N1}| - |A_{D1}|$) can be worked out about 13.5 dB [11] and differential attenuation rate ($\alpha_{D1} - \alpha_{N1}$) can be taken as 1.0 dB/Mm. The theoretical value of $E_{DN}$ from (2) is obtained as 5.7 dB. The diurnal phase change of 375° at 19.8 kHz in terms of $\phi_{DN}$ corresponds to 7.85 $\mu$Mm$^{-1}$. The theoretical value of $\phi_{DN}$ from (3) is estimated 5.22 $\mu$Mm$^{-1}$. The theoretical values of $E_{DN}$ and $\phi_{DN}$ are about 25–30% lower than the experimental values. The phase velocities of VLF waves also depend on the mode of propagation. When multiple modes are present, the different modal phase velocities cause variations in the VLF signal along the signal path and in the value of $\phi_{DN}$. The difference in the experimental and theoretical values of the $E_{DN}$ and $\phi_{DN}$ might be mainly due to the existence of higher modes (>1) particularly in the nighttime which have not been considered in the calculations for simplicity. Bainbridge and Inan [12] using the Long Wave Propagation Capability code for a long propagation path (NAA to Cheyenne, USA) found that the lowest order quasi-TM mode dominates during the daytime, but during the nighttime there are 4 to 5 significant modes with phase velocities ranging from 0.99–1.05 c and attenuation constants ranging from 0–10 dB/Mm. Using the amplitude and phase measurements of 16 kHz signal from Rugby (UK) VLF transmitter in India having TRGCP of 6.681 Mm, Joshi and Iyer [13] estimated the values $E_{DN}$ and $\phi_{DN}$, 14.0 dB and 7.85 $\mu$Mm$^{-1}$, respectively. The value of $\phi_{DN}$ obtained here compares well with results of Joshi and Iyer [13], whereas the value of $E_{DN}$ is lower by about 50% when compared with their value of $E_{DN}$. The day-to-day variability in the times of minima is less during sunrise as compared to that during sunset (Figure 2). Therefore, sunrise minima have been used to estimate the value of $D_{MS}$ using equation (5). From Figure 1, the separation between sunrise minima is found to be 77.5 minutes which corresponds to $D_{MS}$ of 2,150 km. The theoretical value of $D_{MS}$ from equation (5) for $h = 90$ km comes out 2,140 km which matches very well with the experimental value. The values of $D_{MS}$ estimated here both theoretically and experimentally are consistent with the results of Crombie [5] and Lynn [14] for the east-west VLF propagation in the frequency range of 13–22 kHz.

4. Conclusions

Preliminary results presented in this letter on the waveguide mode analysis of VLF waves at 19.8 kHz over a long propagation path, indicate a good consistency between experimental and theoretical values of waveguide model parameters. Detailed study of these parameters during different seasons by considering more modes in the nighttime will further enhance the understanding of this subject and appropriate the waveguide parameters at 19.8 kHz for NWC-Suva path.
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References

[1] S. A. Cummer and U. S. Inan, “Ionospheric E region remote sensing with ELF radio atmospherics,” Radio Science, vol. 35, no. 6, pp. 1437–1444, 2000.
[2] J. R. Wait, Electromagnetic Waves in Stratified Media, Pergamon Press, Oxford, UK, 1962.
[3] R. Barr, D. L. Jones, and C. J. Rodger, “ELF and VLF radio waves,” Journal of Atmospheric and Solar-Terrestrial Physics, vol. 62, pp. 1689–1718, 2000.
[4] E. Yokoyama and I. Tanimura, “Some long-distance transmission phenomena of low-frequency waves,” Proceedings of Institute of Radio Engineers, vol. 21, no. 2, pp. 263–270, 1933.
[5] D. D. Crombie, “Further observations of sunrise and sunset fading of very-low-frequency signals,” Radio Science, vol. 1, pp. 47–51, 1966.
[6] M. A. Clilverd, N. R. Thomson, and C. J. Rodger, “Sunrise effects on VLF signals propagating over a long north-south path,” Radio Science, vol. 34, no. 4, pp. 939–948, 1999.
[7] T. Kikuchi, “Anomalous diurnal phase shifts of Omega VLF waves (10-14 kHz) on the east-west low latitude and trans-equatorial paths,” Journal of Atmospheric and Solar-Terrestrial Physics, vol. 45, pp. 743–751, 1983.
[8] S. Kumar, A. Kishore, and V. Ramachandran, “Higher harmonic tw skew sferics observed at low latitude: estimation of VLF reflection heights and tw skew propagation distance,” Annales Geophysicae, vol. 26, no. 6, pp. 1451–1459, 2008.
[9] D. D. Crombie, “Differences between the east-west and west-east propagation of VLF signals over long distances,” Journal of Atmospheric and Terrestrial Physics, vol. 12, no. 2-3, pp. 110–117, 1958.
[10] M. I. Devi, I. Khan, and D. N. M. Rao, “A study of VLF wave propagation characteristics in the earth-ionosphere waveguide,” Earth Planets and Space, vol. 60, no. 7, pp. 737–741, 2008.
[11] A. D. Watt, VLF Radio Engineering, Pergamon Press, Oxford, UK, 1967.
[12] G. Bainbridge and U. S. Inan, “Ionospheric D region electron density profiles derived from the measured interference pattern of VLF waveguide modes,” Radio Science, vol. 38, no. 4, pp. 161–1621, 2003.
[13] H. P. Joshi and K. N. Iyer, “Waveguide model analysis of VLF wave propagation at 16 kHz,” Journal of Atmospheric and Solar-Terrestrial Physics, vol. 50, no. 6, pp. 507–509, 1988.
[14] K. J. W. Lynn, “Frequency dependence of VLF modal interference effects observed on east-west propagation paths,” Journal of Atmospheric and Terrestrial Physics, vol. 33, no. 6, pp. 951–958, 1971.
