

Received February 22, 2021, accepted March 28, 2021, date of publication April 9, 2021, date of current version April 19, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3072133

Earth-Ionosphere Waveguide Model Parameters Using VLF Transmissions Received in the South Pacific Region

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This work was supported by The University of the South Pacific (USP) Research Committee under Grant 6C464-135 and Grant F7304-RI001-ACC-001. The work of Sushil Kumar was supported by the Strategic Research Theme of USP under Grant F7304-RI001-ACC-001.

ABSTRACT Very Low Frequency (VLF) signals form a novel tool to study the earth-ionosphere waveguide mode parameters. The waveguide model analysis of four VLF transmitter signals: 1) NWC, Australia (19.8 kHz), 2) NPM, Hawaii (21.4 kHz), 3) JJI, Elbino, Japan (22.2 kHz) and 4) NLK, Seattle, USA (24.8 kHz) propagating over long propagation paths to Suva, Fiji, has been carried out using the VLF amplitude and phase data recorded during 2014. The Transmitter Receiver Great Circle Path distances to the receiving station are 6.69 Mm for NWC, 5.07 Mm for NPM, 7.50 Mm for JJI and 9.43 Mm for NLK transmitter signal. Our results show good consistency between experimental and theoretical values of waveguide mode parameters for the west-east (W-E) (NWC/JJI-Suva) and east-west (E-W) (NLK/NPM-Suva) component of the VLF propagation paths. The waveguide mode parameters estimated in our work were found to be higher for the E-W component of the VLF propagation path compared to the W-E component path. We have also employed Long Wave Propagation Capability (V2.1) code to estimate the daytime and nighttime signal strength and daytime to nighttime signal strength ratio (E_{DN}) for all four VLF transmitter signals and found that the nighttime signal strength is generally higher compared to the daytime.

INDEX TERMS Attenuation rate, diurnal phase shift, D -region ionosphere, earth-ionosphere waveguide, modal interference distance, the ratio of nighttime to daytime signal strength, Very Low Frequency transmitters, waveguide mode parameters.

I. INTRODUCTION

The propagation of Very Low Frequency (VLF, 3-30 kHz) signals over a long distance in the waveguide bounded by Earth's surface and the D -region of the lower ionosphere is conveniently described by the means of a waveguide model. The waveguide thus formed is known as the Earth-Ionosphere Waveguide (EIWG). The D -region of the ionosphere because of its altitude range (daytime: ~60–75 km; nighttime 75–95 km) is too low for satellite measurements and too high to be reached by balloons, so remains the least studied region of the ionosphere [1], [2]. High Frequency (HF) radio sounding is also not possible, especially during the night, since electron densities in the D -region of the ionosphere are low to reflect HF radio waves radiated from incoherent

radars and ionosondes [1]. Collisions between charged and neutral particles are dominant in the D -region of the ionosphere. These physical interactions play a significant role in the propagation of VLF waves through the EIWG [2]. The VLF wave propagation in the EIWG is also very sensitive to the D -region conditions along the Transmitter and Receiver Great Circle Path (TRGCP) as a result the amplitude and phase of the VLF wave can change, and these changes may be observed in the VLF signal at the receiver. At VLF, both the upper boundary (D -region of the ionosphere) and the lower boundary (Earth's surface) of the EIWG act as good electrical conductors having sufficient conductivities to reflect these waves when incident upon these boundaries. The guided VLF propagation from navigational transmitters undergoes a low attenuation rate (a few dB per 1000 km), has high phase and frequency stability, a high signal-to-noise ratio, and could be received at large distances from the transmitter.

The associate editor coordinating the review of this manuscript and approving it for publication was Zhengqing Yun¹.

Therefore, VLF radio propagation forms a novel tool to study EIWG mode parameters and ionospheric dynamics [3]–[6]. By studying the ionospheric characteristic using this VLF radio wave technique, Friedrich and Rapp [7] reported that the nighttime D -region parameters vary with solar flux, zenith angle, season, and latitude.

The waveguide mode theory of VLF propagation was first developed in modern form by Budden [8] and subsequently by Wait [3], Galejs [5] and by Pappert [9]. Yokoyama and Tanimura [10] first reported the diurnal field-strength variation of the amplitude of VLF (17.7 and 22.9 kHz) wave propagated over long distances (>5 Mm). Diurnal field-strength variation of VLF signals shows amplitude minima associated with pronounced phase steps during sunrise and sunset transition hours between TRGCP [10]–[12] which could not be supported by single-mode VLF propagation theory. Budden [8] and Wait [3] recommended that multiple modes need to be considered to explain VLF propagation in the EIWG over long distances. Crombie [11] suggested a model based on two waveguide modes being present in the nighttime and only one mode in the daytime portion of the VLF propagation path with significant mode conversion during sunrise and sunset transition hours.

Clilverd *et al.* [12] carried out an extensive long-term study (1990–95) of the occurrence times of amplitude minima observed from NAA transmitter signal (24 kHz) over a long (12 Mm) north-south (N-S) VLF propagation path from Cutler, USA, to Faraday, Antarctica. These authors found that the occurrence time of amplitude minima was consistent with mode conversion taking place at the day/night boundary as the sunrise terminator crosses the VLF propagation path at specific, consistent locations. Lynn [13] first reported an equatorial anomaly occurring in the sunrise transition amplitude and phase pattern of NLK transmitter signal received at Smithfield, South Australia. Joshi and Iyer [14] deduced the waveguide mode parameters of the EIWG by examining the amplitude and phase measurements of 16 kHz VLF transmitter signal transmitted from Rugby, England to Rajkot, India. The authors reported that the sunrise fading generally depends on the angle between the TRGCP and the sunrise terminator, which varies seasonally. Kumar [15] determined the waveguide mode parameters from the observation of amplitude and phase of NWC transmitter signal (19.8 kHz) received at Suva, Fiji during December 2006 and reported that their experimental values of the waveguide parameters were consistent with the theoretical values estimated using the mode theory of VLF wave propagation in the EIWG. The author also recommended that a comprehensive study of waveguide parameters during different seasons by considering more modes in the nighttime will further improve the concept of waveguide mode theory.

Waveguide mode parameters are useful in understanding its dependence on frequency, reflection height, ionospheric gradient, and ground conductivity [4]. Therefore, the purpose of this paper is to study the seasonal variation of the EIWG mode parameters from the observations of the amplitude

and phase measurement of four VLF transmitter signals (NWC, NPM, JJI, and NLK) during different seasons for the year 2014 received at Suva, Fiji. The waveguide mode parameters that have been determined both theoretically and experimentally are, the ratio of nighttime to daytime signal strength (E_{DN}), diurnal phase shift Φ_{DN} , and modal interference distance (D_{MS}). The waveguide mode parameters for the west-east (W-E) and east-west (E-W) components of the VLF propagation path have also been compared. In addition, the simulated daytime and nighttime signal strength, and E_{DN} obtained from LWPC (Long Wave Propagating Capability) modeling are also compared with the theoretical and practical values.

II. THEORETICAL CONSIDERATIONS

In the EIWG, a number of modes are excited when VLF waves are transmitted from a vertical antenna. The electric field component of the VLF wave propagating in the waveguide can be characterized by a superposition of discrete waveguide modes [3], [6] expressed as:

$$E = \frac{E_0}{h} \sum_{m=1}^{\infty} |A_m| \exp(-\alpha_m d) * \exp \left[i\omega \left(t - \frac{d}{v_m} \right) + i \arg A_m \right] \quad (1)$$

where E_0 is a constant, ω is the frequency of operation, h is the height of EIWG, A_m is the excitation factor, α_m is the attenuation rate, d is the distance between TRGCP, t is the time, v_m is the phase velocity, m is the number of modes and arg is the argument.

The attenuation rate in the lower ionosphere is higher during the daytime compared to the nighttime and the higher-order waveguide modes have a larger attenuation rate and are less efficiently radiated. The waveguide mode parameters can be determined considering only one mode in the daytime and two modes at nighttime. At large distances from transmitter greater than 5 Mm, only mode 1 with the lowest attenuation rate is predominant.

The diurnal change of the signal amplitude (E_{DN}) is the ratio of daytime to nighttime signal strengths due to first-order mode. Using the equation of modal superposition of discrete waveguide modes (1) [3], [6] the value of E_{DN} in terms of dB can be stated as:

$$E_{DN} (dB) = \frac{h_D}{h_N} [(|A_{N1} (dB)| - |A_{D1} (dB)|) - (\alpha_{D1} - \alpha_{N1}) d] \quad (2)$$

where D and N refer to day and night, respectively, and $A_N (dB)$ is the antenna excitation factor in dB given by $A_N (dB) = 20 \text{Log}_{10} (A_N)$.

The diurnal phase shift, Φ_{DN} (μs), of the VLF wave normalized over 1 Mm is given as [6]:

$$\Phi_{DN} = \frac{10^4}{3} \left(\frac{c}{v_{N1}} - \frac{c}{v_{D1}} \right) \times d \quad (3)$$

where v is the phase velocity of VLF wave, c is the speed of light in vacuum and d is TRGCP distance in Mm.

The phase velocity of VLF waves considering only one mode in the EIWG of height h can be expressed as [16]:

$$v = c \left[1 - \left(\frac{\lambda_0}{4h} \right)^2 \right]^{-\frac{1}{2}} * \left(1 - \frac{h}{2R_E} \right) \quad (4)$$

where c is the velocity of light in free space, λ_0 free-space wavelength and R_E is the radius of the Earth.

The distance traveled by the terminator sunrise/sunset line between two successive amplitude minima is called the modal interference distance (D_{MS}) [17]. The D_{MS} can be expressed assuming the interference of only two VLF night modes as [11]:

$$D_{MS} = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1} \quad (5)$$

where λ_1 and λ_2 are the waveguide wavelengths of nighttime modes 1 and 2, respectively.

Equation (5) can be simplified to as given by [11]:

$$D_{MS} = \frac{4h_N^2}{\lambda_0} \quad (6)$$

where h_N is the nighttime D -region VLF reflection height.

The D_{MS} can also be calculated by considering the relationship between the terminator speed (V_T) and the time difference (Δt) between two successive terminator times (TTs) or amplitude minima:

$$D_{MS} = V_T * \Delta t \quad (7)$$

The V_T terminator velocity at the midpoint location of the propagation path can be calculated using the well-known relationship:

$$V_T = \frac{2\pi R_E \cos [Latitude]}{24 \text{ hrs}} \quad (8)$$

III. DATA AND ANALYSIS

The experimental set-up comprises a short (1.5 m) whip antenna, a GPS antenna and a service unit (SU) attached with a pre-amplifier installed under the World-Wide Lightning Location Network [18]. The narrowband VLF data are recorded using a Software-based phase and amplitude logger (SoftPAL) which can log phases in degrees and amplitudes in dB above 1μ V/m of up to seven MSK (minimum shift key) VLF transmitters. The whip antenna is sensitive to the vertical electric field component of the incoming electromagnetic wave. The pre-amplifier is designed to provide a good flat frequency response specifically in the frequency range of 10-25 kHz. The signals from four VLF transmitters (NWC, NPM, NLK and JJI) were recorded at a time resolution of 0.1 s (sampling frequency of 10 Hz). A month of data selected from each season of the year 2014 have been analyzed to study the seasonal variation of waveguide mode parameters at 19.8, 21.4, 22.2, and 24.8 kHz signals; NWC, NPM, JJI, and NLK VLF transmitters. A map showing the positions of NWC, NPM, JJI, and NLK VLF transmitters and their TRGCPs to Suva, Fiji, is shown in Fig. 1.

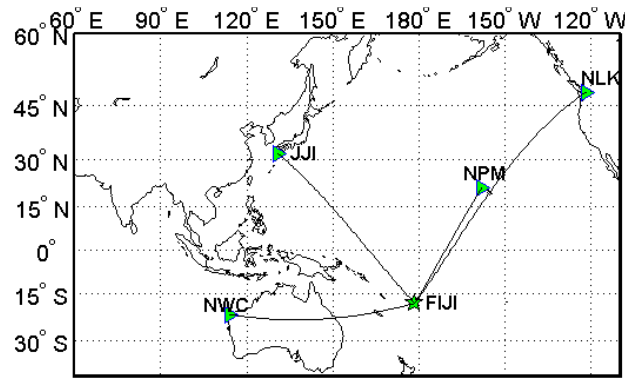


FIGURE 1. Map showing the positions of NWC, NPM, JJI and NLK transmitters and their TRGCPs to receiving station Suva, Fiji.

TABLE 1. The value of first-order mode differential excitation factor and differential attenuation along with the terminator speed for NWC, NPM, JJI and NLK VLF propagation paths.

Parameters	NWC	NPM	JJI	NLK
Differential excitation factor (dB)	13.5	14.5	16	18
Differential attenuation rate (dB/Mm)	1.0	0.9	0.8	1.2
Terminator Speed (km/min ¹)	25.66	-	27.68	26.68

The theoretical values of E_{DN} and Φ_{DN} were calculated using (2) and (3), respectively, using the appropriate values of c/v , A_1 , α_1 and λ_1 given by Galejs [5]. The value of first-order mode differential excitation factor ($|A_{N1}| - |A_{D1}|$) at 19.8, 21.4, 22.2 and 24.8 kHz were estimated to be 13.5 dB, 14.5 dB, 16 dB and 18 dB, respectively [19] which is presented in Table 1. At 19.8 kHz, 21.4 kHz, 22.2 kHz and 24.8 kHz, the value of first-order mode differential attenuation rate ($\alpha_{D1} - \alpha_{N1}$) were estimated as 1.0 dB/Mm, 0.9 dB/Mm, 0.8 dB/Mm and 1.2 dB/Mm, respectively [19]. For further details about these constants and different studies, a reader is referred to chapter 3 of the book: VLF Radio Engineering (pg.304-309, 325-327 and Fig. 3.5.2, 3.5.6, 3.5.19 and 3.5.20). The value of the nighttime (h_N) and daytime EIWG height (h_D) were taken as 90 km and 75 km, respectively, which is a reasonable approximation [15]. The terminator speed, V_T , calculated using (8) for NWC, JJI, and NLK to Suva VLF propagation paths is $25.66 \text{ km min}^{-1}$ (427.67 ms^{-1}), $27.68 \text{ km min}^{-1}$ (461.33 ms^{-1}) and $26.68 \text{ km min}^{-1}$ (444.67 ms^{-1}), respectively.

In this work, we have also employed LWPC code version 2.1 to determine the daytime (at 23 UT) and nighttime (at 11 UT) signal strength versus distance from the transmitter to the receiver for NWC-Suva, NPM-Suva, JJI-Suva and NLK-Suva VLF propagation path. The LWPC code is a widely recognized two-dimensional model used to study VLF signal propagation characteristics within the EIWG using the waveguide mode theory. This code was developed by the Space and Naval Warfare System Center (San Diego, USA) [20] which employs an exponentially increasing conductivity with the height model of the D -region. LWPC code

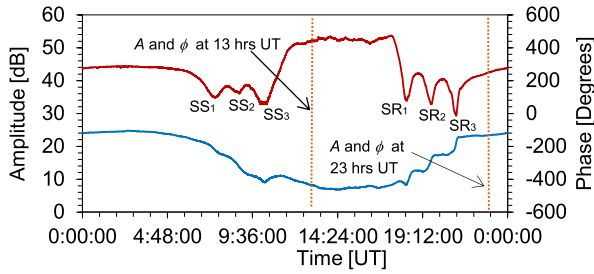


FIGURE 2. A typical diurnal variation of amplitude (red) and phase (blue) of NWC signal received at Suva on 25 January 2014. UT represent universal time.

also computes modal conversion along the VLF propagation path continually to account for different ground conductivity, permittivity and geomagnetic field values at different points along the VLF propagation path between transmitter and receiver. LWPC generates a range of amplitudes and phases for the daytime and nighttime as text files for various TRGCP segments. The simulated daytime and nighttime signal strength obtained from LWPC modeling was also used to estimate E_{DN} for comparison between the theoretical and experimental value of E_{DN} . We have not calculated diurnal phase shift (Φ_{DN}) using LWPC modeling because LWPC code used here produces highly elevated values of phase at the nighttime in all cases, which gives the unrealistic value of Φ_{DN} .

IV. RESULTS

A. WAVEGUIDE MODE PARAMETERS: E_{DN} , Φ_{DN} , AND D_{MS}
 1) NWC – SUVA (19.8 kHz)

The NWC VLF transmitter operating at 19.8 kHz has a relatively high radiated power of 1000 kW and is located in the southern hemisphere with a geographic location (21.816°S, 114.166°E). NWC signal propagates mostly in the West-East (W-E) direction to low-latitude receiving station Suva (18.149°S, 178.446°E) with a TRGCP of 6.696 Mm. A typical diurnal variation of the amplitude and phase of the NWC transmitter signal received at Suva on 25 January 2014, as recorded by SoftPAL, is presented in Fig. 2. NWC transmitter signal received at Suva shows three amplitude minima during both sunrise and sunset transitions hours labeled as SR₁, SR₂, SR₃ and SS₁, SS₂, SS₃ (Fig. 2), respectively along the TRGCP. At sunset, the depth of the first minima (SS₁) is larger than the depth of the second minima (SS₂) and the depth of the third minima (SS₃) is larger than both SS₂ and SS₁. The sunrise transition minima are deeper and more pronounced when compared to the sunset transition minima. The NWC amplitude signals are much higher during nighttime compared to the daytime which could be mostly because the position of receiving station Suva may be around a modal maximum in the nighttime and around a modal minimum in the daytime.

For the NWC (19.8 kHz) transmission, the theoretical value of $E_{DN} = 5.67$ dB, $\Phi_{DN} = 35.35 \mu s$ and $D_{MS} = 2140$ km were calculated using (2), (3) and (7), respectively, for

TABLE 2. Experimental value of waveguide parameters of NWC signal observed at Suva for a period of almost one month during summer (January), winter (August) and equinox (October) month in 2014, against the theoretical value of $E_{DN} = 5.67$ dB, $\Phi_{DN} = 35.35 \mu s$ and $D_{MS} = 2140$ km, for $h_N = 75$ km and $h_D = 90$ km.

Seasons	E_{DN} (dB)		Φ_{DN} (μs)		D_{MS} (km)	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Summer	8.09	1.82	45.68	10.76	2119	73
Winter	9.00	2.08	34.77	16.63	2006	131
Equinox	6.62	2.00	37.75	12.56	2013	68

$h_N = 75$ km and $h_D = 90$ km. Using the data from Fig. 2, the experimental values of waveguide parameters E_{DN} , Φ_{DN} , and D_{MS} for the NWC transmitter were estimated to be 7.5 dB, 44.05 μs and 2027 km, respectively, for 25 January 2014. The theoretical values of E_{DN} and Φ_{DN} are about 20-25% [(7.5 – 5.67)/7.5] \times 100 = 24.4%, (44.05 – 35.35)/44.05 \times 100 = 19.7%] lower than the experimental values whereas the theoretical value of D_{MS} is about 6% [(2140 – 2027)/2027] \times 100 = 5.57%] higher than the experimental value estimated from Fig. 2. The experimental value of E_{DN} in dB and Φ_{DN} in degrees were calculated from nighttime data at 13:00 UT (01:00 Local Time) and daytime data at 23:00 UT (11:00 Local Time) amplitude and phase difference as shown in Fig. 2. The experimental value of D_{MS} was calculated using method (7) which utilizes the relationship between the terminator speed (V_T) and the time difference (Δt) between two successive amplitude minima. The sunrise minima have been considered to determine the D_{MS} since the day-to-day variability in the occurrence times of amplitude minima is less during sunrise compared to sunset transition hours. Similarly, a month of data from different seasons for the year 2014 were analyzed to estimate practical waveguide mode parameters, and the statistical results are summarized in Table 2. The theoretical value of E_{DN} is about 1 dB (6.62 – 5.67 = 0.95 dB) lower than the experimental mean value for the NWC-Suva VLF propagation path during equinox month. The mean experimental value of Φ_{DN} calculated during a winter month is about 1.6% [(35.35 – 34.77)/35.35] \times 100 = 1.64%] lower than the theoretical value. The theoretical value of D_{MS} is about 1% [(2140 – 2119)/2119] \times 100 = 0.99%] higher than the experimental mean value calculated during the summer month. The observational results presented in Table 2 for NWC-Suva VLF propagation path show that the mean experimental value of E_{DN} is higher during winter and lower during summer month. On the other hand, the mean experimental values of Φ_{DN} and D_{MS} are both higher during the summer month and are lower during the winter month. The E_{DN} , Φ_{DN} and D_{MS} values show a lot of variation during the equinox, winter, and summer seasons which suggests that the waveguide mode parameters are dependent on seasons.

2) NPM – SUVA (21.4 kHz)

The NPM transmitter is located in Lualualei (20.4°N, 158.2°W), Hawaii. The NPM signal propagates across the

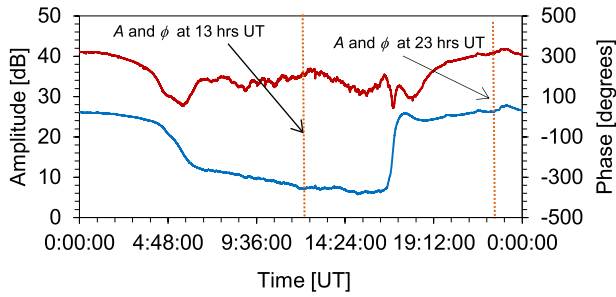


FIGURE 3. A typical diurnal variation of amplitude (red) and phase (blue) of NPM signal on 23 December 2014.

geomagnetic equator over the sea mostly in the N-S direction and comparatively less in the E-W direction. It has a TRGCP length of about 5.07 Mm and radiates 600 kW power. A typical diurnal variation of the amplitude and phase of the NPM transmitter signal received at Suva on 23 December 2014 is presented in Fig. 3. The NPM signal minima shown in Fig. 3 are not as distinct as on the NWC signal and do not show sunrise and sunset transitions very clearly due to the high variability of the signal during sunrise and sunset transition hours. Only two amplitude minima during the sunrise transition and one amplitude minimum during sunset transition can be identified, however, they are not visible as a result we have not estimated D_{MS} for this VLF propagation path. The amplitude and phase signal strength for NPM-Suva path is much lower during nighttime when compared to the daytime as can be observed from Fig. 3. This could be mostly due to the fact that the position of Suva may be around a modal minimum in the nighttime and around a modal maximum in the daytime. The respective change of phase is steeper during sunrise minima than sunset minima and occurs at the same time as the amplitude minimum. The rapid phase change occurs in the direction of decreasing phase delay during sunrise and of increasing phase delay during sunset. The theoretical values of E_{DN} and Φ_{DN} using (2) and (3), respectively, for NPM transmitter signal, are obtained as 8.28 dB and 25.81 μs , respectively. Using the data from Fig. 3, the experimental values of waveguide mode parameters for NPM transmitter signal were estimated on 23 December 2014 using a similar analysis as described above for NWC transmitter signal. The experimental values of E_{DN} and Φ_{DN} estimated from Fig. 3 were found to be $E_{DN} = 6.43$ dB and $\Phi_{DN} = 39.92$ μs , respectively. The theoretical value of E_{DN} is about 29% $[(8.28 - 6.43)/6.43] \times 100 = 28.7\%$ higher and Φ_{DN} about 35% $[(39.92 - 25.81)/39.92] \times 100 = 35.3\%$ lower than the experimental values obtained from Fig. 3, respectively. Similarly, the waveguide mode parameters were estimated for a month of data from different seasons and the statistical results have been summarized in Table 3. The theoretical value of E_{DN} is about 0.1 dB $(8.28 - 8.20 = 0.08$ dB) higher than the observed mean value of E_{DN} during equinox month whereas the theoretical value of Φ_{DN} is about 31% $[(37.43 - 25.81)/37.43] \times 100 = 31.04\%$ lower than the mean experimental value during the summer month. An interesting observation made from Table 3 for NPM-Suva

TABLE 3. Experimental value of waveguide parameters of NPM signal observed at Suva for a period of one month during summer (December), winter (August) and equinox (October) month in 2014, against the theoretical value of $E_{DN} = 8.28$ dB and $\Phi_{DN} = 25.81$ μs , for $h_N = 75$ km and $h_D = 90$ km.

Seasons	E_{DN} (dB)		Φ_{DN} (μs)	
	Mean	Standard Deviation	Mean	Standard Deviation
Summer	7.39	1.98	37.43	3.70
Winter	9.03	2.06	42.11	5.01
Equinox	8.20	1.97	39.88	6.89

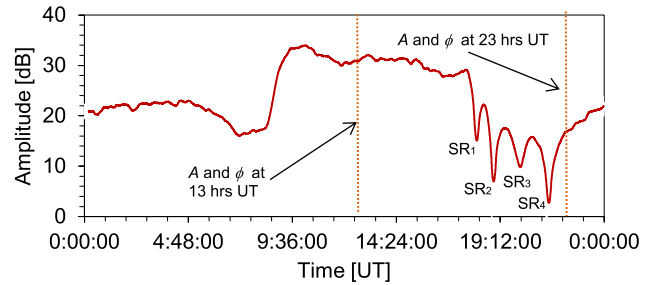


FIGURE 4. A typical diurnal amplitude variation of JJI signal received at Suva on 25 January 2014.

VLF propagation path is that the mean experimental value of E_{DN} and Φ_{DN} are both higher during a winter month and lower during a summer month. It can also be noted from the standard deviation values for E_{DN} and Φ_{DN} that they have large variability during the equinox as compared to summer and winter seasons.

3) JJI – SUVA (22.2 kHz)

The signal from JJI transmitter which is located in Ebino (32.092°N, 130.829°E), Japan, propagates in northwest-southeast direction to Fiji. JJI transmitter radiates a relatively low power of 100 kW and follows a trans-equatorial path over the sea with a TRGCP length of 7.50 Mm. A typical diurnal amplitude variation of JJI signal received at Suva on 25 January 2014 is presented in Fig. 4. JJI is a phase unstable transmitter as compared to NWC and NPM transmitter, thus the diurnal phase variation is not plotted and Φ_{DN} is also not estimated for this VLF propagation path. The amplitude shows a very clear and distinctive diurnal variation as shown in Fig. 4. The amplitude variation shows only four minima during sunrise labeled as SR₁, SR₂, SR₃ and SR₄. The sunset minimum are not clearly visible due to the high variability of the JJI signal during sunset transition hours.

The theoretical values of E_{DN} and D_{MS} calculated from (2) and (7) for JJI transmitter signal are 8.33 dB and 2398 km, respectively. From Fig. 4, the experimental values of waveguide mode parameters for JJI transmitter signal were estimated on 25 January 2014 using the same method as described above for NWC transmitter signal. The experimental values of E_{DN} and D_{MS} for 25 January 2014 were found $E_{DN} = 9.55$ dB and $D_{MS} = 1839$ km which are about 15% $[(9.55 - 8.33)/8.33] \times 100 = 14.6\%$ higher and about 23% $[(2398 - 1839)/2398] \times 100 = 23.3\%$

TABLE 4. Experimental value of waveguide parameters of JJI signal observed at Suva for a period of one month during summer (January), winter (August) and equinox (October) month in 2014, against the theoretical value of $E_{DN} = 8.33$ dB, and $D_{MS} = 2398$ km, for $h_N = 75$ km and $h_D = 90$ km.

Seasons	E_{DN} (dB)		D_{MS} (km)	
	Mean	Standard Deviation	Mean	Standard Deviation
Summer	11.68	3.34	1879	91
Winter	7.50	3.14	859	100
Equinox	9.43	4.80	1564	97

TABLE 5. Experimental value of waveguide parameters of NLK signal observed at Suva for a period one month during summer (January), winter (August) and equinox (October) month in 2014, against the theoretical value of $E_{DN} = 5.57$ dB, and $D_{MS} = 2678$ km, for $h_N = 75$ km and $h_D = 90$ km.

Seasons	E_{DN} (dB)		D_{MS} (km)	
	Mean	Standard Deviation	Mean	Standard Deviation
Summer	4.43	2.00	2849	287
Winter	3.50	2.77	1914	349
Equinox	4.16	2.54	2277	269

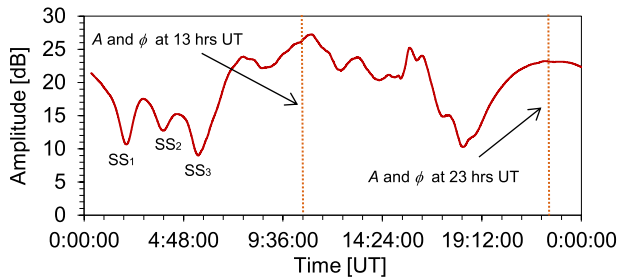


FIGURE 5. A typical diurnal amplitude variation of NLK signal received at Suva on 25 January 2014.

lower than the theoretical value, respectively. Similarly, a month of data each from three different seasons were analyzed to study the seasonal variation of the EIWG mode parameters and statistical results are summarized in Table 4. The theoretical value of E_{DN} is about 1.0 dB ($9.43 - 8.33 = 1.1$ dB) lower than the experimental mean value during equinox whereas the theoretical value of D_{MS} is about 28% [$(2398 - 1879)/1879 \times 100 = 27.62\%$] lower than the mean experimental value during the summer month. The observational results given in Table 4 for the JJI-Suva VLF propagation path show that the mean experimental values of E_{DN} and D_{MS} are both higher during summer and lower during the winter month. The E_{DN} , Φ_{DN} and D_{MS} values show a large variation during the equinox, winter, and summer months.

4) NLK-SUVA (24.8 kHz)

The NLK transmitter is located in Jim Creek (48.203°N, 121.917°W), Washington, USA. The NLK signal propagates from its mid-latitude location in the northern hemisphere to the low-latitude station, Suva, in the southern hemisphere having a northeast-southwest direction of the VLF propagation. NLK transmitter radiates a relatively low power of 192 kW and follows a trans-equatorial path over the sea with a TRGCP length of 9.43 Mm. A typical diurnal amplitude variation of the NLK signal received at Suva on 25 January 2014 is shown in Fig. 5.

During sunset transition hours, three amplitude minima labeled as SS_1 , SS_2 and SS_3 are visible but during the sunrise, none of the minima are clearly visible due to the high variability of the signal during sunrise transition hours. Like JJI transmitter, NLK transmitter is also a phase unstable, thus the diurnal phase variation is not plotted and Φ_{DN} is also not estimated for this VLF propagation path.

For the NLK (24.8 kHz) transmission, the theoretical value of $E_{DN} = 5.57$ dB and $D_{MS} = 2678$ km were calculated using (2) and (7), respectively, for $h_N = 75$ km and $h_D = 90$ km. From Fig. 5, the experimental value of $E_{DN} = 4.61$ dB and $D_{MS} = 2540$ km for NLK transmitter signal were estimated on 25 January 2014 using the same procedure as described above for NWC transmitter signal. The experimental value of E_{DN} and D_{MS} estimated from Fig. 5 are about 17% [$(5.57 - 4.61)/5.57 \times 100 = 17.2\%$] and 5% [$(2678 - 2540)/2678 \times 100 = 5.2\%$] lower than the theoretical value, respectively. Similarly, the waveguide parameters were estimated for a month of summer, winter and equinox and the statistical results are summarized in Table 5.

The theoretical value of E_{DN} is about 1.4 dB ($5.57 - 4.16 = 1.41$) higher than the experimental mean value during equinox month whereas the theoretical value of D_{MS} is about 6% [$(2849 - 2678)/2678 \times 100 = 6.00\%$] lower than the mean experimental value estimated during the summer month. The observational results from Table 5 for the NLK-Suva VLF propagation path show that the mean experimental values of E_{DN} and D_{MS} are both higher during the summer month and are lower during the winter month. The E_{DN} and D_{MS} values have a lot of variation during a winter month compared to an equinox and a summer month which suggests that the waveguide mode parameters are seasonally dependent.

B. VARIATION OF WAVEGUIDE PARAMETERS FOR W-E AND E-W VLF PROPAGATION PATH

The waveguide mode parameters (E_{DN} , Φ_{DN} and D_{MS}) were determined from the amplitude and phase measurements of NWC, NPM, JJI and NLK transmitter signals received at low latitude station, Suva, Fiji. The NWC-Suva and JJI-Suva VLF propagation paths have a significant component of VLF propagation in the W-E direction and NLK-Suva VLF propagation path in the E-W direction. NPM-Suva VLF propagation path is mostly in the N-S direction and comparatively less in the E-W direction. Table 6 summarizes the mean experimental values of waveguide mode parameters for NWC, NPM, JJI, and NLK VLF propagation paths to Suva during different seasons of the year 2014. From the results presented in Table 6, an interesting pattern observed is that the waveguide mode parameters for the NWC-Suva (Φ_{DN} and D_{MS}), NLK-Suva (E_{DN} and D_{MS}) and JJI-Suva (E_{DN} and D_{MS}) VLF propagation path are all maximum during summer and minimum

TABLE 6. The mean experimental and theoretical values of waveguide mode parameters for NWC, NPM, JJI and NLK VLF propagation paths to Suva during different seasons in 2014 are summarized.

Season	NWC			NPM		JJI		NLK	
	E_{DN} (dB)	Φ_{DN} (μ s)	D_{MS} (km)	E_{DN} (dB)	Φ_{DN} (μ s)	E_{DN} (dB)	D_{MS} (km)	E_{DN} (dB)	D_{MS} (km)
Summer	8.09	45.68	2119	7.39	37.43	11.68	1879	4.43	2849
Winter	9.00	34.77	2006	9.03	42.11	7.50	859	3.50	1914
Equinox	6.62	37.37	2013	8.20	39.88	9.43	1564	4.16	2277
Mean Value	7.90	39.27	2046	8.21	39.81	9.54	1434	4.03	2347
Theoretical Value	5.67	35.35	2140	8.28	25.81	8.33	2398	5.57	2679

during the winter month. However, a converse relationship is observed for the NPM-Suva VLF propagation path where waveguide mode parameters especially E_{DN} and Φ_{DN} attain maximum values during winter and minimum during the summer month.

We have also calculated the daytime and nighttime signal strength and E_{DN} using LWPC code version 2.0 for NWC-Suva, NPM-Suva, JJI-Suva and NLK-Suva VLF propagation paths. The LWPC code was run at 23 UT (11 LT) and 13 UT (01 LT) to determine the simulated daytime and nighttime signal strength, respectively, after feeding in the required information such as the bearing angle of the transmitter to receiver, TRGCP length, the receiver location, daytime and nighttime time, and the date. Fig. 6 shows the LWPC modeled output for signal strength versus distance for NWC, NPM, JJI, and NLK transmitter signals during daytime and nighttime conditions. The red and blue lines in this figure show the daytime and nighttime simulated signal strength, respectively. The vertical lines in the panels represent the position of the receiver away from the transmitter. The LWPC model plots (Fig. 6) show that at any fixed location between transmitter and receiver path, the nighttime signal strength is generally higher compared to the daytime signal strength for all four VLF transmitter signals received at Suva. The difference in the values of simulated signal strength at the receiving station, Suva, (orange line) for nighttime at 13 UT and daytime at 23 UT as observed in Fig. 6 along with the theoretical values and mean experimental value of E_{DN} for all four transmitter signals are given in Table 6. The daytime signal strengths at 23 UT (NWC = 57 dB, NPM = 57 dB, JJI = 45 dB and NLK = 35 dB) are less when compared to the nighttime signal strengths at 13 UT (NWC = 62 dB, NPM = 59 dB, JJI = 56 dB and NLK = 37 dB) for all four VLF transmitter signals which are clearly evident in Table 7. Table 7 also indicates that the LWPC generated signal strength during daytime and nighttime for the W-E VLF propagation path (NWC-Suva) are stronger compared to LWPC modeled signal strength for the E-W component of VLF propagation path (NLK-Suva). LWPC modeling showed the existence of seven daytime modes for NWC, NPM, JJI and NLK to Suva VLF propagation whereas for nighttime VLF propagation path, it showed the existence of 18 modes for these transmitter paths to Suva except for NWC-Suva path which showed the existence of 11 modes. The E_{DN}

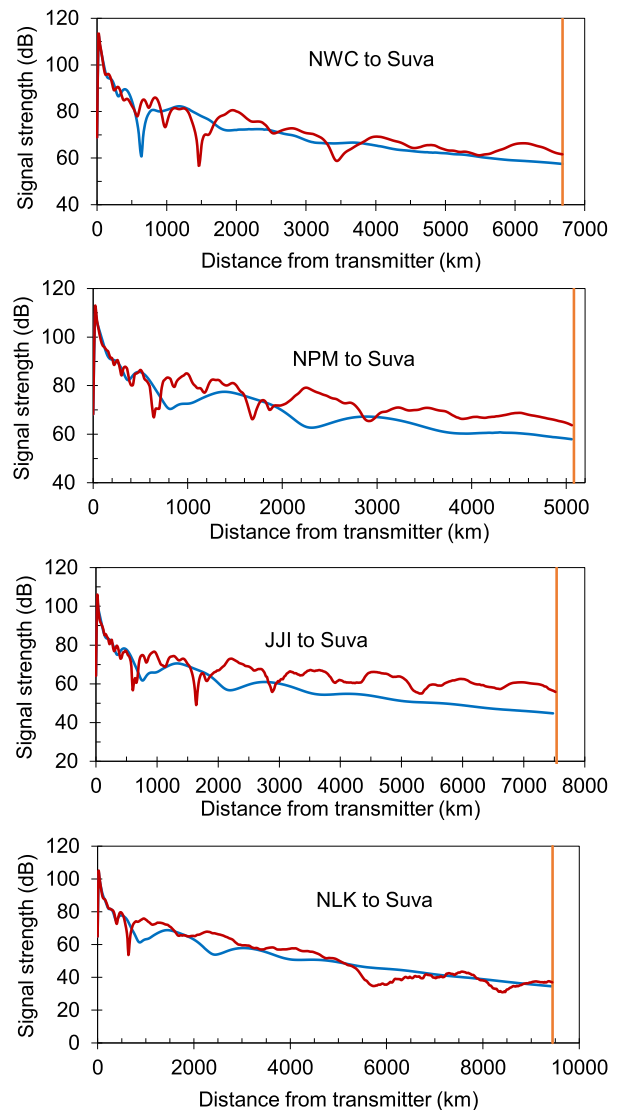


FIGURE 6. LWPC output for signal strength versus distance from the transmitter to the receiver for NWC, NPM, NLK and JJI signals during daytime (blue line) and nighttime (red line) on 25th January, 2014. The vertical orange lines in the panel indicate the position of the receiver away from the transmitter.

calculated using LWPC modeling for NWC-Suva, NLK-Suva and NPM-Suva VLF propagation path is about 1-6 dB (5.67 – 4.14 = 1.53, 5.57 – 2.44 = 3.13 and 8.28 – 2.17 = 6.11) lower than the theoretical value of E_{DN} estimated using (2). For the JJI-Suva VLF propagation path, the E_{DN} estimated using LWPC (daytime and nighttime signal strength are about 2.9 dB 11.18 – 8.33 = 2.85) is higher compared to the theoretical value of E_{DN} . A similar relationship is also observed between simulated E_{DN} (obtained using LWPC modeling) and mean experimental values of E_{DN} . The simulated E_{DN} for NWC, NPM and NLK transmitter signal are about 3-6 dB (7.9 – 4.14 = 3.8, 8.21 – 2.17 = 6.0, 4.03 – 2.44 = 1.6) lower than the mean experimental value of E_{DN} estimated using daytime and nighttime signal strength observed from SoftPAL

TABLE 7. The daytime and nighttime amplitude, and diurnal change of the signal amplitude (E_{DN}) obtained from LWPC modeling for 25 January 2014 along with the theoretical values and mean experimental value of E_{DN} for NWC, NPM, JJI and NLK VLF propagation paths to Suva are presented.

TRGCP Path	Daytime Amplitude in dB (23 UT)	Nighttime Amplitude in dB (13 UT)	E_{DN} in dB (LWPC)	Theoretical value of E_{DN} in dB	Mean Experimental Value of E_{DN} in dB
NWC-Suva	57.49	61.63	4.14	5.67	7.90
NPM - Suva	56.50	58.67	2.17	8.28	8.21
JJI - Suva	44.61	55.80	11.18	8.33	9.54
NLK - Suva	34.51	36.95	2.44	5.57	4.03

data recording. However, for JJI transmitter signal, the simulated E_{DN} is about 2 dB ($11.18 - 9.54 = 1.64$) higher than the experimental mean value of E_{DN} . We have also tried to run the LWPC code for other days in different seasons and found that the simulated daytime and nighttime signal strength remains constant throughout the year and no seasonal variation is evident. The LWPC model assumes perfectly smooth day and night ionospheric conditions and it does not take into account the effects of solar and geomagnetic activities that can perturb the ionosphere. Due to these limitations, we were unable to observe any seasonal variations from E_{DN} obtained using LWPC modeling.

V. DISCUSSION

The times of amplitude minima and day-night amplitude and phase difference due to the movement of solar terminator between transmitter and receiver have been utilized to study the seasonal variation of waveguide mode parameters. The successive minima during sunrise and sunset transitions hours are generated as a consequence of destructive interference or superposition of propagating modes at the receiver [12]. The relationship between terminator speed and the time difference between two successive amplitude minima was considered to estimate the experimental value of D_{MS} .

The observed values of E_{DN} , Φ_{DN} and D_{MS} were found to best match with the theoretical values for the nighttime EIWG height (h_N) = 90 km and the daytime EIWG height (h_D) = 75 km. The mean experimental value of E_{DN} is 4% [$(8.21 - 7.90)/7.90 \times 100 = 3.92\%$] larger for E-W component of the propagation path (NPM-Suva) than for W-E propagation path (NWC-Suva). The E_{DN} values for W-E component of the VLF propagation path (JJI -Suva) and E-W component of the VLF propagation path (NLK-Suva) are both higher during summer and lower during winter. The mean experimental value of Φ_{DN} is about 1.4% [$(39.81 - 39.27)/39.81 \times 100 = 1.36\%$] larger for E-W component of the propagation path (NPM-Suva) than for W-E propagation path (NWC-Suva). The Φ_{DN} for W-E VLF propagation path (NWC-Suva) is higher during summer and lower during winter whereas, for the E-W VLF component path (NPM-Suva), a converse relationship is shown where Φ_{DN} are larger during winter and lower during summer. The mean experimental value of D_{MS} for the E-W component of the VLF propagation path (NLK-Suva) is greater than that for

W-E VLF propagation path (NWC-Suva) by about 15% [$(2347 - 2046)/2046 \times 100 = 14.7\%$]. Like E_{DN} , the D_{MS} for W-E path (JJI-Suva) and for the E-W component of the VLF propagation path (NLK-Suva) are also larger during summer and lower during winter. The nighttime LWPC simulated signal strength for the W-E VLF propagation path (NWC-Suva) is higher compared to LWPC simulated signal strength for the E-W component of the VLF propagation path (NLK-Suva). The existence of higher modes (i.e. NLK-Suva = mode 18) during nighttime for the E-W component of the VLF propagation path compared to the existence of lower modes at the nighttime for the W-E path (NWC-Suva = mode 11) could have attributed to the weaker signal strength. The simulated signal strengths obtained from LWPC modeling for all four VLF transmitters are higher at nighttime compared to the daytime signal strength which is well reflected from our observational results illustrated in Fig.2-5. This could be because the attenuation of modes is lower at nighttime compared to the daytime. The position of Suva for all four VLF propagation path must be lying around the modal maximum in the nighttime and minimum in the daytime. Using LWPC code, Kumar and Kumar [21] modeled the nighttime (at 14 UT) and daytime (at 02 UT) signal strength at 14 UT of NWC, NPM and NLK transmitter signal and reported that their model plots depict that the nighttime signal strength for NWC-Suva VLF propagation path is more (63 dB) when compared to the daytime signal strength (55dB), which is consistent with our result. However, for the NPM and NLK transmitter signals, their simulated nighttime signal strengths (NPM = 57 dB and NLK = 26 dB) are less when compared to the daytime signal strengths (NPM = 58 dB and NLK = 30 dB) which is not reflected in our LWPC modeled result. In this work, we have modeled nighttime signal strength at 13 UT and daytime at 23 UT whereas Kumar and Kumar [21] have modeled the nighttime signal strength at 14 UT and daytime at 02 UT. Therefore, the difference in our result could have been attributed to the different times chosen to model the nighttime and daytime signal strength.

The discrepancy between experimental and theoretical values of the E_{DN} calculated for NWC-Suva, JJI-Suva, NLK-Suva VLF propagation paths and Φ_{DN} calculated for NWC-Suva and NPM-Suva VLF propagation path might be mainly due to the higher attenuation rate of EIWG for the daytime VLF propagation and the presence of higher modes (> 1) particularly at the nighttime which have not been accounted in the calculations for simplicity [15]. When multiple modes exist, the different modal phase velocities cause fluctuation in the VLF signal along the propagation path and since Φ_{DN} is related to phase velocity, different modal phase velocities may affect Φ_{DN} [15], [22]. Generally, our results indicate that the waveguide mode parameters are mostly higher for the E-W component of VLF propagation path (NLK/NPM-Suva) than for the W-E propagation path (NWC/JJI-Suva). The attenuation rate of VLF signals for the E-W propagation path is greater than that for the W-E path [4], [23], [24] which may be the reason

why our waveguide mode parameters are much higher for the E-W component of the VLF propagation path compared to the W-E propagation path. The transverse horizontal Earth's magnetic field may have also affected the E-W VLF propagation path [24]. Swanson *et al.* [25] used Omega (10.2 kHz) signal and observed that the estimated Φ_{DN} was 10% greater for E-W propagation than for W-E propagation on the Hawaii-Canal Zone path. The authors reported that this difference occurred at night, which is in agreement with our results for Φ_{DN} for E-W and W-E VLF propagation paths. Kikuchi [6] explained the diurnal amplitude and phase variation of Omega transmitter signal (13.6 kHz) for a trans-equatorial W-E VLF propagation path and have shown that the Φ_{DN} at Omega signal frequency on the E-W trans-equatorial path is 35% less than that on the W-E VLF propagation path at 13.6 kHz with which our results are not consistent. Kikuchi [6] reported that the Φ_{DN} for the W-E propagation path is $7.8 - 8.7 \mu\text{s Mm}^{-1}$ at 13 kHz on the trans-equatorial and mid-latitude paths and for the E-W propagation, it is $11.3 \mu\text{s Mm}^{-1}$. In 1986, Kikuchi [26] again reported the value of Φ_{DN} , E_{DN} and D_{MS} as $7.8 \mu\text{s Mm}^{-1}$, 7.1 dB and 1390 km, respectively, for the W-E VLF propagation path using the reference height of the ionosphere as 75.0 km (daytime) and 88.5 km (nighttime). Our experimental mean value of $E_{DN} = 7.50$ dB for JJI-Suva VLF propagation path, estimated during winter and $D_{MS} = 1564$ km, estimated during the equinox, agrees reasonably well with the results obtained by Kikuchi [26]. Joshi and Iyer [14] analyzed the amplitude and phase measurements of 16 kHz signal on the Rugby (UK) – Rajkot (India) path and estimated the values of E_{DN} and Φ_{DN} as 14.0 dB and $7.85 \mu\text{s Mm}^{-1}$ (52.44 μs), respectively. Our experimental mean value of $\Phi_{DN} = 45.68 \mu\text{s}$ obtained for NWC-Suva path during summer is about 13% [$((52.44 - 45.68)/52.44) \times 100 = 12.89\%$] lower than the value obtained by Joshi and Iyer [14], whereas our value of $E_{DN} = 9.00$ dB for NWC-Suva path estimated during winter is lower by about 36 % [$(14 - 9.00)/14 \times 100 = 35.71\%$]. Kumar [15] observed the amplitude and phase measurement of 19.8 kHz transmission from NWC transmitter received at Suva, Fiji and calculated the values of E_{DN} , Φ_{DN} and D_{MS} as 7.5 dB, $7.85 \mu\text{s Mm}^{-1}$ and 2150 km, respectively. Our experimental values of E_{DN} , Φ_{DN} and D_{MS} obtained here agree reasonably well with the results of Kumar [15].

Samanes *et al.* [17] analyzed an extensive database of almost 5 years (2007-11) from three different W-E oriented VLF propagation paths (NPM-ATI, NPM-PLO, and NPM-ICA) provided by the South America VLF Network, and determined the mean value of D_{MS} based on the measurement and analysis of the pronounced VLF amplitude minima. The authors estimated the mean value of D_{MS} for NPM-PLO, NPM-ATI and NPM-ICA VLF propagation path as 2160 ± 60 km, 2190 ± 60 km, and 2170 ± 50 km, respectively. Their values of D_{MS} agree reasonably well with our $D_{MS} = 2119$ km estimated for W-E oriented VLF propagation path (NWC-Suva). Chand and Kumar [27] determined the mean

values of D_{MS} for W-E (NWC-Suva) and E-W (NLK-Suva) oriented VLF propagation path to Suva, Fiji for the year 2013-14. Their mean value of D_{MS} estimated for the E-W component of the VLF propagation path was 16 % higher than that for the W-E oriented VLF propagation path which is consistent with our results. The authors also estimated a mean value of $D_{MS} = 2103 \pm 172$ km and 2507 ± 373 km for W-E and E-W component (NLK-Suva) of VLF propagation, respectively, which also agrees reasonably well with our result.

Bainbridge and Inan [28] reported that the lowest-order quasi-transverse magnetic mode dominates during the daytime when the electron density is relatively high in the *D*-region of the ionosphere, however, during the nighttime, when the electron density is remarkably low, higher modes are significant and are propagated to greater distances. The mean experimental values of D_{MS} estimated for four different transmitter signals agree reasonably well with the theoretical values calculated using (7) during different seasons for the year 2014. The values of D_{MS} estimated (2119 km) in this paper using NWC transmitter signal during summer are very consistent with the D_{MS} values of 2150 km reported by Kumar [15]. The values of D_{MS} estimated here both theoretically and experimentally are also consistent with the results of Crombie [11] and Lynn [29] for the E-W VLF propagation in the frequency range of 13-22 kHz.

The signal variability of NWC, NPM, JJI and NLK transmitter signals is mostly larger during the nighttime of TRGCP than during the daytime as observed from highly variable signal strengths (Fig. 2-6) indicating that the VLF propagation path is more stable during the daytime which is clearly evident in Fig. 6. This difference in the signal variability is attributed to the *D*-region conductivity changes during the nighttime and due to the higher attenuation of EIWG for the daytime VLF propagation [19]. During nighttime conditions, VLF signals undergo mirror-like reflection compared to diffusive type from the *D*-region in the daytime which attributes to the lower attenuation rate during nighttime and higher attenuation rate during daytime [24]. Clilverd *et al.* [12] suggested daytime signal variation is low due to the presence of fewer modes to interfere during daytime and nighttime signal variation is high because of the increase in the number of significant modes (five or more) and the consequent complex interference between them. The received intensity of each mode depends on various factors such as the distance between transmitter and receiver, transmitter power and frequency, the excitation of modes, path attenuation, surface conductivity, ionosphere height, and direction of propagation [30]–[32]. Generally, the larger the TRGCP length, the more is the signal variability due to an increase in attenuation with distance and stronger the radiated power of the VLF transmitter, the higher is the signal strength and signal-to-noise ratio. NLK transmitter signal has a greater TRGCP distance as a result it has high variability compared to the NWC transmitter signal. On the other hand, the NWC transmitter signal has very little variability

since it has relatively high radiated power compared to the NLK transmitter which has low radiated power of 192 kW. The variability of the VLF signal can also be affected by dynamical processes such as winds, tides, planetary waves, and gravity waves [33] which affect the *D*-region of the ionosphere.

VI. SUMMARY AND CONCLUSION

Results presented in this paper on the waveguide mode analysis of VLF waves at 19.8, 21.4, 22.2 and 24.8 kHz during different seasons for the year 2014 indicate a good consistency between experimental and theoretical values of waveguide mode parameters. Our observations show that the waveguide mode parameters are seasonally dependent, however, this has not been verified using LWPC modeling due to its limitation to show seasonal variation. The estimated value of waveguide mode parameters especially E_{DN} and D_{MS} for W-E (JJI-Suva) and E-W component of the VLF propagation path (NLK-Suva) are both higher during summer and lower during winter. For the W-E VLF propagation path (NWC-Suva), Φ_{DN} follows a similar pattern as E_{DN} and D_{MS} (estimated from JJI-Suva path) where maximum values are observed during summer and minimum during winter, however, for the E-W VLF component path (NPM-Suva), a converse relationship is shown where Φ_{DN} is maximum during winter and minimum during summer. The waveguide mode parameters estimated in this paper were found to be about 15% higher for the E-W component of the VLF propagation path compared to the W-E VLF propagation path. The LWPC simulated signal strengths for all four VLF transmission are generally higher during nighttime compared to daytime signal strength which is consistent with our results. In addition, the LWPC simulated signal strength during daytime and nighttime for E-W component of the VLF propagation path (NLK-Suva) is weaker compared to the simulated signal strength for the W-E VLF propagation path (NWC-Suva). The E_{DN} calculated using LWPC modeling for NWC-Suva, NLK-Suva and NPM-Suva VLF propagation path is about 1-6 dB lower than the theoretical and experimental value of E_{DN} whereas for the JJI-Suva VLF propagation path, the simulated E_{DN} is about 1.5-3.0 dB higher compared to the theoretical and experimental value of E_{DN} . A detailed study of waveguide mode parameters using long-term data by considering more modes in the nighttime may reveal stronger seasonal and solar cycle variations of waveguide mode parameters which will further enhance the understanding of this subject.

ACKNOWLEDGMENT

The data were recorded at their station and are available with Atishnal Elvin Chand.

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