AGU PUBLICATIONS

Radio Science

RESEARCH ARTICLE

10.1002/2016RS006221

Special Section:
Special Issue of the 2016 URSI Asia-Pacific Radio Science Conference

Key Points:
- Modal interference distance and nighttime reflection height (h_N) were measured for two paths having E-W and W-E components of propagation
- Day-to-day variability and seasonal variability were clearly identified for the h_N
- Day-to-day variability of h_N was about 10 km for W-E and 23 km for E-W VLF propagation component paths, respectively

Correspondence to:
A. E. Chand,
atishnalchand@gmail.com

Citation:
Chand, A. E., and S. Kumar (2017), VLF modal interference distance and nighttime *D* region VLF reflection height for west-east and east-west propagation paths to Fiji, *Radio Sci.*, *52*, 1004–1015, doi:10.1002/2016RS006221.

Received 1 DEC 2016
Accepted 29 JUL 2017
Accepted article online 3 AUG 2017
Published online 26 AUG 2017
Corrected 18 SEPT 2017

This article was corrected on 18 SEPT 2017. See the end of the full text for details.

VLF modal interference distance and nighttime *D* region VLF reflection height for west-east and east-west propagation paths to Fiji

Atishnal Elvin Chand[1] and Sushil Kumar[1]

[1]School of Engineering and Physics, University of the South Pacific, Suva, Fiji

Abstract Very low frequency (VLF) signals from navigational transmitters propagate through the Earth-ionosphere waveguide formed by the Earth and the lower conducting ionosphere and show the pronounced minima during solar terminator transition between transmitter and receiver. Pronounced amplitude minima observed on 19.8 kHz (NWC transmitter) and 24.8 kHz (NLK transmitter) signals recorded at Suva (18.149°S, 178.446°E), Fiji, during 2013–2014, have been used to estimate the VLF modal interference distance (D_{MS}) and nighttime *D* region VLF reflection height (h_N). The NWC transmitter signal propagates mostly in west-east direction, and the NLK transmitter follows a transequatorial path propagating significantly in the east-west direction. The values of D_{MS} calculated using midpath terminator speed are 2103 ± 172 km and 2507 ± 373 km for these paths having west-east and east-west components of VLF subionospheric propagation, respectively, which agree with previously published results and within 10% with theoretical values. We have also compared the D_{MS} estimated using a terminator time method with that calculated using terminator speed for a particular day and found both the values to be consistent. The h_N values were found to be maximum during winter of Southern Hemisphere for NWC signal and winter of Northern Hemisphere for NLK signal VLF propagation paths to Suva. The h_N also shows significant day-to-day and seasonal variabilities with a maximum of about 10 km and 23 km for NWC and NLK signal propagation paths, respectively, which could be due to the atmospheric gravity waves associated with solar terminator transition, as well as meteorological factors such as strong lightnings.

1. Introduction

Very low frequency (VLF, 3–30 kHz) radio waves generated by navigational transmitters propagate over great distances in the Earth-ionosphere waveguide (EIWG) which is considered as spherical waveguide bounded by the ground (land or sea) surface and the lower ionosphere (*D* region). The *D* region ranges from ~60 to 75 km altitude in the daytime and ~75 to 95 km at nighttime [*Hargreaves*, 1992]. Some research has been conducted on the nighttime lower ionosphere mainly using radars and rockets because of lower electron density [*Schunk and Nagy*, 2000], which is insufficient to reflect high frequency used in other radio sounding (e.g., ionosonde and incoherent radars). The *D* region is also too high for balloons and too low for satellite to probe but can be diagnosed using extremely low frequency and VLF narrowband signals [*Cummer et al.*, 1998].

The daily VLF amplitude and phase variations show typical features such as amplitude minima due to destructive modal interference observed during sunrise and sunset transitions on long distance VLF propagation paths [*Crombie*, 1964; *Samanes et al.,* 2015]. The number of minima depends upon the length of east-west component of the VLF propagation and vice versa. The diurnal VLF phase variations were first observed by *Pierce* [1955] and *Crombie* [1958], and their results showed that the phase advanced during sunrise with pronounced steps coincident with amplitude minima. *Budden* [1961] and *Wait* [1962] first reported the diurnal phase and amplitude variation both during sunrise and sunset transitions. *Crombie* [1964] studied the sunrise/sunset effect on west-east VLF propagation path and proposed a model by assuming two modes (first order and second order) being present in the nighttime portion of the VLF propagation path and only one mode in the daytime portion of the VLF propagation path in the EIWG. The results for this particular study for west-east VLF propagation path provided strong evidence that at the sunrise terminator (day/night boundary), a significant mode conversion can be assumed to occur (nighttime second-order mode converted into daytime first-order mode) to ensure the continuity of the electric field across the step discontinuity produced by the terminator line. For the sunset effect on west-east VLF propagation, *Crombie*

[1964] also assumed mode conversion of the daytime first-order mode into nighttime first- and second-order modes which may subsequently interfere with each other in the nighttime portion of path. *Walker* [1965] verified the ionospheric model put forward by *Crombie* [1958] using NBA transmitter (18 kHz) signal and proposed that for the west-east VLF propagation path all the points on the dayside of the dawn discontinuity should experience the signal minima simultaneously, and at dusk the interference pattern should be on the dark side of the discontinuity and that the minima time depends on the location of the receiver.

Clilverd et al. [1999] carried out a detailed study on the occurrence of amplitude minima and the effect of the sunrise terminator (when it is parallel to a propagation path) during the period 1990–1995 over a long north-south path (12 Mm) using NAA transmitter (24 kHz) from Cutler, USA, to Faraday, Antarctica. They found that the timings of the minima were consistent with modal conversion occurring as the day/night boundary (sunrise terminator) crossed the VLF propagation path at specific and consistent locations. *Lynn* [1967] first reported an equatorial anomaly associated with the sunrise transition fading, by examining 1 year phase and amplitude records of the transmitter NLK signal received at Smithfield, South Australia. The distance travelled by the terminator sunrise/sunset line between two successive amplitude minima is called the model interference distance (D_{MS}). *Lynn* [1967] and *Meara* [1973] estimated an anomalous value of the D_{MS} for east-west transequatorial VLF propagation paths when the minimum amplitude was located in the vicinity of the magnetic equator. The D_{MS} reported by *Lynn* [1967] for sunrise transition fading is approximately 2000 km for the terminator located in midlatitudes, that is, in excess of ±20° from the geomagnetic equator. *Lynn* [1967] concluded from his observations that the change in D_{MS} resulted from a change in the difference of phase velocity of two modes and from a change in the relative phases of the appropriate mode conversion coefficients. The explanation of a possible cause for these changes was left unanswered by *Lynn* [1967]. Later, *Lynn* [1977] investigated the frequency and latitudinal dependence of sunrise modal interference observed over long west-east VLF propagation path and reported that the phase and amplitude anomalies are not associated with transequatorial propagation over west-east VLF propagation path and the D_{MS} values for east-west VLF propagation path at middle latitudes are slightly higher than those for west-east VLF propagation path. The anomalous effects also observed in the nighttime amplitude and phase of the transequatorial (crossing over the geomagnetic equator) signals [e.g., *Lynn*, 1967; *Araki*, 1973; *Kikuchi*, 1983] have been explained by *Thomson and McRae* [2009].

Kumar [2009] determined the waveguide parameters at 19.8 kHz signal from NWC transmitter recorded at Suva during December 2006 and estimated that the experimental values of the waveguide parameters were consistent by 25–30% with the theoretical values calculated using the mode theory of VLF wave propagation in the waveguide. Recently, *Samanes et al*. [2015] developed a better methodology called terminator time (TT) method to estimate the D_{MS} from the occurrence time of the pronounced VLF amplitude minima and reported that their results show good agreement with other methods. These minima are produced as a result of processes of modal interference in which significant mode conversion is expected to occur at the sunrise or sunset line [*Crombie*, 1964; *Walker*, 1965]. *Crombie* [1966] using a simple sharply bounded isotropic model of the ionosphere determined wavelengths of the first- and second-order waveguide modes in the nighttime portion of the EIWG and found that the appropriate nighttime VLF reflection height (h_N) was about 85 km, also confirming that the mode interference was occurring in the nighttime portion of the VLF propagation path. *Samanes et al*. [2016] utilized D_{MS} to estimate h_N for a transequatorial path (NPM-ATI) having west-east VLF propagation component in the American sector.

In this paper, we have used a method that considered the relation between $D_{MS,}$ terminator speed and the difference between two successive amplitude minima times to calculate the D_{MS} which is then used to determine h_N using the relationship between h_N and D_{MS} [*Crombie*, 1966], for NWC VLF transmission mostly in the west-east direction and NLK in the northeast-southwest direction, respectively, to the receiving station Suva (18.149°S, 178.446°E), Fiji. The Transmitter Receiver Great Circle Path (TRGCP) length for NWC-Suva and NLK-Suva VLF propagating path is 6.696 Mm and 9.43 Mm, respectively. Since the distance between two consecutive amplitude minima (D_{MS}) is simply related to the phase velocities of nighttime propagation modes, which in turn is related to the lower ionospheric changes, the D_{MS} can be a useful tool for obtaining valuable information on the nighttime *D* region VLF reflection height. We also discuss the typical properties of h_N for paths having west-east and east-west components of VLF subionospheric propagation especially for day-to-day variability on monthly and seasonal scales.

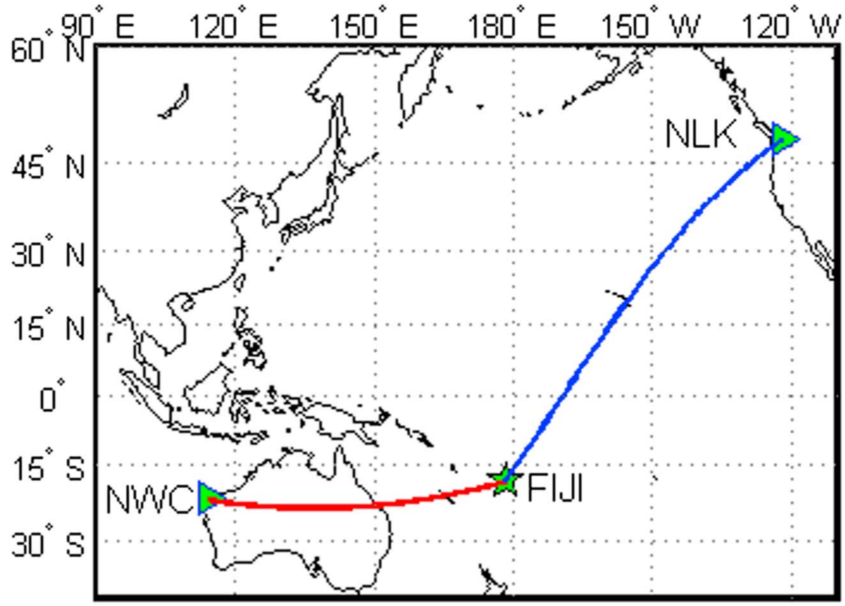

Figure 1. Map showing the positions of NWC and NLK transmitters and their TRGCPs to receiving station Suva, Fiji.

2. Data and Analysis

Experimental setup consists of a short (1.5 m) whip antenna, preamplifier, VLF service unit coupled with preamplifier, and a Software based Phase and Amplitude Logger termed as "SoftPAL." The whip antenna receives the vertical electric field component of the transverse magnetic mode of the VLF propagation. SoftPAL is a state of the art data acquisition system developed by AD Instruments, New Zealand, which can log amplitudes (in dB above 1 μV/m) and phases (in degrees) of seven MSK (minimum shift key) VLF transmitters. The NWC and NLK signals are recorded at a time resolution of 0.1 s (i.e. sampling frequency of 10 Hz) and are run continuously using LabChart for Windows software. The continuous operation is chosen to monitor the diurnal variation in the signal strength and to study the nighttime and daytime short-timescale VLF perturbation. To estimate the D_{MS} and h_N more accurately, the mean value of D_{MS} and h_N, and temporal and seasonal variability of D_{MS} and h_N, we have analyzed the amplitude minima times for NWC and NLK transmitter signals for two (2013 and 2014) years. A map showing the positions of NWC and NLK VLF transmitters and their TRGCPs to Suva, Fiji, is shown in Figure 1. The NWC transmitter operates at 19.8 kHz and is located in the Southern Hemisphere with geographic coordinates (21.816°S, 114.166°E), and its signal propagates completely in the Southern Hemisphere to low-latitude receiving station Suva (18.149°S, 178.446°E). The NLK transmitter operates at 24.8 kHz and is located in the Northern Hemisphere with geographic coordinates (48.203°N, 121.917°W). The NLK signal propagates from its midlatitude location in the Northern Hemisphere to low-latitude station Suva in the Southern Hemisphere having northeast-southwest direction of propagation.

3. Theoretical Considerations

The D_{MS} between the successive signal minima (fades) at receiver can be simply defined by considering the interference of only two night modes and one day mode and is given as [*Crombie*, 1966]:

$$D_{\mathrm{MS}} = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1} \tag{1}$$

where λ_1 and λ_2 are the waveguide wavelengths of the first- and second-order modes in the nighttime portion of the EIWG, respectively.

Equation (1) can be simplified as given by *Crombie* [1966]:

$$D_{MS} = \frac{4{h_N}^2}{\lambda_0} \tag{2}$$

where h_N and λ_0 are the undisturbed nighttime *D* region VLF reflection height and free space wavelength, respectively.

The D_{MS} in terms of signal frequency (*f*) and relative phase velocities of the first-order (V_{N1}) and second-order (V_{N2}) nighttime propagation modes can be expressed as [*Lynn*, 1977]:

$$D_{MS} = \frac{V_{N1}V_{N2}}{f(V_{N2} - V_{N2})} \tag{3}$$

Recently, *Samanes et al*. [2015] developed a better technique, terminator time (TT), method to estimate the $D_{MS.}$ This method is based on the measurement and analysis of TTs which are the times when the pronounced amplitude minima are observed during the subionospheric VLF propagation during sunrise and sunset transition hours. The daily sunrise times are computed to find the location along the transmitter-receiver VLF propagation path where the sunrise time matches the observed TT_i, using solar zenith angle (SZA) in the range 95°–98°. Using this location, its distance to the transmitter is calculated and then equation (4) gives the mean D_{MS}:

$$D_{MS} = \frac{\sum D_J}{N} \tag{4}$$

where D_j is the daily distance and *N* is the total number of days used.

The D_{MS} can also be calculated using the terminator speed (V_T) and the time difference (Δ*t*) between two successive TTs or amplitude minima:

$$D_{MS} = V_T * \Delta t \tag{5}$$

We have calculated V_T at midpoint latitude of the propagation path using the well-known relationship:

$$V_T = \frac{2\pi R_E \cos[\text{Latitude}]}{24 \text{ hrs}} \tag{6}$$

Equation (2) can also be manipulated to calculate the h_N:

$$h_N = \sqrt{D_{MS}\lambda_0/4} \tag{7}$$

4. Results and Discussion

4.1. The D_{MS} for West-East and East-West VLF Propagation Component Paths

We have used almost 2 years of data monitoring of sunset (SS) and sunrise (SR) amplitude minima times at Suva for 19.8 kHz and 24.8 kHz transmissions from NWC and NLK transmitters to determine the mean D_{MS} using equation (5). A sample record of NWC and NLK signals amplitude recorded on 20 and 4 October 2013, respectively, is shown in Figure 2. For NWC-Suva VLF propagation path, three amplitude minima each during sunset (SS_1, SS_2, and SS_3) and sunrise (SR_1, SR_2, and SR_3) were observed. However, for NLK-Suva VLF propagation path only three sunset amplitude minima labeled as SS_1, SS_2, and SS_3 were clearly visible and during sunrise a minima appears which is not always clearly visible due to high signal variability of the signal during the sunrise transition hours. The single sunrise minima cannot be used for the D_{MS} analysis; therefore, only sunset minima have been used.

We have estimated the D_{MS} using both SR and SS amplitude minima times using the TT method [*Samanes et al.,* 2015] and the method which uses the relation between D_{MS} and terminator speed (equation (5)) for Figures 2a and 2b. TT is a time when the terminator line crosses given locations along the VLF propagation path creating amplitude minima at the receiver [*Samanes et al.,* 2015]. It is also defined as the time of amplitude minimum that coincides very well with the time of maximum rate of phase change [*Muraoka*, 1982]. The mean D_{MS} calculated using the TT method for NWC-Suva and NLK-Suva VLF propagation paths is 1979 ± 251 km and 2722 ± 266 km, respectively. We have used the TT method in a similar manner as described by *Samanes et al*. [2015]. The estimate of the D_{MS} for Figure 2 data using TT method was

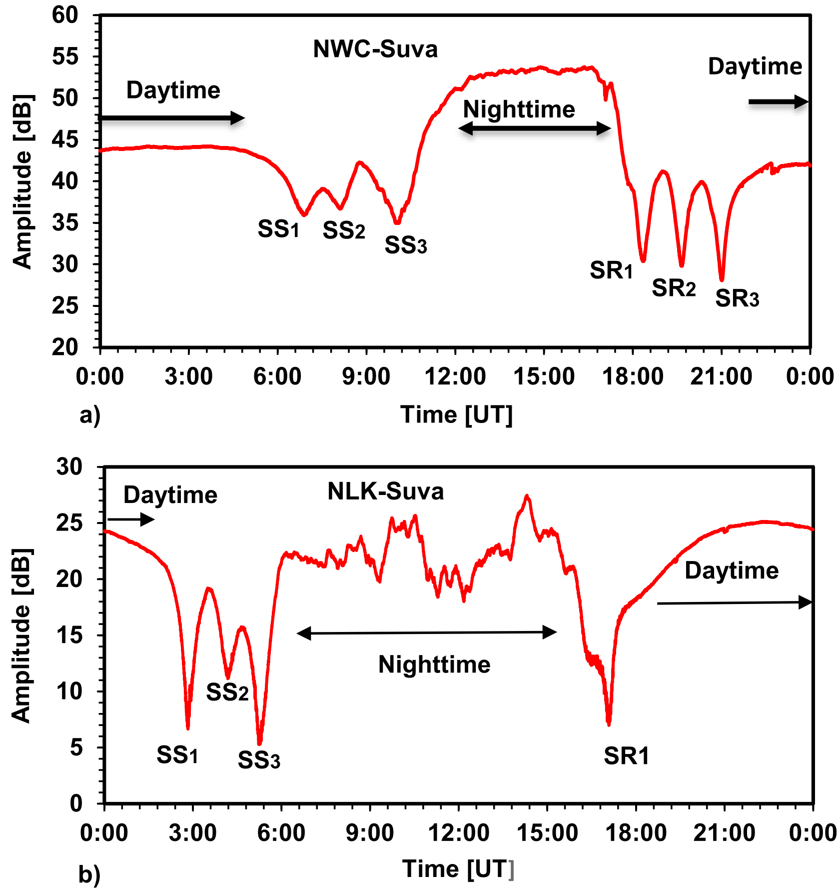

Figure 2. Amplitude record of (a) NWC signal on 20 October and (b) NLK signal on 4 October 2013 at Suva. Three sunset (SS1 to SS3) and three sunrise minima (SR1 to SR3) were observed on NWC-Suva VLF propagation path, while three sunset minima (SS1 to SS3) and a sunrise minima (not so clear) were observed on NLK-Suva VLF propagation path. The durations of day and night times along the paths are indicated by arrowhead lines.

computed as follows: (1) we determined the sunrise and sunset amplitude minima times; (2) both the transmitter-receiver paths (NWC-Suva path and NLK-Suva path) were divided into 1300 parts; (3) at each location in the path for each transmitter, the SR and SS times were computed to determine the SZA; (4) for each one of the three SR and SS amplitude minima times, we found the location along the path where the SR and SS times matched the observed SR and SS amplitude minima times (we used SZA of 96° for both the paths); and (5) once this location was determined, its distance to the transmitter NWC and NLK was calculated. Using the second method (equation (5)), the mean D_{MS} estimated for NWC-Suva and NLK-Suva VLF propagation path are 1984 ± 244 km and 2513 ± 113 km, respectively. The terminator speed, V_T, calculated using equation (6) for NWC-Suva and NLK-Suva VLF propagation paths is 25.66 km/min (427.67 m/s) and 26.68 km/min (444.67 m/s), respectively. The comparison shows that the D_{MS}, calculated using both the methods, is consistent and also consistent with theoretical values of D_{MS}. Therefore, for an entire database of 2 years, both for NWC-Suva and NLK-Suva VLF propagation paths, we have used the second method (equation (5)) to estimate the D_{MS}.

The daily variation of SR and SS amplitude minima times for west-east (NWC) VLF propagation path for two years 2013–2014 is shown in Figures 3a and 3b. It can be seen from this figure that SR minima times repeat themselves with good regularity and show a clear seasonal variation for both the years which is consistent with study of *Raulin and Samanes* [2011]. However, there is a slight variation in the SS minima times as compared to SR minima times for NWC-Suva VLF path. It can be noted that SS_1 and SR_1 occur when the terminator is closer to the transmitter (farthest from the equator) and SS_3 and SR_3 occur when the terminator is closer to the receiver (closest to equator). We used SSs for NLK signal analysis since SRs were not quite visible. The data gap around the day 260–290 as indicated by (No Data) for sunrise (Figure 3a) corresponds to a period when

10.1002/2016RS006221

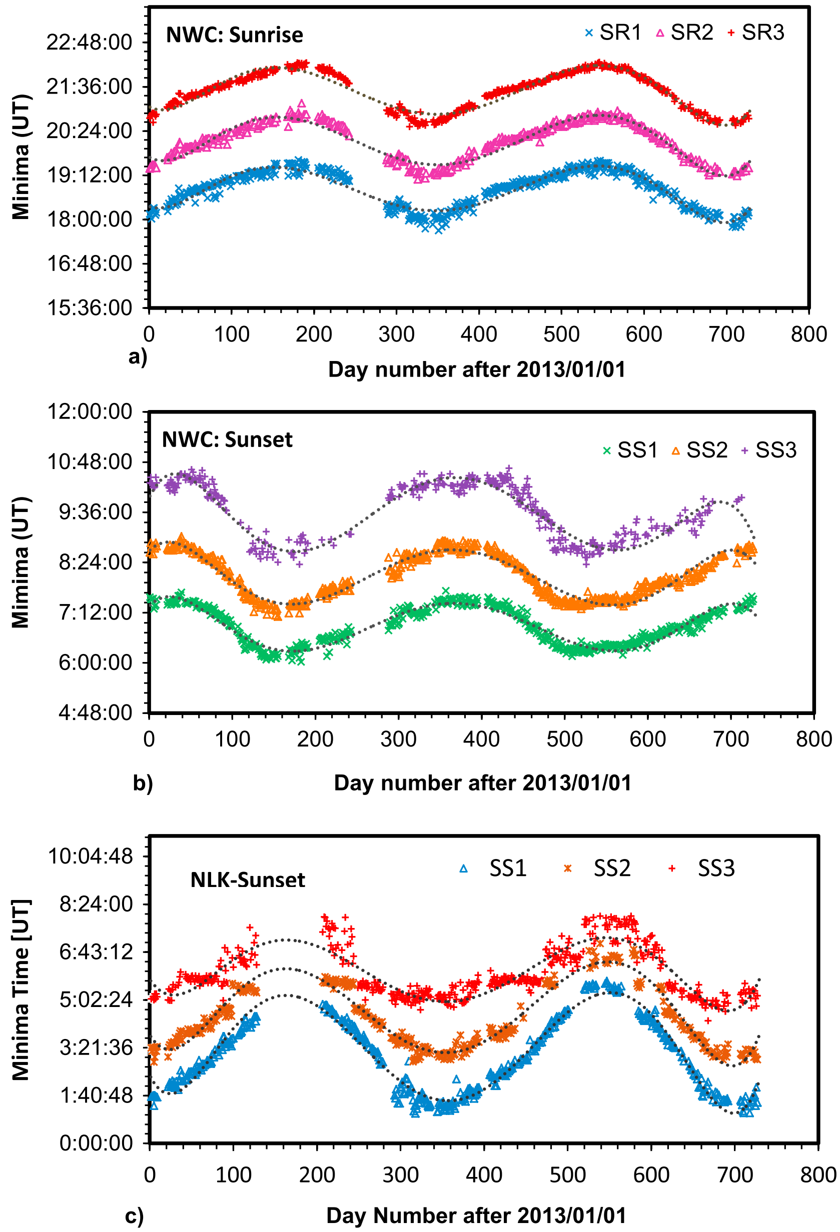

Figure 3. (a) Sunrise and (b) sunset minima times measured from the daily amplitude curves for NWC-Suva and (c) sunset minima times for NLK-Suva VLF propagation paths.

the NWC transmitter was off the air. The results on the D_{MS} for a west-east (NWC) VLF propagation path using equation (5) were presented in 2016 Union Radio Scientifique Internationale Asia-Pacific Radio Science Conference held during 21–25 August 2016, Seoul, Korea [*Chand and Kumar*, 2016]. For NLK-Suva VLF propagation path only three SS minima time are observed. However, only two SS minima time were used since SS_3 had high variation as compared to SS_1 and SS_2. Figure 3c shows a plot of the occurrence times of SS for NLK signal received at Suva. It is also observed from Figure 3c that SS_2 has larger variation compared to SS_1.

The SR amplitude minima occur corresponding to TTs occurrence at specific locations along the night part of the VLF propagation NWC-Suva path, where destructive interference of the first and second-order modes may be taking place [*Raulin and Samanes*, 2011]. We have therefore used these minima times to find the $D_{MS.}$ This has been calculated using first, second, and third sunrise minima (SR_1, SR_2, and SR_3) as shown in Figure 4a for NWC signal with mean values shown by dashed black line. The values are consistent over

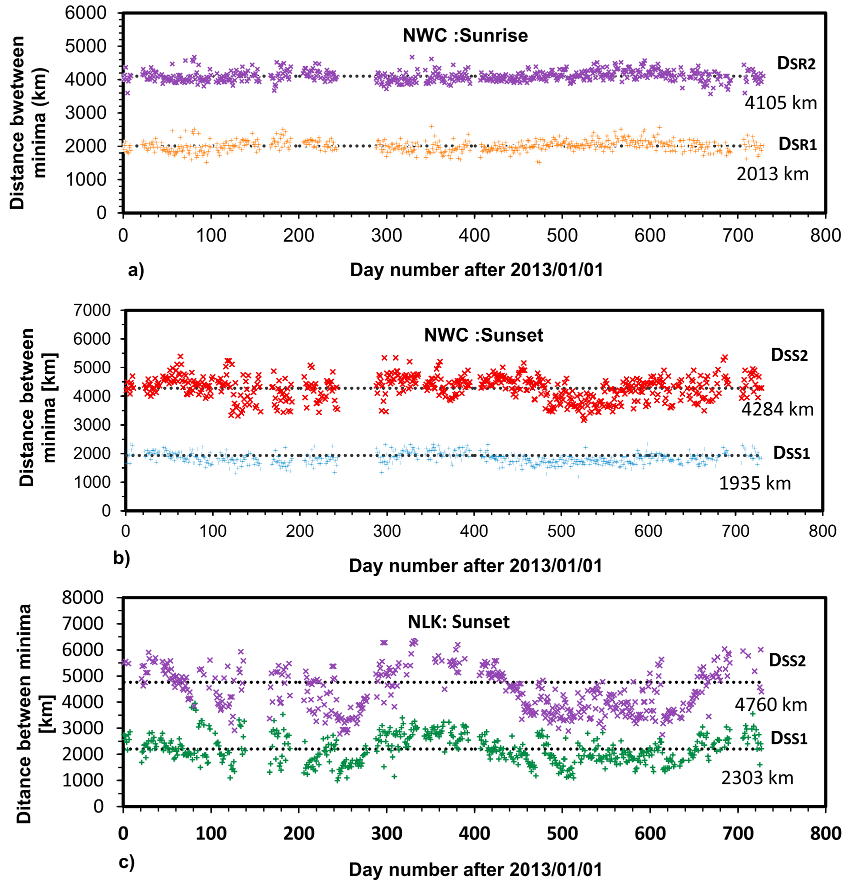

Figure 4. (a–c) Variation of modal interference distances (D_{MS}) during the year 2013–2014. D_{SS1} corresponds to the distance estimated from first and second minima which gives D_{MS}, and D_{SS2} corresponds to the distance estimated from first and third minima which gives two times the D_{MS}. Similarly, DSR1 and DSR2 are estimated using sunrise minima.

both the years (2013–2014). Therefore, D_{SRi} from Figure 4a corresponds to the distance between first and second minima and first and third minima giving D_{MS} and 2 times D_{MS}, respectively. At a distance of 4105 km from SR_1 to SR_3, nighttime modes 1 and 2 may interfere destructively, producing daily deep minima that were observed at the particular times. The important point from Figure 4a is that the consistency of the $D_{MS} = D_{SR1}$ = 2092 km (4105 km–2013 km) (using SR_3, SR_2, and SR_1) with $D_{MS} = D_{SR2}/2$ (4105/2 km) (using SR_3 and SR_1). Similarly, SS_i minima have been used to find the D_{ssi} and the D_{MS} for NLK-Suva path, as shown in Figure 4c. It can be noted from this figure that D_{SS2} has more variation compared to D_{SS1}.The D_{MS} estimated using SS_1, SS_2, and SS_3 minima times for NLK-Suva VLF propagation path is 2457 km (4760–2303 km).

The summary of mean the D_{MS} for both NWC and NLK VLF propagation paths to Suva is given in Table 1, where we have listed the estimated D_{MS} values. Here we use the notation $D_{SSki} = V_T[SS_k - SS_i]$ in order to distinguish between each distance obtained from two successive minima, for example, $D_{SS21} = V_T[SS_2 - SS_1]$, $D_{SS32} = V_T[SS_3 - SS_2]$ and so on. We note from Table 1 that for the NWC-Suva path, the D_{MS} calculated from SS and SR are very similar to each other and this is also same for NLK-Suva path. The mean experimental values of D_{MS} for NWC-Suva (west-east) and for NLK-Suva (northeast-southwest) VLF propagation paths are 2103 ± 172 km and 2507 ± 373 km, respectively, which agree reasonably well within 10% (1.2–8.5%) with the theoretical values of 2130 km and 2310 km, respectively, calculated using equation (3) [*Samanes et al.*, 2015] where V_{N1} and V_{N2} have been taken from those tabulated by *Wait and Spies* [1964]. The mean experimental value of D_{MS} estimated for NLK-Suva path is about 16% [((2507–2103)/2507) × 100 = 16%] higher than that for NWC-Suva path. On the basis of experimental observations, *Crombie* [1966] reported that D_{MS} for east-west VLF propagation path was about 50% higher than that of the west-east VLF propagation path.

Table 1. Estimated Values of Modal Interference Distance (D_{MS}) With Standard Deviations for NWC-Suva Path Using Sunrise and Sunset Amplitude Minima and for NLK-Suva Path Using Sunset Amplitude Minima[a]

	D_{SS21} (km)	D_{SS32} (km)	$D_{SS\overline{31}}$ (km)	D_{SR21} (km)	D_{SR32} (km)	$D_{SR\overline{31}}$ (km)	Theoretical D_{MS}
NWC-Suva Path							
Mean value	2003	2295	2145	2022	2106	2048	2138
Standard deviation	163	256	219	171	117	104	
NLK-Suva Path							
Mean value	2437	2547	2537	-	-	-	2678
Standard deviation	369	405	344	-	-	-	-

[a]$D_{SS\overline{31}}$ shows the mean D_{MS} calculated using D_{MS} estimated from SS_1-SS_2 and SS_2-SS_3.

We compared the D_{MS} calculated in this paper with the value obtained by *Lynn* [1977], who analyzed 29 days data for west-east transequatorial VLF propagation path between NSS (at 21.4 kHz, USA) transmitter and the receiver station TAA (Madagascar). Using six amplitude minima, *Lynn* [1977] obtained a mean value of D_{MS} equal to 2207 ± 202 km, which agrees reasonably well with our mean value of D_{MS}, 2239 ± 201 km, obtained for NWC-Suva path. The standard variation for D_{MS} is quite high (373 km) for NLK-Suva path due to the high day-to-day amplitude minima time variability of the NLK transmitter signal, as observed in Figure 3c. This is because the NLK signal has a longer propagation path and the larger range of local time zones traveled to reach our station Suva. Recently, *Samanes et al*. [2015] analyzed a long-term database of almost 5 years from three different VLF propagation paths, mainly oriented along the west-east direction (NPM-ATI, NPM-PLO, and NPM-ICA) from the South America VLF Network, and estimated the mean value of D_{MS} using the methodology as described in this paper. The authors estimated the mean value of D_{MS} for NPM-ATI, NPM-PLO, and NPM-ICA path as 2190 ± 60 km, 2160 ± 60 km, and 2170 ± 50 km, respectively. Their values of D_{MS} are in good agreement with our D_{MS} (2103 ± 172 km) estimated for NWC transmitter for west-east VLF propagation path. The values of D_{MS} estimated here both theoretically and experimentally are also consistent with the results obtained by *Crombie* [1966]. We have compared our values of D_{MS} with the values obtained by other methods, which are in good agreement. Thus, we recommend this method for future studies on this subject.

In Figure 5, we plotted the theoretical $D_{MS,}$ calculated using equation (3), versus frequency shown by red points and line. We also added the experimental D_{MS} for west-east and east-west VLF propagation component path with the estimated inaccuracies and observed that the D_{MS} estimated for west-east VLF propagation path agrees reasonably well with the theoretical value when compared to east-west propagation path. The theoretical D_{MS} versus frequency was extrapolated up to the NLK signal frequency, first using a polynomial fit, which gave best value of r^2 = 0.9998, but D_{MS} values for NLK showed about 25% less than mean experimental values. We then tried a next best fit that is logarithm as shown in Figure 5 by blue dashed line, which gives r^2 = 0.9226, but it gives D_{MS} value less than mean experimental value by about 8%.

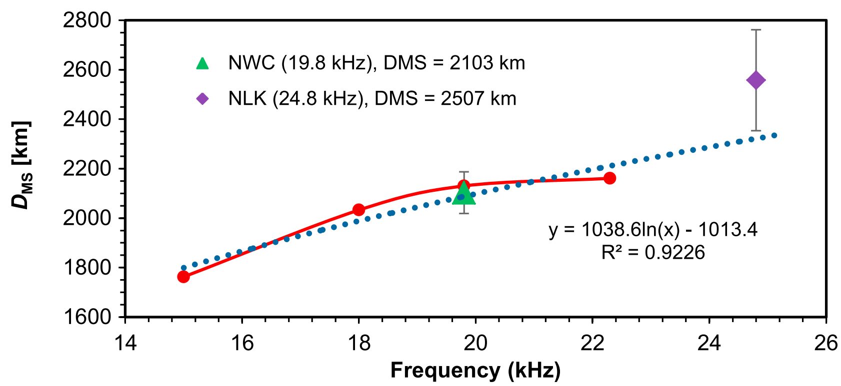

Figure 5. Theoretical modal interference distance (D_{MS}) as a function of the frequency is shown by red color points and line. The mean value of D_{MS} for NWC-Suva VLF path is shown by a green symbol and for NLK-Suva path by purple symbol. The D_{MS} is further extrapolated using logarithmic fit shown by blue color dashed line.

Table 2. Estimated Values of Nighttime Lower Ionospheric Reflection Height (h_N) With Standard Deviations During Summer, Winter, and Equinox for NWC-Suva Path Using Sunrise and Sunset Amplitude Minima and for NLK-Suva Path Using Sunset Amplitude Minima

	Summer (November–February) (km)	Winter (May–August) (km)	Equinox (March, April, September, and October) (km)	All Seasons
		NWC-Suva Path		
Mean value	87.55	88.65	87.59	87.96
Maximum	91.83	92.45	91.63	92.45
Minimum	82.27	83.04	82.19	82.19
Standard deviation	1.60	1.50	1.47	1.61
		NLK-Suva Path		
Mean value	87.43	80.50	81.57	83.84
Maximum	91.88	94.64	92.50	94.85
Minimum	74.38	71.88	72.38	71.88
Standard deviation	3.04	5.45	5.47	6.24

4.2. The h_N for West-East and East-West VLF Propagation Component Paths

In section 4.1, we have calculated the daily values of D_{MS} for west-east and for path having east-west (also transequatorial) component of VLF propagation using the daily SS and SR amplitude minima times. The D_{MS} has been used to calculate h_N using equation (7) for both the VLF propagation paths. The main characteristic of h_N is its temporal variability in different timescales (day to day, month, and season), as is evident from the standard values given in the Table 2.

The first variability corresponds to the values that h_N assumes on a day-to-day basis [*Samanes et al*., 2016]. *Han and Cummer* [2010] studied the nighttime lower ionosphere for a midlatitude station in the Northern Hemisphere during July to August 2005 using lightning-generated ELF-VLF waveforms and found that h_N assumes a mean value of 84.9 ± 1.1 km. The authors also observed that the maximum variation in the 5 h period was around 4.0 km and that the maximum variation in the 1 h period was around 1.3 km, with sharper gradients observed over shorter time periods. *Maurya et al*. [2012] analyzed lightning-generated dispersive sferics (tweeks) recorded at low-latitude stations in the Indian sector and estimated a *D* region day-to-day variability of about 9 km (82–98 km) and temporal variability of about 1–2 km on any day in any 1 h duration. Recently, *Samanes et al*. [2016] estimated the h_N for a west-east VLF propagation path between the NPM (21.420°N, −158.154°W, 21400 Hz) VLF transmitter signal and a receiving station ATI in the South America using a long-term database of almost 6 years (2006 to 2011) provided by the South America VLF Network. They reported well-defined day-to-day variability of h_N with maximum variation of about 5 km. In Figure 6, we present day-to-day variability of h_N for west-east (NWC-Suva, using SS amplitude minima) and for path having east-west (NLK-Suva, using SS amplitude minima) component of VLF propagation with crosses, monthly variation with a 30 days running average (black dashed line), and general pattern with a sixth-order polynomial trend line (red solid line).

As shown in Figure 6a, for the west-east path, the h_N varies mostly between 85 and 92 km with a maximum value during June of the winter season and a minimum during November and December of the summer season. The general and monthly variations of h_N seem to be quiet consistent with not much spread between both. However, for the path having east-west component (NLK-Suva), the h_N varies over wide range 72–95 km with a maximum value during the November and December of the summer season and minimum during May and June of the winter season of the Southern Hemisphere. Both general and monthly variations show large variability, with significant spread at times. The maximum day-to-day variability is about 10 km (92–82 km) for west-east and 23 km (94–71 km) for the path having east-west component, respectively. For the NLK-Suva path, we estimated the mean value of h_N as 83.8 ± 6.4 km with a maximum day-to-day variability of about 23 km. The comparison of h_N during both the years does not show any noticeable change, primarily due to moderate solar activity level during 2013 (sunspot number, R_Z, 65, http://www.sws.bom.gov.au/Educational/2/3/6) and 2014 (R_Z, 79) of maximum of current solar cycle phase. The range and day-to-day variability of h_N seem to be consistent with those determined using the tweeks atmospherics observations at

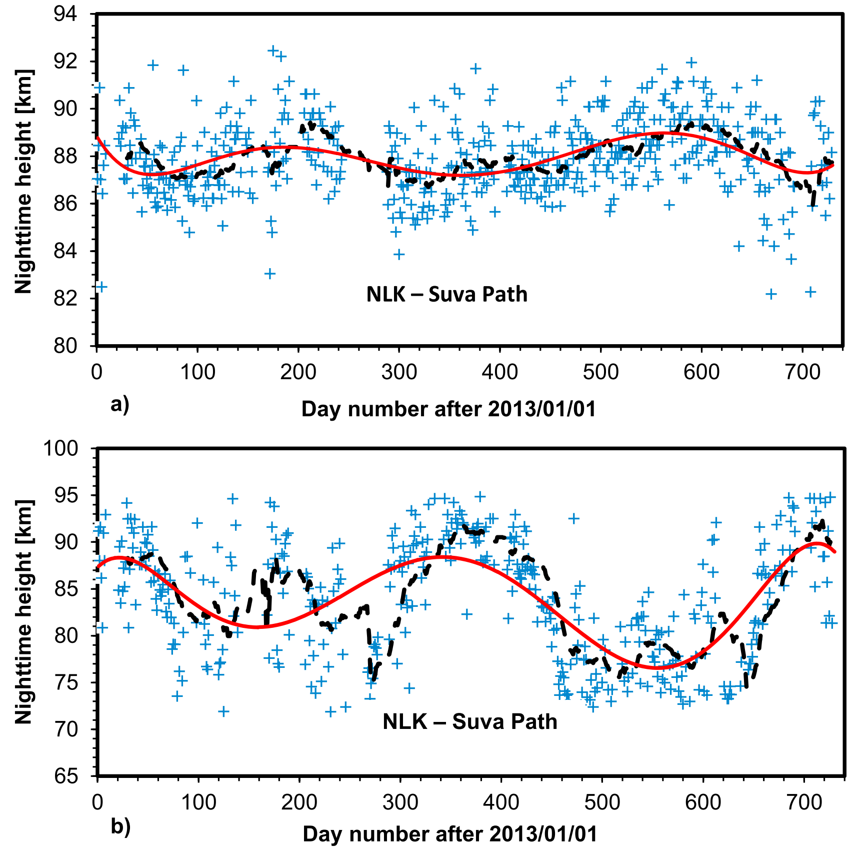

Figure 6. (a, b) Estimated nighttime reflection height (h_N) of lower ionosphere as a function of the day number after 1 January 2013 for NWC-Suva and NLK-Suva paths (blue symbol). Red line illustrates curve smoothed of h_N using polynomial fit and black dashed line using 30 days running average.

low-latitude stations in India and Vietnam [*Maurya et al.*, 2012; *Tan et al.*, 2015]. The day-to-day variability of h_N could be attributed to direct energy coupling between lightning discharges and the lower ionosphere [*Inan et al.*, 1993; *Han and Cummer,* 2010; *Maurya et al.*, 2012], as well as to the atmospheric gravity waves (AGWs) generated by the solar terminator. The daytime *D* region ionosphere is also affected by the solar flares particularly by *M* and *X* classes which reduce the reference height significantly [e.g., *Thomson et al.*, 2005; *Raulin et al.*, 2006; *Kumar and Kumar*, 2014]. *Beer* [1973] first theoretically suggested that solar terminator might generate AWGs; this was confirmed using the ground-based and satellite observations [e.g., *Raitt and Clark,* 1973; *Galushko et al.,* 1998; *Forbes et al.*, 2008 *Miyoshi et al.*, 2009]. The AGWs have frequencies lower than the buoyancy frequency or the Brunt-Vaisala frequency [*Yeh and Liu*, 1974] and are strong sources of short-time scale ionospheric variability, as they create ionization ripples. The AGWs propagate obliquely upward and couple to the ionosphere, and propagation can be altered by background wind [*Cowling et al.*, 1971]. The short-term variability of Lyman α and β flux and scattered Lyman α which are the main sources of the ionospheric *D* region formation, through the ionization of NO and variations in other minor *D* region constituents such as O_3 and H_2O, due to neutral atmosphere changes may also contribute to h_N day-to-day variability.

The second variability can be clearly observed in Table 2 and also by the smoothed curve of h_N (black line) in Figure 6. The statistical analysis of h_N for three different seasons and annually for the years 2013 and 2014 is given in Table 2. Seasonally, for the NWC-Suva VLF propagation path, the mean value of h_N is almost the same (about 87.6 km) for summer and the equinox which is lower by almost 1 km as compared to winter (88.7 km), with nearly similar amount of difference in maximum and minimum values of h_N during these seasons. For the NLK signal, the h_N is highest during summer (87.43 km) and lowest during winter (80.5 km) with moderate values during equinox (81.6 km). The summer months of the Northern Hemisphere correspond to the winter months of the Southern Hemisphere. The highest value of h_N during summer (89.2 km) indicates that the h_N

estimated at Suva for NLK signal is primarily dependent upon the seasons in the Northern Hemisphere which is obvious from its larger proportion of VLF propagation path in the Northern Hemisphere. There is no significant difference in the maximum values of h_N during three seasons for both the NWC and NLK propagation paths; however, there is a significant difference in the minimum values of h_N during three seasons being larger by about 10 km on the NWC-Suva path as compared to the NLK-Suva path. Thus, Table 2 gives that h_N is dependent upon the VLF propagation path, seasons, and also frequency of the transmitter. In a review article, *Friedrich and Rapp* [2009] have reported the dependence of the nighttime *D* region on zenith angle, solar activity, latitude, and season. Our results on larger values of h_N during winter indicate the lower *D* region ionization as compared to summer and equinox seasons. *Samanes et al*. [2016] studied the dynamics of the nighttime lower ionosphere and reported that the h_N assumes maximum values during the winter of the Northern Hemisphere while assuming minimum values during the summer for the west-east VLF propagation path (NPM to ATI). The NPM-ATI path being almost 50% each in the Northern and Southern hemispheres was transequatorial. This is also the case in our results that for west-east VLF propagation path, h_N assumes maximum value during southern winter and minimum value during southern summer. *Samanes et al*. [2016] estimated the mean value of h_N for summer and winter period as 86.89 ± 0.13 km and 88.21 ± 0.24 km, respectively. From our observations, we deduced the mean values of h_N = 87.55 ± 1.60 km during summer and h_N = 88.65 ± 1.50 km during winter, which are about 0.7 km (0.4–0.7 km) larger than those estimated by *Samanes et al*. [2016] for transequatorial west-east (NPM-ATI) path. Our values of h_N are consistent with the nighttime height of the lower ionosphere ($h_N \approx 85$ km) as determined by *Crombie* [1966].

5. Summary and Conclusions

In this paper, we have estimated the D_{MS} based on the measurement of the occurrence times of pronounced amplitude minima observed for west-east (NWC) and northeast-southwest (NLK) subionospheric VLF propagation paths to Suva, Fiji, using the sunrise and sunset amplitude minima times during the years 2013 and 2014. The mean values of the D_{MS} are 2103 ± 172 km and 2507 ± 373 km for west-east and for the path having east-west component (NLK-Suva) of VLF propagation, respectively, which agree well with previously published results. The D_{MS} value estimated here for NLK-Suva VLF path is about 16% higher than that for NWC-Suva path which may be due to longer propagation path and the larger range of local time zones traveled by NLK signal to our station Suva. We have also estimated the h_N for both NWC-Suva and NLK-Suva VLF propagation paths by monitoring the daily values of the D_{MS}. Two types of variabilities that were clearly observed in h_N are (a) day-to-day variability which has shown maximum variation of about 10 km for the west-east and 23 km for the path having east-west component of VLF propagation and (b) seasonal variability that showed maximum values during winter of the Southern Hemisphere with a mean value of h_N = 88.65 ± 1.50 km for the west-east path and 87.43 ± 3.04 km for the path having east-west component of VLF propagation during summer (or winter of the Northern Hemisphere). Thus, the mean value of h_N for the west-east VLF propagation path is higher than that for the path having east-west component of transequatorial VLF propagation. The NKL-Suva path has different geophysical characteristics due to north-south propagation component with significant part in the tropical region which is the source of frequent and intense lightings causing short-term h_N variability through AGWs. We suggest extending this study for disturbed conditions due to severe space weather (e.g., geomagnetic storms) and terrestrial events (tropical cyclones) for *D* region dynamics under severe terrestrial and space weather conditions.

Acknowledgments
The authors are thankful to the Faculty Research Committee for the financial support (grant 6C464-1351) to carry out this research. The author (A.E.C.) is thankful to Abhikesh Kumar of School of Engineering and Physics for his suggestions related with data analysis. The author (A.E.C.) is thankful to the Research Office of the University of the South Pacific for providing financial support to present a part of this work in the 2016 Asia-Pacific Radio Science Conference, Seoul, Korea, 21–25 August 2016. The data were recorded at our station and are available from the corresponding author.

References

Araki, T. (1973), Anomalous diurnal changes of trans-equatorial VLF radio waves, *J. Atmos. Terr. Phys.*, *35*, 693–703, doi:10.1016/0021-9169(73)90200-6.

Beer, T. O. M. (1973), Supersonic generation of atmospheric waves, *Nature*, *242*(5392), 34–34.

Budden, K. G. (1961), *The Waveguide Mode Theory of Wave Propagation*, Prentice Hall, Englewood, Cliffs, N. J.

Chand, A. E., and S. Kumar (2016), VLF modal interference distance for a west-east propagation path to Fiji, in *IEEE Explore Proceedings of URSI Asia-Pacific Radio Science Conference*, 1606–1609, Electronic, Seoul, Korea, doi:10.1109/URSIAP-RASC.2016.7601184.

Clilverd, M. A., N. R. Thomson, and C. J. Rodger (1999), Sunrise effects on VLF signals propagating over a long north-south path, *Radio Sci.*, *34*(4), 939–948, doi:10.1029/1999RS900052.

Cowling, D. H., H. D. Webb, and C. K. Yeh (1971), Group rays of internal gravity waves in a wind-stratified atmosphere, *J. Geophys. Res.*, *76*, 200–213, doi:10.1029/JA076i001p00213.

Crombie, D. D. (1958), Differences between the east-west and west-east propagation of VLF signals over long distances, *J. Atmos. Terr. Phys.*, *12*(2–3), 110–117, doi:10.1016/0021-9169(58)90081-3.

Crombie, D. D. (1964), Periodic fading of VLF signals received over long paths during sunrise and sunset, *Radio Sci.*, *68D*(1), 27–34.
Crombie, D. D. (1966), Further observations of sunrise and sunset fading of very-low-frequency signals, *Radio Sci.*, *1*(1), 47–51, doi:10.1002/rds19661147.
Cummer, S. A., U. S. Inan, and T. F. Bell (1998), Ionospheric *D* region remote sensing using VLF radio atmospherics, *Radio Sci.*, *33*(6), 1781–1792, doi:10.1029/98RS02381.
Forbes, J. M., S. L. Bruinsma, Y. Miyoshi, and H. Fujiwara (2008), A solar terminator wave in thermosphere neutral densities measured by the CHAMP satellite, *Geophys. Res. Lett.*, *35*, L14802, doi:10.1029/2008GL034075.
Friedrich, M., and M. Rapp (2009), News from the lower ionosphere: A review of recent developments, *Surv. Geophys.*, *30*, 525–559.
Galushko, V. G., V. V. Paznukhov, Y. M. Yampolski, and J. C. Foster (1998), Incoherent scatter radar observations of the AGW/TID events generated by the moving solar terminator, *Ann. Geophys.*, *16*, 821–827.
Han, F., and S. A. Cummer (2010), Midlatitude nighttime *D* region ionosphere variability on hourly to monthly time scales, *J. Geophys. Res.*, *115*, A09323, doi:10.1029/2010JA015437.
Hargreaves, J. K. (1992), The solar-terrestrial environment, Cambridge Atmospheric And Space Science Series, Cambridge Univ. Press, pp. 249–263.
Inan, U. S., J. V. Rodriguez, and V. P. Idone (1993), VLF signatures of lightning-induced heating and ionization of the nighttime *D* region, *Geophys. Res. Lett.*, *20*(21), 2355–2358, doi:10.1029/93GL02620.
Kikuchi, T. (1983), Anomalous diurnal phase shifts of Omega VLF waves (10–14 kHz) on the east-west low-latitude and transequatorial paths, *J. Atmos. Terr. Phys.*, *45*(11), 743–751.
Kumar, S. (2009), Waveguide parameters of 19.8 kHz signal propagating over a long path, *Res. Lett. Phys.*, doi:10.1155/2009/216373.
Kumar, A., and S. Kumar (2014), Space weather effects on the low latitude *D*-region ionosphere during solar minimum, *Earth Planets Space*, *66*, 76, doi:10.1186/1880-5981-66-76.
Lynn, K. J. W. (1967), Anomalous sunrise effects observed on a long transequatorial VLF propagation path, *Radio Sci.*, *2*(6), 521–530, doi:10.1002/rds196726521.
Lynn, K. J. W. (1977), VLF modal interference over west-east paths, *J. Atmos. Terr. Phys.*, *39*(3), 347–357, doi:10.1016/S0021-9169(77)90149-0.
Maurya, A. K., B. Veenadhari, R. Singh, S. Kumar, M. B. Cohen, R. Selvakumaran, S. Gokani, P. Pant, A. K. Singh, and U. S. Inan (2012), Nighttime *D* region electron density measurements from ELF-VLF tweek radio atmospherics recorded at low latitudes, *J. Geophys. Res.*, *117*, A11308, doi:10.1029/2012JA017876.
Meara, L. A. (1973), VLF modal interference effects observed on transequatorial paths, *J. Atmos. Terr. Phys.*, *35*(2), 305–315, doi:10.1016/0021-9169(73)90096-2.
Miyoshi, Y., H. Fujiwara, J. M. Forbes, and S. L. Bruinsma (2009), Solar terminator wave and its relation to the atmospheric tide, *J. Geophys. Res.*, *114*, A07303, doi:10.1029/2009JA014110.
Muraoka, Y. (1982), A new approach to mode conversion effects observed in a mid-latitude VLF transmission, *J. Atmos. Terr. Phys.*, *44*(10), 855–862, doi:10.1016/0021-9169(82)90038-1.
Pierce, J. A. (1955), The diurnal carrier-phase variation of a 16-kilocycle transatlantic signal, *Proc. IRE*, *43*(5), 584–588, doi:10.1109/JRPROC.1955.278102.
Raulin, J.-P., A. A. Pacini, P. Kaufmann, E. Correia, and M. A. G. Martinez (2006), On the detectability of solar X-ray flares using very low frequency sudden phase anomalies, *J. Atmos. Sol. Terr. Phys.*, *68*, 1029–1035, doi:10.1016/j.jastp.
Raitt, W. J., and D. H. Clark (1973), Wave-like disturbances in the ionosphere, *Nature*, *243*, 508–509, doi:10.1038/243508a0.
Raulin, J., and J. Samanes (2011), Characteristics of nighttime west-to-east VLF waves propagation using the South America VLF Network (SAVNET), paper presented at General Assembly and Scientific Symposium, 2011 XXXth URSI, 13–20 Aug.
Samanes, J. E., J.-P. Raulin, E. L. Macotela, and W. R. Guevara Day (2015), Estimating the VLF modal interference distance using the South America VLF Network (SAVNET), *Radio Sci.*, *50*, 122–129, doi:10.1002/2014RS005582.
Samanes, J., J. Raulin, and C. Jinbin (2016), *Estimation of the nighttime height of the lower ionosphere using VLF waves propagation*, IEEE, URSI Asia-Pacific Radio Science Conference Proceedings, 1310–1312, doi:10.1109/URSIAP-RASC.2016.7601185.
Schunk, R. W., and A. F. Nagy (2000), *Ionospheres: Physics, Plasma Physics and Chemistry*, Cambridge Univ. Press, Cambridge, U. K.
Tan, L. M., N. N. Thu, T. Q. Ha, and Q. N. Luong (2015), Seasonal variations of nighttime D-region ionosphere in 2013 solar maximum observed from a low-latitude station, *Earth Planets Space*, *67*, 163–174, doi:10.1186/s40623-015-0331-y.
Thomson, N. R., and W. M. McRae (2009), Nighttime ionospheric *D* region: Equatorial and nonequatorial, *J. Geophys. Res.*, *114*, A08305, doi:10.1029/2008JA014001.
Thomson, N. R., C. J. Rodger, and M. A. Clilverd (2005), Large solar flares and their ionospheric *D* region enhancements, *J. Geophys. Res.*, *110*, A06306, doi:10.1029/2005JA011008.
Wait, J. R. (1962), *Electromagnetic Waves in Stratified Media*, Pergamon, Tarrytown, N. Y.
Wait, J. R., and K. P. Spies (1964), Characteristics of the Earth-ionosphere waveguide for VLF radio waves, Tech. Note 300, Natl. Bur. of Stand., Boulder, Colo.
Walker, D. (1965), Phase steps and amplitude fading of VLF signals at dawn and dusk, *Radio Sci.*, *69D*(11), 1435–1443.
Yeh, K. C., and C. H. Liu (1974), Acoustic-gravity waves in the upper atmosphere, *Rev. Geophys. Space Phys.*, *12*, 193–216.

Erratum

In the originally published version of this article, "hN" appeared erroneously in the Y axis of Figure 6 (a, b). This has since been corrected and this can now be considered the version of record.