VLF modal interference distance for a west-east propagation path to Fiji

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***Abstract*— Pronounced amplitude minima are observed on 19.8 kHz signal recorded at Suva (18.149°S, 178.446°E), Fiji, from a VLF navigational transmitter located in North West Cape (NWC), Australia. The propagation path is mixed over land and sea having Transmitter-Receiver Great Circle Path distance 6.7 Mm. In this paper the modal interference distance (D_{MS}) for west-east propagation path (NWC-Suva) has been estimated using Terminator Time method which is based on the measure and analysis of the occurrence times of amplitude minima. The experimental values of D_{MS} were found to be consistent with the theoretical values calculated using the mode theory of VLF wave propagation in the Earth-ionosphere waveguide.**

Keywords—modal interference distance; earth-ionosphere waveguide; terminator time; amplitude minima.

I. 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 D-region of the ionosphere. The D-region is far too high for balloons to probe and too low for satellite measurements but can be diagnosed using VLF narrowband signals, therefore, remains least studied region of the ionosphere and requires continued research [1].

The daily VLF amplitude and phase curves show typical features as periodic minima due to modal interference observed during sunrise and sunset transitions on long distance VLF propagation paths [2] having east-west component of propagation.The diurnal VLF phase variations were first observed by *Pierce* [3] and *Crombie* [4], and their results showed that the phase advanced during sunrise with pronounced steps coincident with amplitude minima. *Budden* [5] and *Wait* [6] first reported the diurnal phase and amplitude variation both during sunrise and sunset transitions. *Crombie* [7] studied the sunrise/sunset effect on west-east VLF propagation path and proposed a model by assuming two modes (first- and second-order) being present in the night-time portion of the path and only one mode in the daytime portion of path in the EIWG. The results for this particular study provided strong evidence that at the sunrise terminator (day/night boundary), a significant mode conversion is assumed to occur (night-time second-order mode converted into daytime first-order mode). For the sunset effect, *Crombie* assumed mode conversion of daytime first-order mode into night-time first and second-order modes which may subsequently interfere with each other in the night-time portion of path. *Walker* [8] verified the ionosphere model put forward by *Crombie* [4] using NBA transmitter (18 kHz) signal and proposed that all points on the dayside of the dawn discontinuity experienced signal minimum simultaneously.

Clilverd et al. [9] presented a detailed study on the presence 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 [10] first reported an equatorial anomaly associated with sunrise transition fading from the examination of one year's phase and amplitude records of transmitter NLK at Smithfield, South Australia. *Lynn* [10] and *Meara* [11] estimated anomalous value of the modal interference distance (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* [10] for sunrise transition fading is approximately 2000 km for the terminator located in mid-latitudes, that is, in excess of ± 20° from the geomagnetic equator. *Lynn* [10] concluded from his observations that the change in D_{MS} resulted from a change in the difference of phase velocity of two modes as well as 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* [6]. Later, *Lynn* [12] investigated the frequency and latitude dependence of sunrise modal interference observed over long west-east propagation path and reported that the phase and amplitude anomalies are not associated with transequatorial propagation over west-east propagation path and D_{MS} values for east-west propagation at middle latitudes are slightly higher than those for west-east propagation.

Kumar [13] estimated 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, Raulin, Macotela and Guevara Day* [2] 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.

II. Instrumentation and Data

Experimental set-up consists of a short (1.5 m) whip antenna, pre-amplifier, VLF service unit (SU) coupled with pre-amplifier, and Software based Phase and Amplitude Logger termed as "SoftPAL". The whip antenna receives the vertical electric field component of transverse magnetic (TM) mode of the VLF propagation. SoftPAL is a state of art data acquisition system 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 signals are recorded at a time resolution of 0.1s (*i.e.* sampling frequency of 10 Hz) and are run continuously using Chart for Windows software. Transmitter Receiver Great Circle Path (TRGCP) for NWC-Suva path is 6.696 Mm. The continuous operation is chosen to monitor the diurnal variation in the signal strength and to study night and daytime VLF perturbation. To estimate the D_{MS} more accurately, mean value of D_{MS}, temporal and seasonal variability of D_{MS}, we have analyzed the TTs for NWC transmitter signal propagation for two (2013 and 2014) years.

III. Results

We have used almost 2 years of the monitoring of sunset (SS) and sunrise (SR) TT_s at Suva for 19.8 kHz transmission from NWC to determine mean D_{MS}. TT is a time when the terminator line crosses given locations along the propagation path creating amplitude minima at the receiver [2]. It is also defined as the time of amplitude minimum that coincides very well with the time of maximum rate of phase change [14]. A sample record of NWC signal amplitude and phase recorded on 10th May 2014 is shown in Fig.1. For this path three minima each during sunset (SS_1,SS_2,SS_3) and sunrise (SR_1,SR_2,SR_3) TT_s were observed.

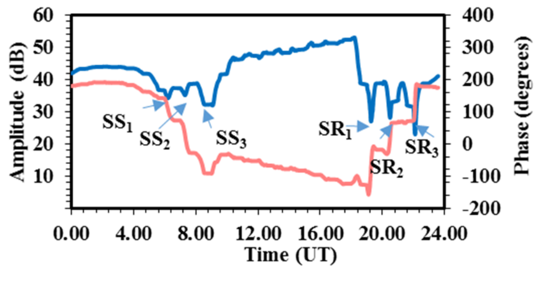

Fig 1. Typical variation of amplitude and phase of NWC signal at Suva on 10th May 2014.

The daily variation of TTs is shown in Fig 2. It can be seen from this figure that SR TT repeat themselves with good regularity thus the TT shown do present a clear seasonal variation which repeat itself every year [15]. However, there is a slight variation in the SS TT as compared to SR TT. It can be noted that SS_1 and SR_1 occur when the sunset terminator is closer to the transmitter (furthest from the equator) and SS_3 and SR_3 occur when the terminator is closer to the receiver (closest to equator).

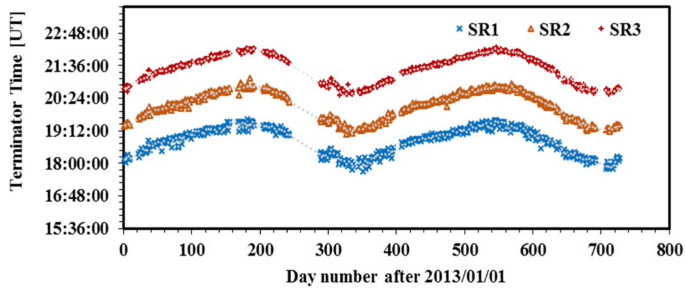

Fig 2. Sunrise Terminator Times (in UT) measured from the daily amplitude curves for NWC – Suva VLF propagation path.

The D_{MS} was calculated using this relation "$D_{MS} = V_T \times \Delta t$" where V_T is the velocity (km/min) of the terminator line and Δt is the time (min) difference between two successive TTs (for example, "$\Delta t = [SR_k - SR_i]$") [2]. SR TTs occur at specific locations along the night part of the VLF propagation path where destructive interference of the first and second order modes takes place [15].Thus we can compute these times to find the distance between the transmitter and the position of the terminator line that will pass at these specific locations. This has been done for first SR TT (SR_1) as shown in Fig 3 by blue color points with mean values shown by dashed black line. The values are consistent over both the years (2013-2014).

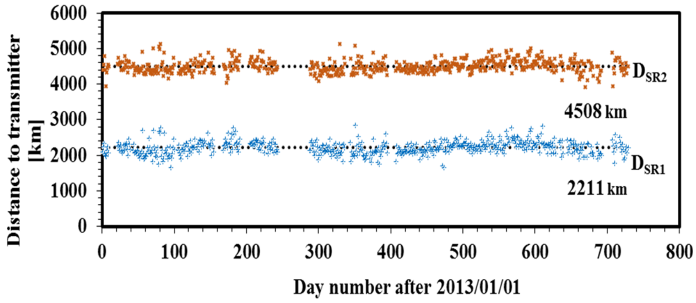

Fig 3. Interference distances from the transmitter location at NWC to the points on the great circle path where periodic amplitude sunrise terminator times are observed.

Fig 3 shows the distances, D_{SRi}, to the receiver Suva that correspond to the SR_i observed using the NWC – Suva propagation path as a function of day number. Therefore, D_{SRi} correspond to the distance between the NWC transmitter and the position of the terminator line at the SR_i. At a distance of 4508 km from the receiving site (Suva), that is close to the NWC transmitter, nighttime modes 1 and 2 interfere destructively producing daily deep minima that were observed at the particular times. The important point from Fig 3 is that the consistency of interference distance 2211 km (using SR_2 and SR_1) and 4508/2 (2254 km) (using SR_3 and SR_2) between locations where TTs are observed.

The main results of this study are shown in Table 1.0, where we have listed the estimated D_{MS} values. Here we use the notation "$D_{SR_{ki}} = V_T[SR_k - SR_i]$" in order to distinguish between each distance obtained from two successive amplitude minima, for example, "$D_{SR_{21}} = V_T[SR_2 - SR_1]$", "$D_{SR_{32}} = V_T[SR_3 - SR_2]$" and so on. $D_{SR\overline{31}}$ is the D_{MS} calculated by taking the average time between 3 successive minima, for example, "$D_{SR_{\overline{31}}} = V_T\,[SR_3 - SR_1]/2$". We note in Table I, that for the NWC – Suva path the distances calculated from the SR TT are very similar with each other.

TABLE I. Mean Value of the VLF Modal Interference Distance (D_{MS})

	D_{SS21} (km)	D_{SS32} (km)	$D_{SS\overline{31}}$ (km)	D_{SR21} (km)	D_{SR32} (km)	$D_{SR\overline{31}}$ (km)
Mean Value	2218	2204	2255	2209	2303	2249
Standard Deviation	220	251	241	191	186	115

[a]Mean value of the Modal Interference Distance was estimated using the measure and analysis of the occurrence times of the sunrise and sunset terminator time of the NWC signal.[b]

IV. DISCUSSION

The D_{MS} for a VLF propagation path using 19.8 kHz NWC VLF transmitter signal was estimated using TTs for the years 2013 and 2014 to calculate the average and more accurate D_{MS} value for NWC-Suva path which is mostly in west-east direction. Both SR and SS pronounced amplitude minima were used for the analysis. The generation of successive amplitude minima at the receiver during SR and SS transitions is due to the destructive interference or superposition of propagating modes [9]. The mean experimental value of D_{MS} was estimated as 2239 ± 201 km which agrees reasonably well with the theoretical values calculated using the equation given by *Crombie* [16] "$D_{MS} = 4h^2/\lambda_0$," where h is the VLF reflection height and λ_0 is free space wavelength of VLF transmitter signal. For NWC signal at 19.8 kHz for "h = 90 km," D_{MS} come out to be 2,140 km which is within 5% of D_{MS} obtained from Fig 3.

We compared the D_{MS} calculated in this paper with that obtained by *Lynn* [12] who analyzed 29 days of data for west-east transequatorial VLF propagation path between the transmitter NSS (at 21.4 kHz, USA) and the receiver station, TAA (Madagascar).Using six amplitude minima *Lynn* [12] obtained a mean value of D_{MS} equal to 2207 ± 202 km, which agrees reasonably well with our mean value given in Table 1. *Kumar* [13] using the phase and amplitude measurement of 19.8 kHz signal from NWC transmitter signal recorded at Suva, on 10th December 2006 estimated the value of D_{MS} as 2150 km which is consistent with our results.

Recently, *Samanes, Raulin, Macotela and Guevara Day* [2] analyzed a long-term database of almost 5 years from three different VLF propagation paths (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, 2170 ± 50 km, respectively. Their values of D_{MS} are in good agreement with our mean value of D_{MS} , 2239 ± 201 km.The values of D_{MS} estimated here both theoretically and experimentally are consistent with the results obtained by *Crombie* [16].We have compared our values of D_{MS} with the values obtained by other methods which are in good agreement, thus we recommend estimation of D_{MS} by TT method.

V. CONCLUSION

In this paper, we have estimated the D_{MS} based on the measurement of the occurrence times of pronounced amplitude minima observed during 19.8 kHz (NWC) subionospheric VLF propagation during sunrise and sunset transition hours. Our result of mean "D_{MS} = 2239 ± 201 km" using two years of data is consistent with theoretical estimation by 4.42% and have shown a good agreement with the value estimated by other methods by several researchers. Further, analysis of D_{MS} for east-west path is in progress which in conjunction with this study will appear in separate communication.

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