# Daytime modelling of VLF radio waves over land and sea, comparison with data from DEMETER Satellite

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**Abstract**. Very Low Frequency (VLF) radio waves propagate with little attenuation within the Earth-ionosphere waveguide. Perturbations of the lower ionosphere produce a modification of the geometry of the waveguide, resulting in a disruption of the VLF propagation conditions. A model based on the Wait's mode theory is developed to investigate temporal and spatial changes in ionospheric conditions. As VLF waves propagating from a transmitter reflect off the lower ionosphere, a portion of the energy leaks up into space leaving a 'fingerprint' of the modal structure of the fields at the reflection height. Simulations are compared to averaged data taken over a year from the DEMETER satellite over the NWC transmitter in North-West Australia to test the validity of the model.

## 1. Introduction

VLF radio waves can be used as an extremely useful probe of the lower ionosphere since it is at too low an altitude for direct satellite observation and too high for balloons. Rocket borne instruments can provide excellent information, but this is a once off, localised and expensive method of gathering information. Around the world there exist a number of narrowband VLF transmitters which serve as excellent scientific tools to study radio wave propagation. As the radio waves travel vast distances while suffering little attenuation, the signal observed at a receiver allows investigation of the properties of the waveguide along the propagation path.

For VLF waves, the D- and E-regions of the ionosphere are of interest. The D-region exists only during the day at an altitude of around 70km and arises mostly due to Lyman-α radiation from the Sun ionising NO. The E-region is the lowest region during the night and starts around 85-90km [1,2]. Electromagnetic wave propagation in a waveguide can be explained in terms of waveguide modes that occur when reflections of the waves off the boundaries of the waveguide interfere with each other. The solar influence on the ionosphere has a diurnal and seasonal dependence resulting in the waveguide height, and modal interference pattern, also having similar periodic variance.

## 2. Method

The approach used in these simulations is based on Wait's mode theory description of waveguide propagation and uses Wait's ionospheric parameters, height (H' in km) and sharpness ($\beta$ in $km^{-1}$) [3,4]. The model makes certain assumptions and approximations such as flat Earth, constant propagation conditions along path and treats transmitters as vertical electric dipoles. Input parameters include ionospheric (H', $\beta$), ground (surface conductivity and dielectric constant, $\sigma_g$ and $\varepsilon_g$), ambient magnetic field strength and direction (**$B_0$**), electron-neutral collision frequency ($\nu$) and wave frequency (*f*), bearing and maximum number of modes ($n_{max}$). The electron density profile ($N_e$) depends only on height, and is calculated using Wait's parameters as,

$$N_e(z)=1.43\times10^{13}exp[-0.15H'+(\beta-0.15)(z-H')]m^{-3}. \quad (1)$$

The other important height dependent quantity is the electron neutral collision frequency, which takes the form:

$$\nu(z)=1.816\times10^{11}exp[-0.15z]s^{-1}. \quad (2)$$

The electron density is used to determine the plasma frequency ($\omega_p$) while the ambient magnetic field is used to calculate the electron gyro-frequency ($\omega_B$). These two frequencies, along with the electron-neutral collision frequency represent the three fundamental parameters used in the Appleton-Hartree equation for a cold magnetised plasma. These parameters are used to find the height at which the VLF waves are reflected as well as the refractive index for the frequency in question at the reflection height.

At high altitudes (> 100 km), the effect from electron-neutral collisions is stronger than the Debye shielding effect produced by the electron density. As altitude decreases, the electron-neutral collisions become less dominant and the plasma frequency increases. At a certain height the Debye shielding caused by the applied electric field on the plasma becomes strong enough that the electron-neutral collisions no longer suppress the shielding effect which now blocks the waves from propagating further. This height is then taken as the reflection height, or upper boundary of the waveguide. Initially assuming that the ionosphere has a reflection coefficient of -1, the first $n_{max}$ eigenangles are calculated. These angles along with the ambient magnetic field direction and bearing of the wave are then used to calculate the angle between the magnetic field and each mode of propagation which is needed to find the complex refractive index that the wave will experience when reflecting off the ionosphere. Recalculation of the eigenangles is then done using the complex refractive index and the initial angles in a perturbative method. The eigenangles essentially contain all necessary information to calculate the electric fields at any distance from the transmitter. An additional height variability function, $f_n$, allows for the calculation of the fields at any height in the waveguide. The electric fields can then be calculated at any point along a path at any height in the waveguide with the use of a zero-order Hankel function of 2nd kind and the height function [3].

$$E_z(\rho,z)=\frac{\mu\,\omega\,Ids}{2h}\sum_{n=1}^{n=n_{max}}sin^2\theta_n H_0^{(2)}(ksin\theta_n\rho)f_n(z) \quad (3)$$

## 3. Data and Results

Even though the bulk of the VLF energy remains in the waveguide, a portion of it does leak up into space and should allow satellites with radio receivers to observe the modal interference pattern around a transmitter. To test the validity of this model, simulation results are compared to satellite data from the DEMETER satellite which is in a sun-synchronous orbit and always passes over a given location at a fixed local time. Figure 1 shows the observed modal interference pattern observed while passing over the NWC transmitter in Australia which operates at 19.8 kHz.

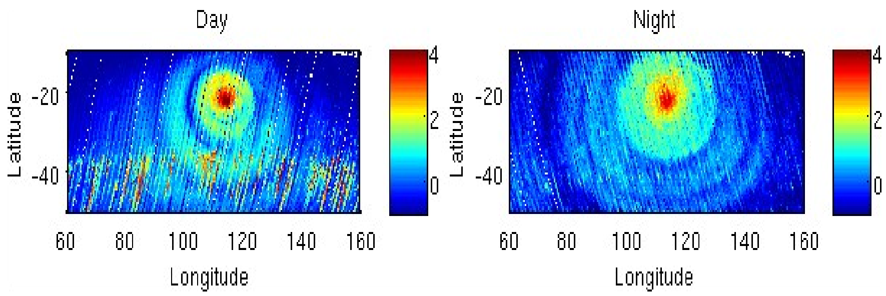


Figure 1: Averaged data over the year 2005 for day (10:30 LT) and night (22:30 LT). Each row and column correspond to 0.5° latitude and longitude respectively.

For convenience sake, to compare data to simulation results, horizontal sections three rows wide were extracted from the data ranging just over 5000km long. Three rows were taken to minimise the effects of missing data points and to create a smoother curve. One advantage of using the NWC transmitter is that it is on the North-West coast of Australia meaning that westward propagation is sea only and eastward is almost entirely land, making it appropriate for comparison with this model which does not take mode conversion into account at the interface of different waveguide slabs.

The height of the ionosphere has a seasonal dependence and changes throughout the year. This means that the observed data cannot be explained very well in terms of one waveguide height, but rather the average of a few heights. Figure 2 shows the variation between night and day as well as eastward versus westward propagation. Eastward propagation tends to show lower field strengths than westward which is expected as this is over land which is a far poorer conductor than sea water. The modal pattern is quite clear for the daytime propagation whereas the night time data does not show such a clear pattern. This can be attributed to the higher waveguide height during darkness that leads to a modal interference pattern which is less well defined. Due to the lower attenuation at night, there will be more of a contribution from higher order modes that would also reduce the clarity of the modal structure. For this reason, only comparison with daytime data will be made.

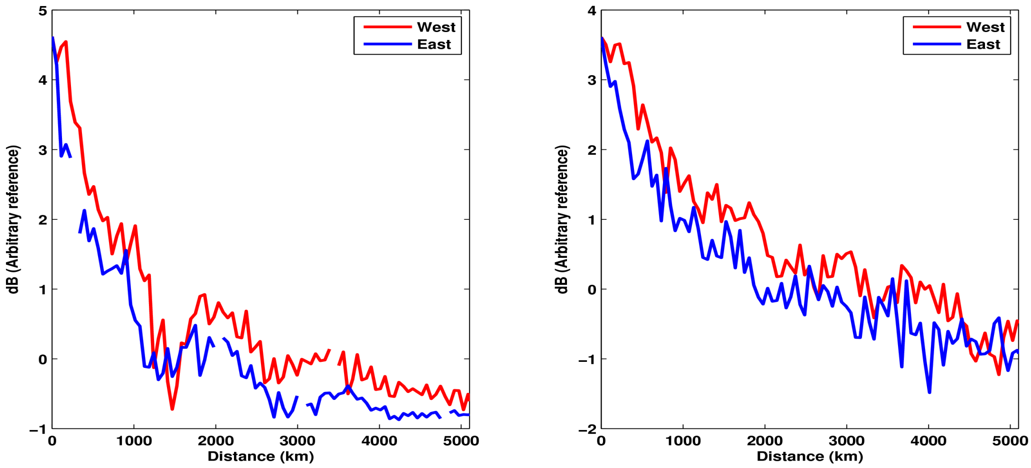


Figure 2: Observed field strength for west- and eastward propagation from NWC transmitter.

To find the best comparison between data and simulation, a minimisation of the error between the two was performed. Bearing in mind the model is working on certain assumptions, the minimisation was performed within a certain region that excluded the area close (< 1017 km) to the transmitter and the area past a certain point (> 4068 km). The first region was excluded from the comparison since in this region the ground wave and evanescent modes can contribute to the field which are not included in the simulation. As for the far field region, this was excluded due to the flat Earth approximation which is good at short and intermediate distances but can become inaccurate at distances that are close to the radius of the Earth.

The minimisation process was done using the MATLAB optimisation toolbox and by searching for different ionospheric heights and a global adjustment or gain that was added to appropriately compare data and simulation results. Various values of $\beta$ were tested manually, the value that gave the best results with a sets of 3, 4, 5 and 6 heights was selected and had a value of 0.35 $km^{-1}$, falling between normal day time summer and winter values. Up to 9 heights were used but it was seen that using 4 or 5 heights was sufficient if looking at propagation in one direction only and adding more values only increased the time taken to run the minimisation process with no improvement in error. When looking to minimise the average error for the two directions, it was found that more heights were needed to deliver satisfactory results. Figure 3 shows the results when a single set of values was used for both directions and the average error in the region of interest was minimised.

It should be noted that another factor that can play a significant role is the conductivity of the surface of the lower boundary of the waveguide. For westward propagation over water, the conductivity was taken to be 4 S/m [5], and the ground was given the value of $4.5 \times 10^{-3}$ S/m for the eastward propagation. Ground conductivities of dry land are generally between $10^{-2}$ S/m and $10^{-4}$ S/m and have been reported to be around $10^{-3}$ S/m in this area [6]. With the use of this value in the simulation, the results did not fit the data well so it was adjusted to the slightly higher value of $4.5 \times 10^{-3}$ S/m.

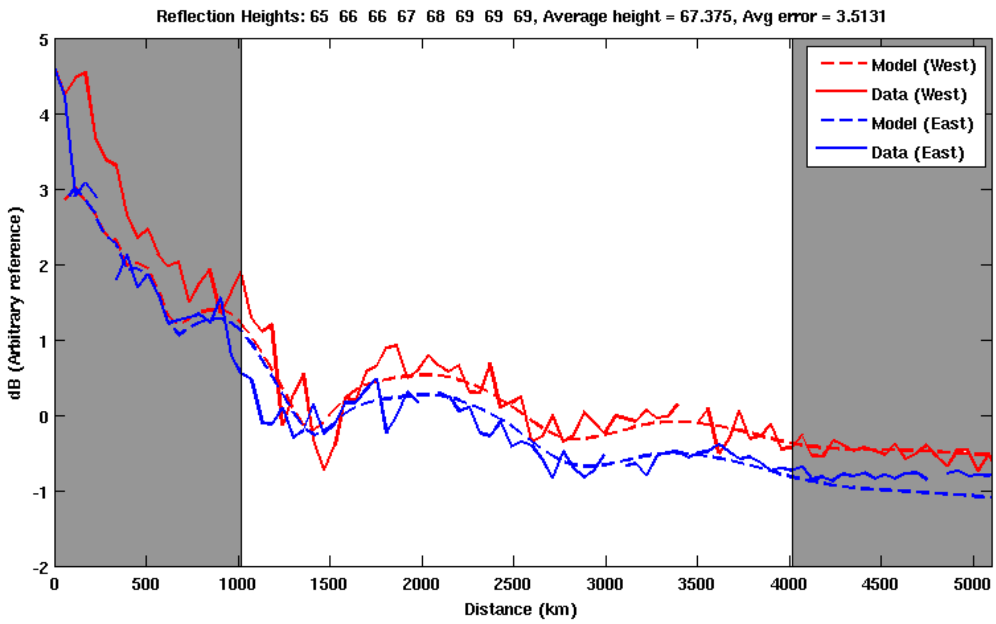


Figure 3: Comparison of simulated results with data. One set of heights used for both directions.

## 4. Conclusion and Discussion

The average height of the reflection layer around NWC is found to be around 68 km with heights ranging from 65 km to 69 km for summer and winter respectively. These are reasonable results but are somewhat lower than the results published in a study done in 2009 that reported heights of 70 km and 72 km around NWC [5]. This disagreement could be due to the fact that the method of calculating the reflection height and the use of Wait's parameters differs to the methods used here. There is definite space for future improvement to the model which could further increase its validity.

## References


1. N.R. Thomson and W.M. McRae (2009), Nighttime ionospheric D region: Equatorial and nonequatorial, *J. Geophys Res.,* Vol.114*,* A08305, doi:10.1029/2008JA014001.

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

3. J.R. Wait, *Electromagnetic Waves in Stratified media,* Pergamon Press, 1962.

4. J.R. Wait and K.P. Spies, Characteristics of the Earth-ionosphere waveguide for VLF radio waves, *National Bureau of Standards, Technical Note 300*, 30 December 1964.

5. N.R. Thomson (2010), Daytime tropical D region parameters from short path VLF phase and amplitude, *J. Geophys Res.,* Vol.115*,* A09313, doi:10.1029/2010JA015355.

6. N.R. Thomson (1993), Experimental daytime VLF ionospheric parameters, *J. Atmos and Terr Phys,*Vol.55, No 2, pages 173 – 184, doi:10.1016/0021-9169(93)90122-F.