Exploiting LF/MF signals of opportunity for lower ionospheric remote sensing

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Abstract We introduce a method to diagnose and track the D region ionosphere (60–100 km). This region is important for long-distance terrestrial communication and is impacted by a variety of geophysical phenomena, but it is traditionally very difficult to detect. Modern remote sensing methods used to study the D region are predominately near the very low frequency (VLF, 3–30 kHz) band, with some work also done in the high-frequency and very high frequency bands (HF/VHF, 3–300 MHz). However, the frequency band between VLF and HF has been largely ignored as a diagnostic tool for the ionosphere. In this paper, we evaluate the use of 300 kHz radio reflections as a diagnostic tool for characterizing the D region of the ionosphere. We present radio receiver data, analyze diurnal trends in the signal from these transmitters, and identify ionospheric disturbances impacting LF/MF propagation. We find that 300 kHz remote sensing may allow a unique method for D region diagnostics compared to both the VLF and HF/VHF frequency bands, due to a more direct ionospheric reflection coefficient calculation method with high temporal resolution without the use of forward modeling.

1. Introduction

The D region of the ionosphere, which ranges from about 60–100 km, is too high for continuous in situ measurements, such as with high-altitude balloons, and too low for satellite-based measurements. Some direct D region diagnostics have been made, including rocket-based measurements, partial reflection technique, and incoherent scatter radar (ISR). In rocket-based measurements [e.g., Seddon, 1953; Bennett et al., 1972], the Faraday rotation of a signal that propagates upward or downward through the D region is measured. The partial reflection technique relies on backscatter of waves in the 1–6 MHz range to measure the ratio of the transmitted and reflected power and therefore determine the reflection coefficients of the D region ionosphere [e.g., Belrose, 1970; Hocking and Vincent, 1982]. Incoherent scattering radar (ISR) technique utilizes a high-powered pulsed radio wave transmitted vertically upward and the received weak backscatter to characterize the change in refractive index of the ionosphere [e.g., Sechrist, 1974; Mathews, 1984]. These methods have a common problem: they are spatial point measurements and, because of the weak reflections, require long time integration to characterize the D region.

Utilization of very low frequency (VLF, 3–30 kHz) radio waves has proven to be more useful for global, continuous D region diagnostics. A ground-based radio receiver detects a signal from some distant source. Propagation in the “Earth-ionosphere waveguide” allows signals to efficiently reach global distances [Wait and Murphy, 1956]. Changes in the signal with time are known to correspond to changes in the ionospheric conditions [Barr et al., 2000; Inan et al., 2010]. There are two chief sources of these signals: (1) one of a few dozen VLF transmitters typically operated by a navy for submarine communication [McRae and Thomson, 2000; Thomson et al., 2007] or (2) the broadband radio atmospheric, or sferic, originating from lightning [e.g., Burton and Boardman, 1933; Cummer et al., 1998].

However, while the relatively low attenuation over very long distances makes VLF remote sensing useful on a large spatial scale, it also means the receiver signal is inherently “multimode,” which makes inferring characteristics of the ionosphere difficult if using only experimental observations. The current method to connect VLF observations to ionospheric parameters is to utilize a forward modeling approach in which a propagation model is tweaked so that predictions match observations. This leads to a fundamental uncertainty and ambiguity and constrains VLF remote sensing from becoming a quantitative D region measurement the way GPS TEC measurements are for the F region. Recent work has utilized miniarrays to analyze multipath
propagation of low-frequency radio waves and map VLF lightning observations to provide a $D$ region diagnostic [e.g., Füllekrug et al., 2015a, 2015b, 2016].

Ideally, we would like a remote sensing technique that allows direct ionospheric observation without the use of forward modeling, such as the partial reflection approach, while still being applied with high time resolution and over long distances, such as VLF remote sensing. In this paper, we propose a method of $D$ region remote sensing that may achieve this by utilizing the gap between the HF and VLF bands. We utilize signals of opportunity from the Nationwide Differential Global Position System (NDGPS) network, a collection of beacons which transmit ionospheric correction factors on frequencies between 285 and 325 kHz. Waves in the LF/MF range are known to reflect off the ionosphere and travel in the Earth-ionosphere waveguide, like VLF waves, but with much less efficiency; thus, only a small number of modes reach medium to long distances [Belrose et al., 1959]. On the other hand, LF/MF waves reflect efficiently enough to be detected thousands of kilometers away from the source, at least if a sufficiently sensitive receiver is used, allowing large ionospheric regions to nonetheless be observed. Research in the twentieth century has exploited this phenomena to yield an abundance of publications [e.g., Sprenger et al., 1962; Huxley and Ratcliffe, 1949]. In this sense, LF/MF remote sensing is advantageous for ionospheric remote sensing.

In this paper, we show preliminary observations from LF/MF beacons detected up to 2400 km away, analyze diurnal trends, identify ionospheric disturbances, utilize theoretical modeling, and then discuss the advantages and disadvantages of this method. Our results indicate that utilization of 300 kHz radio reflections from the ionosphere may provide the high temporal resolution of VLF remote sensing, while also providing a more direct measurement method such as what HF/VHF methods provide.

2. Description of Data
2.1. NDGPS Transmitter Configuration
The United States Coast Guard (USCG) operates the Nationwide Differential Global Position System (NDGPS). As of August 2016, the network consists of 46 sites which broadcast the difference between a known, fixed location and the received GPS coordinates to improve the accuracy of commercial GPS to centimeter accuracy. The current coverage and site locations of NDGPS can be found on the United States Coast Guard website [United States Government, 2016b]. The data used in this paper were collected prior to August 2016 when there were 84 operational NDGPS sites [United States Government, 2016a]. These sites transmit correction values on beacon frequencies between 285 and 325 kHz using four different antenna types and are geographically clustered along the coast and major waterways [Wolfe et al., 2000].

2.2. Radio Receiver
We have designed and developed an upgraded version of the Stanford University VLF AWESOME Receiver [Cohen et al., 2010]. The updated receiver, called the LF AWESOME Receiver, consists of two orthogonal air-core loop antennas and has a sampling rate of 1 MHz, giving a band pass of approximately $0.5 - 480$ kHz, sensitivity up to $0.03 \text{ fT/} \sqrt{\text{Hz}}$ at 30 kHz and $0.1 \text{ fT/} \sqrt{\text{Hz}}$ at 300 kHz, and RMS timing accuracy of $15 - 20 \text{ ns}$ for the RMS accuracy of all the timing pulses that make up the 1 MHz clock (implying precise phase estimation of $< 1.5^\circ$ at 300 kHz); there is no frequency drift/offset in the clock detectable with 0.5 ppb resolution. In order to fully take advantage of the receiver sensitivity, the receiver must be in an electromagnetically quiet location. The data collected for this paper came from three of these sites located at the Pisgah Astronomical Research Institute (PARI) in Rosman (North Carolina), Baxley (Georgia), and Juneau (Alaska). The key distinguishing feature of the receiver is its high sensitivity, which enables even weak LF/MF signals to be detected at long range.

3. LF/MF Propagation in the Earth-Ionosphere Waveguide
The Earth-ionosphere waveguide, as previously discussed, is bounded by the Earth on the bottom and the ionosphere, a dispersive and anisotropic medium, on the top. The ground wave propagates along the surface of the Earth, guided by diffraction along the curvature of the Earth. The sky waves reflect off the ionosphere and the Earth one or more times. Due to higher attenuation rates, LF/MF propagation may support only a small number of rays reaching the receiver implying that unlike VLF propagation, it may be possible to experimentally decompose a signal into its underlying components and therefore directly infer the ionospheric characteristics. Experimental evidence to confirm this picture is shown in the next sections. In addition, the reflection of LF/MF signals is probably not at the same altitude as $20$ kHz VLF signals. The reflection is thought to occur roughly at the altitude where $\omega = \omega_p^2 / \nu$, where $\omega$ is the wave frequency, $\omega_p$ is the plasma frequency,
and $\nu$ is the collision frequency. A preliminary analysis using typical ionospheric profile indicates that 300 kHz waves reflect 10–15 km higher than 20 kHz signal for daytime hours, and 5–10 km higher during nighttime. So although LF/MF signals still reflect within the $D$ region, they may access different altitudes. A more thorough analysis is outside the scope of this paper.

3.1. Long-Range Detection

Figure 1 demonstrates the long signal detection range of our receivers. The green dots represent the locations of the NDGPS transmitters as of April 2016, and the blue star is the location of our receiver at PARI (North Carolina). Figure 1 (right) shows 1 min of data, integrated and presented as a frequency spectrum. The detected signal is a mix of spread-spectrum and coherent MSK signals, since the transmitted bits are not necessarily randomized. From examining the SNR of many transmitters, we ascertain that our receivers have a daytime range of approximately 750 km, as shown by the orange circle on the map, and a nighttime range of approximately 2400 km, as shown by the blue circle on the map, although there is some variation based on the type of antennas used by NDGPS sites. Figure 1 (bottom left) shows an example of the analysis used to determine the detection range. The black dots represent the approximate amplitude of some observed transmitters. The red line represents the noise floor for this particular site, and the blue dashed line is a linear fit to the transmitter amplitudes, where the two lines intersect is the approximate range. The red path in the map shows one particular signal, transmitted at 310 kHz from Whitney (Nebraska), nearly 2000 km away from PARI. As seen in the thumbnail in Figure 1 (right), the Whitney transmission is detected at PARI with $\sim$20 dB SNR. From this, we can establish that LF/MF waves can be used for ionospheric characterization over very large regions, unlike single-point techniques like rockets, HF partial reflections, and incoherent scatter radar.

3.2. Diurnal Variations of the Sky Wave

The ionization in the $D$ region of the ionosphere is primarily due to Lyman $\alpha$ radiation during the day and cosmic rays and Lyman $\beta$ backscatter from the Earth’s hydrogen exosphere at night [Kotovsky and Moore, 2016]. Thus, $D$ region electron densities are substantially larger during the day and are subject to diurnal, seasonal, and solar cycle variation. On the other hand, during the day, the ionospheric conditions are highly stable and predictable apart from during transient solar flare disturbances. These time variations in the sky wave for LF signals around 100 kHz are well documented in early studies [e.g., Bickel, 1957; Belrose et al., 1959; McKerrow, 1960; Clarke, 1962]. Previous analysis of the sky wave from NDGPS transmitters thus far has been limited to a radio engineering approach and focused on mitigating signal outages caused by fading (interference between the ground wave and sky wave) [e.g., Last and Poppe, 1996, 1997].

In order for the LF/MF signals from NDGPS transmitters to be utilized as a diagnostic tool for the $D$ region of the ionosphere, the sky wave component of the signal must be detectable by our receiver. Figure 2 shows 48 h of narrowband data collected by the LF AWESOME receiver located at PARI from the transmitter in Dandridge, Tennessee, located 99 km away from the receiver. The diurnal variation apparent in Figure 2 is consistent with
Figure 2. Observed diurnal variation of the signal from a NDGPS transmitter.

other observations, such as [Last and Poppe, 1997]. Figure 2 (bottom) shows the full 48 h of amplitude data, with the nighttime and daytime periods labeled. The daytime data are very nearly constant with time. As the sky wave is heavily attenuated during the day, the reflection coefficient is approximately 2 to 3 orders of magnitude lower [International Telecommunications Union Radiocommunication Assembly (ITU-R), 2012]; hence, the daytime signal for this particular transmitter-receiver link is dominated by the ground wave, which does not change with time. However, as Figure 2 (top left) shows, as the Sun sets the attenuation of the sky wave decreases and a fading pattern appears. The steadily intensifying oscillations result from phase interference caused by constructive and destructive interference between the ground wave and the steadily strengthening (and phase-varying) sky wave. Figure 2 (top right) shows the interference pattern in the deep nighttime hours. It is evident that at night the signal is highly variable with approximately a 30 dB variation in the amplitude of the depicted signal. This type of fading pattern is consistent with a small number of components, likely one sky wave and one ground wave, since a large number of rays are unlikely to produce such perfect cancelation as often as we are observing in this 48 h period at nighttime. Since there appears to be only two dominant components to the nighttime signal, it is in principle possible to mathematically separate the two components using the amplitude and phase of the transmitter signal at the receiver. Extracting the phase requires demodulation of the minimum-shift-key modulation imposed on the NDGPS beacons and also requires a coherent

Figure 3. Observed amplitude diurnal variation in Juneau, AK, from a nearby NDGPS beacon. (top right) A map of the transmitter-receiver geometry; (bottom right) An image of the mountain range. The photograph in Figure 3 (bottom right) was taken by [Brooks, 2015].
and phase-stable source or a method of mitigating source-phase instabilities. Once this has been achieved, the detected signal will actually be an absolute measurement, not a differential or scattered measurement.

3.3. Ground Wave Propagation

With VLF signals, the Earth can be approximated to be perfectly smooth, since the wavelength of the signals are often significantly larger than any terrain obstacles (such as mountains or buildings). However, at LF/MF, the wavelength (~1 km) is comparable in size to medium-size mountains or even particularly tall buildings. Hence, the flat-terrain approximation is no longer valid and existing VLF propagation models such as the Long Wave Propagation Capability (LWPC) [Ferguson, 1998] cannot be reliably used in many situations.

As an example, we consider the propagation of a LF/MF signal across a mountain range, as is the case for a NDGPS transmitter near Gustavus (Alaska) detected at the receiver in Juneau (Alaska). Figure 3 shows the diurnal variation of the amplitude for this scenario. The propagation path is 50 km and nearly in a west-to-east direction, divided in the middle by a north-south mountain range with some peaks reaching well over 1 km in height, or more than a wavelength tall. The nighttime period is approximately between 5 UTC to 15 UTC and is distinguishable by the greater variability in the signal. The diurnal variation demonstrated here is markedly different from that shown in Figure 2. We explain this difference as being due to the attenuation and shadowing caused by the mountain range.

To model the ground wave attenuation for various propagation paths, a finite difference time domain (FDTD) code was built and run. Topographic profiles of the Earth were acquired using the NASA/METI Advanced Spaceborne Thermal Emission and Reflection (ASTER) Global Digital Elevation Model data set, a product of NASA and METI. Conductivity and permittivity parameters of the Earth were acquired from look-up tables and inferred for the ground [ITU-R, 1992]. In the case of the propagation from Gustavus to Juneau, the path is only about 50 km and so the curvature of the Earth is neglected. Figure 4 shows the results from the FDTD model. Figure 4 (top) shows the difference between the magnetic field for a simulation with the terrain profile and one with no terrain, i.e., propagating over salt water. The transmitter is located at the bottom left, which causes the feature at around 1 km, and the receiver is located at the bottom right. The color indicates the extra path loss, in decibels, due to the realistic terrain, additional resistivity, and other effects inherent to the FDTD method, such as geometric dilution. Figure 4 (bottom) shows this path loss along the profile of the terrain border with realistic conductivity values. Near the receiver, the effect of the terrain and higher resistivity, or the difference in the two simulations, is about 15–20 dB. This level of attenuation is quite significant for such a short path and would otherwise have been missed with a simple flat Earth approximation. More importantly, it means that the ground wave is sufficiently attenuated so that the balance between the ground wave and the first-hop sky wave is significantly altered.

4. Application of LF/MF for D Region Observations

We now introduce the use of LF/MF remote sensing to detect ionospheric disturbances. “Early/fast” events are prompt onset (<20 ms) nighttime D region perturbations that occur simultaneously (<20 ms) to a lightning
Figure 5. Detected early/fast event coinciding with a lightning stroke over South Carolina.

Discharge in a localized vicinity and typically recover in about tens to hundreds of seconds [Johnson et al., 1999] and have been the subject of an abundance of research [e.g., Inan et al., 1996a, 1996b, 2010, and references therein]. Using Vaisala’s National Lightning Detection Network (NLDN) [Cummins and Murphy, 2009], we were able to detect all lightning strokes that occurred near the great circle path of a receiver in Baxley (Georgia) and the NDGPS transmitter in New Bern (North Carolina). Figure 5 shows the amplitude data from one channel at the Baxley receiver. The data have the characteristic features of an early/fast event: a very sudden onset and a much more gradual recovery. In this case, a positive cloud-to-ground lightning stroke with peak current 98 kA occurred within 18 km of the New Bern, North Carolina, to Baxley, Georgia, path. Early/fast events typically occur within 50–200 km of the path [Johnson et al., 1999; Salut et al., 2013]. This is one of a few early/fast events observed on this path and day alone and demonstrates potential usefulness of LF/MF signals from NDGPS transmitters as a diagnostic tool for geophysical phenomena associated with the D region of the ionosphere.

5. Conclusion and Discussion

In this paper we have outlined a new approach to D Region diagnostics, using a frequency band that has been largely ignored. Leveraging an advanced high-sensitivity receiver, we have shown that the detectable signal range for 300 kHz enables ionospheric measurements over a large area of the United States. An FDTD model confirms the importance of ground wave propagation with inclusion of terrain and suggests that received signals can eventually be split into ground and sky waves. Such a measurement has the potential to lead to direct calculations of the ionospheric reflection coefficient without the ambiguities that plague VLF remote sensing, while at the same time the high SNR makes the temporal resolution much more promising than what HF and VHF remote sensing currently achieves. We have also shown direct evidence that ionospheric disturbances from lightning may be sensed using our methodology. Continued efforts are needed to further develop this method as a diagnostic tool for the ionosphere.

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