Using the World Wide Lightning Location Network (WWLLN) to Study Very Low Frequency Transmission in the Earth-Ionosphere Waveguide: 1. Comparison With a Full-Wave Model

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Abstract We investigate a novel way to quantify Very Low Frequency transmission in the Earth-Ionosphere Waveguide, using data from the World Wide Lightning Location Network (WWLLN). The lightning signals from intense and long-duration storm clusters are recorded at several stations. Any individual stroke amplitude is in principle unknown, so that the recorded electric field from that stroke varies semi-randomly from the recorded field due to other strokes from that storm cluster. Thus, it is not possible to straightforwardly infer the channel characteristics from a stroke recorded at a single station. However, if two stations record the signal from the same stroke, then the inter-station ratio of the recorded amplitude on the two fixed propagation paths is (in the absence of noise) independent of source power. We develop a procedure to provide information on time-variations in the waveguide transmission, using an approach based on ratios of amplitudes from pair of stations which record the same strokes. These amplitude-ratio data are then compared to an existing model of full-wave Very Low Frequency reflection from the underside of the ionosphere.

Plain Language Summary Lightning strokes emit radio waves of varying strength. The global lightning-monitoring system known as the World Wide Lightning Location Network provides an opportunity to infer features of radio attenuation of these radio waves as they propagate from the lightning to the network sensors. Although we do not know the amplitude of individual lightning strokes, we can form ratio's of each stroke's signal between pairs of stations that detect and record the same stroke's signal. We investigate the use of such ratios to study the radio attenuation process in the waveguide formed between the Earth's conductive surface and the conductive ionosphere about 70–90 km above the surface. In particular, we are able to account for the difference between daytime and nighttime attenuation, using a physics-based model of radio reflection from the ionosphere.

1. Introduction

We will describe a research effort to infer that part of the attenuation of broadband (5–20 kHz) radio signals in the Earth-ionosphere waveguide which is caused by reflections from the waveguide's upper boundary (ionospheric D-layer). To attempt this, we exploit intense, pulsed broadband signals generated by lightning strokes.

Many previous measurements of this attenuation have exploited anthropogenic narrow-band radio beacons (McRae & Thomson, 2000; Thomson, 1993; Thomson & Clilverd, 2001; Thomson & Rodger, 2005; Thomson et al., 2004, 2007). Those measurements relied on detailed and reliable knowledge of the source power of the beacons. Our approach differs from the beacon work, in that our sources' power is taken to be completely unknown. Our source is also broadband.

A key innovation of inferring ionospheric effects using broadband lightning radio emissions (Cheng & Cummer, 2005; Cheng et al., 2006, 2007; Cummer et al., 1998) exploited the distortion of the spectrum of lightning, caused by reflections from the ionospheric boundary. This was a very good adaptation to the fact that the radio source amplitude is unknown. A similar approach was to use radio sensors close enough to the source that the “ground wave” as well as an ionospheric reflection could be jointly recorded, so that the “ground wave” served to calibrate the lightning source power (Jacobson et al., 2007; Shao & Jacobson, 2009). That approach is possible for short-range observations, <800 km, which allow both the “ground wave” and the “sky wave” to be recorded.
The World Wide Lightning Location Network (WWLLN) detects, locates, and times lightning strokes globally, with ~10-km spatial accuracy and ~10-microsec temporal accuracy (Abreu et al., 2010; Holzworth et al., 2019; Hutchins et al., 2012, 2013; Rodger et al., 2004, 2005). Presently WWLLN comprises over 60 active stations, at each of which is a VLF (Very Low Frequency; 3–30 kHz) receiver. The location/timing is done by time-of-group-arrival (“TOGA”) of the stroke's VLF signal at the various stations (Dowden et al., 2002). The TOGA is determined by “dechirping” the recorded signal for the waveguide's dominant mode (first transverse magnetic, or first TM) for long-range propagation. For shorter ranges, for example, 1,000 km or shorter), the group time of arrival may be due to a mode mix involving higher-order modes than first TM (Dowden et al., 2002). This can make the short-range path's time-of-group arrival inconsistent with those from the longer-range paths, in which the first TM mode dominates. Therefore, when there is a mix of stations competing to control the solution for a stroke location/time, the short-range stations are at a disadvantage, as their timing error will be higher. For this reason, the location/timing solutions tend to be provided by longer-range stations (several-thousand km).

WWLLN in essentially its present form has operated globally and constantly for over a decade; WWLLN's operating costs are already borne by its lightning-location function. It would be desirable and useful, as well as essentially cost-free, to derive from WWLLN some collateral benefit in testing models of broadband VLF radio propagation in the lower ionosphere. Using lightning in such a model test exploits a powerful, naturally-occurring, and widely distributed radio source. The Great-Circle Paths along which the lightning signals propagate from the lightning to the sensor collectively cover most of the planet. The rest of this paper describes one approach to developing a VLF-propagation model test using the WWLLN lightning data.

Since 2009, WWLLN has archived not only the stroke locations and times, but also estimates of the stroke VLF energy radiated into the Earth-ionosphere waveguide (Hutchins, 2014; Hutchins et al., 2012). Along with these estimates, WWLLN retains the signal packet's amplitude at each station participating in the solution, in analog-to-digital-converter units. Amplitude is defined as follows: The WWLLN station software examines each triggered record and “dechirps” the recorded signal as appropriate for the lowest Transverse Magnetic waveguide mode. The software then determines the peak amplitude of this dechirped wavetrain. It is stored in “analog-to-digital converter units,” which is proportional to the wave electric field, except that we have not in the present exercise invoked a station calibration, which would be required to make that proportionality. A wealth of explanatory material on WWLLN is also available at the project's website (http://wwlln.net). The network provides this data for, typically, more than a half-million strokes per day.

For all but a handful of WWLLN stations, we have verified that the station’s own system gain is stable over periods exceeding several days, so that repeated arrivals of the same electric-field amplitude from the same bearing will give essentially the same ADC amplitude. The routine verification of the stability of each station's system gain occurs as follows: One WWLLN station is the “master station” (Hutchins, 2014; Hutchins et al., 2012). This is Scott Base on the edge of Antarctica, in an exceptionally VLF-quiet location. Unlike all the other stations, Scott Base’s sensor is magnetic rather than electric. This further reduces the effect of local environmental noise. Every year, the Scott Base sensor is manually calibrated by being surrounded by a VLF electromagnet. We observe that ever since its initial calibration in 2009, the Scott Base sensitivity (wave magnetic field per analog-to-digital increment) has remained essentially constant. Scott Base then spawns daily calibrations of all WWLLN stations by the “bootstrap” method of calibration transfer. This bootstrap daily calibration is the core procedure of WWLLN's energy estimates, which equally rely on the Long Wave Propagation Capability (LWPC) code (Pappert & Ferguson, 1986). From day-to-day, we normally observe excellent day-to-day stability of each station's bootstrapped calibration factor.

There is no automatic gain control in the receiver. The system gain is manual and is fixed in time, so that, absent any occasional equipment malfunction, the observed stability of a station's gain is what we expect. The stability of station gains over periods of days is necessary for the energy estimates.

The WWLLN estimate of stroke VLF energy radiated into the Earth-ionosphere waveguide relies on a periodic relative calibration of the network (Hutchins, 2014; Hutchins et al., 2012). The relative calibration relies on calculations of path attenuation in the Earth-ionosphere waveguide performed by the Long Wave Propagation
In this article we describe a research project which steps back from the LWPC support, but still relies on the station gain's temporal stability, at least over the course of a day. We investigate using WWLLN's recorded ADC amplitudes to infer the conditions of waveguide attenuation due to the lower-ionosphere boundary at the top of the waveguide, in an independent manner that does not presuppose the LWPC.

In this particular project, we shall assume:

1. Each stroke has an unknown and random radiated energy.
2. Each station is stable but has an unknown absolute calibration (V/m per ADC unit).
3. Each stroke's radiated VLF, departing from the stroke, is statistically isotropic versus departure azimuth.

2. Our Approach: Concept, and Preliminary Steps

2.1. Concept

Figure 1 shows this work's basic idea. A lightning stroke radiates VLF signals toward both stations #1 and #2. Although the single-station signal amplitude is not useful by itself, because the lightning source strength is unknown, the ratio of the signals (#1 divided by #2) should, in principle, be independent of the unknown source strength. Due to noise, however, much averaging of the ratio (over temporally close strokes from approximately the same location), is required. Going into this project, it was unknown a priori if such averaging would yield a usefully “clean” time-series of the two-station, sliding-averaged amplitude ratio. By “clean” we mean that the time-variations of the sliding averaged ratio must be primarily determined by ionospheric effects rather than by system drifts or statistical noise.

2.2. Identifying Stroke Spatial Clusters

To begin the project, we had to see if the WWLLN-located strokes can be grouped into spatial clusters that contain enough members, distributed with enough temporal coverage of several hours to a day, to allow us to discern ionospheric effects. We use a simple search for stroke-clusters in each day. Because we deal with a considerable number of days (over a decade's worth), we have automated the identification of stroke clusters. The automated procedure ingests all the data from a WWLLN day file, and outputs a somewhat smaller file containing only those strokes which fit into clusters whose population exceeds a threshold.

There is a tradeoff between choosing spatially compact clusters, or more extensive clusters. It is an example of the usual tradeoff of statistical strength versus data quality: A spatially compact cluster assures that the paths to a station remain essentially the same, from stroke to stroke during the time development of the cluster. However, the compact cluster contains fewer members, and so its usefulness to temporally track the time-varying amplitude ratio continually over a day with a running temporal average is impaired. A spatially larger cluster collects a larger stroke membership and provides stronger statistics and temporal coverage. However, the larger cluster risks mixing paths (to a given station) which differ sufficiently to compromise an understanding of ionospheric effects. We experimented with this trade-space and settled on a compromise choice of cluster size, explained as follows:

First, we take all strokes for a UT day (numbering typically 0.5–0.8 \times 10^6), and take the nearest-integer versions of both their longitudes and latitudes. This places them on a spatial grid dimensioned 360 \times 180, in longitude \times latitude. We tally the population of each integer grid point. We then define larger (5° \times 5°) boxes, overlapping 80% so they continue to be centered on each grid point of the 1° \times 1° grid. These larger boxes must not be centered within 2° of either the longitude or the latitude boundaries, else the box's volume would be reduced. Hence we are slightly vignetting the spatial domain, by 2° at each of the four boundaries. This leads to a 4°-wide band of “empty” longitudes at the International Date Line, within which we are prevented from identifying a 5° \times 5°
cluster. The large clusters are identified in the following order: First, the stroke membership of each 5° × 5° box is tallied. Second, the highest-membership box is identified. Third, the members of that highest-membership box are marked “already taken” and are removed from possible membership in subsequently identified clusters. We iterate these steps to identify other clusters, until the newest “winner” of the membership contest contains fewer than 8,000 strokes. Then we stop. The only accepted clusters have at least 8,000 members each, and any member stroke belongs exclusively to only one cluster.

Figure 2a shows the cluster result for one UT day, June 1, 2020. The membership is marked by color, from 8,000 (blue) to 78,725 (red). The four most populous clusters are all in or near the western Atlantic, from Central America up to alongside Florida. The overrepresentation of that region is quite typical of boreal summer. Partly,
that is, due to that region's optimal WWLLN coverage, but partly also it is due to that region's long-duration electrified-storm systems that last much of a day and that drift very slowly.

2.3. Temporal Running Averages of Amplitude Ratio

Here we face another tradeoff between statistical strength, and temporal resolution, analogous to the tradeoff seen earlier between statistical strength, and spatial resolution. After experimenting with different temporal-averaging windows, we settled on a sliding window of width 500 s, stepped by 100 s, so that there is a similar overlap factor (80%) as the spatial sampling earlier. We take the strokes from a given cluster and allocate them to these temporal windows. Now it is allowed for a stroke to belong to adjacent temporal-averaging windows. Within each 500-s-wide window, we require the membership of that window to be at least 10. If smaller, that window does not contribute to the time-series of averaged ratios. Within each accepted temporal window, the median (not average) amplitude ratio is tallied. We use the median to avoid corruption of the time series from occasional single-stroke saturations at a station's ADC.

Let us examine the most-populated cluster, shown as the red square in Figure 2a above. Figure 2b shows the time series (red square symbols) of the median amplitude-ratio of 500-s-wide windows advanced by 100 s steps, for that cluster. The missing symbols are for occupancy <10 strokes. The smaller black square symbols indicate the estimated error from the internal scatter within each window. The two WWLLN stations in this example are Lisbon (Portugal), in the ratio's numerator, and St. Johns (Newfoundland, Canada) in the denominator. Although the cluster contains 78,725 strokes, only 14,931 of them are jointly located by Lisbon and St. Johns stations. The data curve in Figure 2b utilizes only the jointly-located 14,931 strokes.

2.4. Relating Amplitude-Ratio Time Series to Solar Zenith Angle

The data symbols in Figure 2b, following the amplitude ratio (Lisbon/St. Johns) during the course of a full day, indicate clear and systematic temporal variations that dwarf the statistical noise level. There are two dominant fast transients. The first occurs between \(~15,000~s~(4.2~h)~UT~and~\sim30,000~s~(8.3~h)~UT\). The second occurs between \(~73,000~s~(20.3~h)~UT~and~the~end~of~the~UT~day\). These can be related to the controlling role of solar zenith angle. Since the paths from the lightning to either Lisbon or St. Johns are quite long, so that the solar zenith angle varies spatially along the path at any given instant of time, we show in Figure 2b the solar zenith angle (referred to ground altitude) at five different locations. The green curve is the solar zenith angle versus UT time at the center of the lightning cluster. At shortly before 60,000 s (16.7 h) UT, the sun culminates almost overhead the cluster. The solid black horizontal line marks 99.6°, the ground-level solar zenith angle corresponding to the passage of the terminator at altitude 90 km. This altitude notionally is close to the nighttime ionospheric D-layer altitude. The solid red curve in Figure 2b is the ground-level solar zenith angle at St. Johns. The solid blue curve is for Lisbon. The dashed red and blue curves are for the midpoints of the lightning-to-St. Johns path and the lightning-to-Lisbon path, respectively. Each of these five colored curves intersects the horizontal black line for the 90-km-altitude terminator, and the times of those intersections are marked by corresponding colored vertical lines.

We see from Figure 2b that the “sunset” and “sunrise” periods are prolonged in time, due to the large scale of the paths from the lightning to the stations. From \(~1,000~s~(0.3~h)~UT~to~\sim15,000~s~(4.2~h)~UT\), all portions of both paths at 90-km altitude are in darkness. From \(~31,000~s~(8.6~h)~UT~to~\sim75,000~s~(20.8~h)~UT\), all portions are in daylight. From \(~15,000~s~(4.2~h)~UT~to~\sim31,000~s~(8.6~h)~UT\), the sunrise terminator is somewhere along at least one of the two paths, while from \(~75,000~s~(20.8~h)~UT~thru~the~end~of~the~UT~day\), the sunset terminator is somewhere along at least one of the two paths.

2.5. Sorting the Sliding-Average Amplitude-Ratio Data

The sliding-average amplitude-ratio data shown in Figure 2b is for just one pair of stations, for just one lightning cluster, and for just one single day. Typically we have a few acceptable clusters worldwide per day, and several station pairs per cluster. So, with the presence of more than a decade of days’ worth of data, we have available tens-of-thousands of time series to consider for further processing. Thus, the procedure for sorting the time-series data is best automated.
In all data that we have studied, the solar-terminator effects dominate the variations of the time series, compared to the residual variations during either “pure darkness” or “pure daylight” periods. To a first-order approximation, the daytime ionization state of the D-region is most controlled by the local solar zenith angle. But beyond that approximation, there are important complications due to the dependence of the photochemistry on the global atmospheric circulation pattern (Krivolutsky et al., 2015; Kulyamin & Dymnikov, 2015; Turco & Sechrist, 1972a, 1972b). This spatially and temporally modulates the availability of readily ionizable species, foremost of which is the molecule NO. According to both of the two modern numerical coupled D-region/global circulation models (Krivolutsky et al., 2015; Kulyamin & Dymnikov, 2015), the departures from a simple solar-zenith-angle control are most apparent at low latitudes and at the latitude of the sub-solar point.

We have no way in our simple model of VLF attenuation to model the irregularities introduced by global circulation, so instead we simply limit our project to those paths which exhibit dominant solar-zenith-angle control. This translates into limiting our project to those pairs of paths whose amplitude ratio is sufficiently constant during either the pure-night phase of the record or the pure-day phase of the record, compared to the terminator-passage transitions. The data of Figure 2b above, for example, is quiet enough during the pure-day or pure-night portions, to justify testing whether the terminator-passage transitions can be related to the rapid change of solar zenith angle during those transitions.

The automated sorting algorithm goes through all the time sliding-average time series and slices each series into smaller pieces, so as to extract the periods of terminator passage. This slicing routine will be illustrated fully in Section 4. This will allow the model to focus on periods of rapid excursion, when there is the most reason to attribute control to the solar-zenith-angle changes occurring along the paths, but to avoid modeling the residual (and smaller) variations observed during pure-day or pure-night conditions. Logically, the latter are more likely related to complicated atmospheric-circulation effects on the photochemistry (Krivolutsky et al., 2015; Kulyamin & Dymnikov, 2015) than they are simply to rapid changes of the solar illumination.

3. The Approximate Model

3.1. Form of the Model

We seek to test whether the quantifiable changes in solar illumination during terminator passage can at least approximately account for the observed excursions of the sliding-average amplitude ratio during terminator passage. Toward that end, we keep the model simple and heuristic, which suffices to compare with the noisy data on amplitude ratio. We want the model to stand independently of this field’s standard tool (the LWPC code). We also want the model to be heuristic and transparent, something that the LWPC legacy code is not.

First we shall assume that the attenuation of a VLF signal in the Earth-ionosphere waveguide is an exponential function of distance. Because the local factors determining the attenuation vary along the path, as well as vary versus time, the exponential actually is of a path integration over local and instantaneous local variables. The path is the Great Circle Path from the lightning to the WWLLN station.

Thus we model the electric-field amplitude after propagating along a Great Circle Path from lightning location “m” to WWLLN station “i” as:

$$E_{i,m}(t) = C(P_{i,m}, E_{m}, G_i, \int_0^{\alpha_{i,m}} g(Z_{i,m}(t), \alpha_{i,m}, I_{i,m}) ds_{i,m})$$

where

- $C = \text{geometrical (non-lossy) signal-dilution factor for spherical-shell waveguide}$
- $P_{i,m} = \text{path factor due to Earth's surface conductivity (constant in time), range is } 0 < P_{i,m} < 1$
- $E_{m} = \text{source factor of lightning at location } m$
- $E_{i,m}(t) = \text{signal at station } i \text{ due to lightning at location } m$
- $G_i = \text{gain (unknown) of station } i$
\[ L_{i,m} = \text{arcdistance along Great Circle Path from lightning location } m \text{ to station } i \]

\[ Z_{i,m}(t) = \text{time-dependent, location-dependent solar zenith angle along path } i,m \]

\[ \alpha_{i,m} = \text{location-dependent magnetic propagation azimuth along path } i,m \]

\[ I_{i,m} = \text{location-dependent magnetic dip angle along path } i,m \]

\[ g(Z_{i,m}(t), \alpha_{i,m}, I_{i,m}) \text{ zenith-angle and geomagnetic effect on local and instantaneous attenuation} \]

\[ ds_{i,m} = \text{differential path element along Great Circle Path } i,m \]

Notes:

The station gain \( G_i \) is taken to be unknown but stable in time.

The source factor \( E_m \) of lightning at location \( m \) is taken to be unknown but statistically omnidirectional.

The arguments of the zenith/geomagnetic factor \( g \) depend on position, and (via \( Z \)) on time.

The strategy is to form the ratio \( r_{i,k,m}(t) \) of the signals at two stations \((i,k)\) observing the same lightning strokes \((m)\) at the same times. The ratio is used in order to render the (unknown) lightning source strength irrelevant, as it is common to the signals on both stations \(i\) and \(k\). When we say the “same strokes,” we mean that in detail:

A stroke needs to be recorded at each of the two stations, for a “ratio” to be formed for that stroke and those two stations.

The ratio is as follows:

\[
r_{i,k,m}(t) = \frac{E_{i,m}(t)}{E_{k,m}(t)} \quad (2)
\]

The next step is to take the natural logarithm Equation \(2\):

\[
\ln(r_{i,k,m}(t)) = \ln\left(\frac{E_{i,m}(t)}{E_{k,m}(t)}\right) \quad (3)
\]

Inserting Equation \(1\) into Equation \(3\), we get

\[
\ln(r_{i,k,m}(t)) = \ln\left[C(L_{i,m})P_{i,m}E_mG_i\right] - \ln\left[C(L_{k,m})P_{k,m}E_mG_k\right] \\
+ \int_0^{L_{k,m}} g\left[Z_{i,m}(t), \alpha_{i,m}, I_{i,m}\right] ds_{i,m} - \int_0^{L_{k,m}} g\left[Z_{k,m}(t), \alpha_{k,m}, I_{k,m}\right] ds_{k,m} \quad (4)
\]

The first two terms on the rhs of Equation \(4\) are independent of time, while the last two terms depend on time via the solar zenith angle, \(Z\). If we take the time difference of Equation \(4\) between times \(t\) and \(t_0\), then the time-independent terms drop out, and we are left with

\[
\ln(r_{i,k,m}(t)) - \ln(r_{i,k,m}(t_0)) = \int_0^{L_{k,m}} g\left[Z_{i,m}(t), \alpha_{i,m}, I_{i,m}\right] ds_{i,m} - \int_0^{L_{k,m}} g\left[Z_{k,m}(t), \alpha_{k,m}, I_{k,m}\right] ds_{k,m} \\
- \int_0^{L_{k,m}} g\left[Z_{i,m}(t_0), \alpha_{i,m}, I_{i,m}\right] ds_{i,m} + \int_0^{L_{k,m}} g\left[Z_{k,m}(t_0), \alpha_{k,m}, I_{k,m}\right] ds_{k,m} \quad (5)
\]

This time-differenced form of the model equation enjoys some important simplifications: There is no dependence on the stations’ system gain. Nor is there any dependence on the ground losses (via the factors \(P_{i,m}\) etc).

However, this simplification comes at a cost: The model form of Equation \(5\) can be used only to fit that portion of the observed time-series data that varies with time. Any constant baseline in that data is lost with the simplified Equation \(5\). In the comparisons with data below (Section 4), all we can fit is the data’s temporal excursions, but Equation \(5\) gives no information on any constant baseline on which those excursions are superimposed.

In Equation \(5\) and the results to follow, the model needs accurate inputs of the magnetic propagation azimuth and magnetic dip angle. We calculate these inputs using the IGRF, or International Geomagnetic Reference Field.
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3.2. Choice of Physical Content of the Model

Equation 5 is the form of the model which we shall compare with data. As yet unspecified, however, is the actual physical content of the model, that is, the function \( g(Z_i, \alpha_i, m, I_i) \) which contains all the effects of local, instantaneous solar zenith angle, as well as of both local propagation magnetic azimuth and local magnetic dip angle.

For the physical content of our model, we will now use an existing full-wave calculation of anisotropic VLF reflection from the ionospheric D-layer (Jacobson et al., 2009, 2010). This calculation (henceforth called “J2009”) explicitly predicts the dependence of the reflection coefficient on angle-of-incidence, propagation magnetic azimuth, and magnetic dip angle. J2009 has been shown to account well for the observed spectral reflection coefficient of wideband VLF pulses due to lightning return strokes, and to correctly predict the dependence of that reflection on magnetic propagation azimuth (Jacobson et al., 2012). The J2009 calculation is not an entirely new approach; rather, it applies an approach pioneered half a century earlier in the United Kingdom (Piggott et al., 1965; Pitteway, 1965). Like almost all D-layer-reflection models, J2009 describes the ionosphere by an idealized profile. It uses the standard altitude profile of electron-collision rate in line with prior work (Jacobson et al., 2009), as well as an exponential profile of electron density within the D-layer:

\[
N_e(z) = N_{e0} \exp(q(z - Z_0))
\]

This exponential profile is characterized by three parameters: The reference electron density \( N_{e0} \), the reference altitude \( Z_0 \), and the logarithmic derivative \( q \). Following the pioneering descriptions of the D-layer (Volland, 1995; Wait & Spies, 1964), we use \( N_{e0} = 3 \times 10^8 \text{ m}^{-3} \). For daytime, we use \( Z_0 = 73 \text{ km} \) and \( q = 0.3 \text{ km}^{-1} \). For nighttime, we use \( Z_0 = 85 \text{ km} \) and \( q = 0.45 \text{ km}^{-1} \).

Figure 3 shows the predictions of the J2009 calculation for amplitude reflection during nominal (a) daytime and (b) nighttime conditions. Color indicates magnetic dip angle absolute value, from 0° (blue) through 85° (red) in 1° increments. The calculation assumes angle of incidence is 85°. Results shown here are an average over the passband 5–20 kHz, in 1-kHz steps. The frequency average is appropriate to the spectrum of the broadband VLF signals captured by WWLLN stations (Hutchins, 2014). The choice of angle of incidence is not critical at this point; the effect of varying the angle from the chosen 85° to, for example, 80°, merely rescales the overall reflection coefficient deviation from unity. That scale factor will be adjusted anyway in our final fitting of the model to the data (below).

3.3. Preliminary Implications of the Model

The model for amplitude reflectivity (Figure 3) has a couple of key features that are perhaps not widely appreciated, although they should be latent in any correct full-wave calculation. The first key feature in Figure 3 is that the azimuthal asymmetry is profoundly modulated by the magnetic dip angle. The “east/west” asymmetry is most extreme at dip angle = 0° (Magnetic Equator) and gets smaller with increasing magnitude of dip angle, reaching zero at dip angle = ±90° (the Magnetic Poles). The latter should be trivially obvious by symmetry: For a vertical magnetic field, azimuth becomes an ignorable coordinate in the Maxwell’s equations.
with the anisotropic susceptibility tensor (Pitteway, 1965), which are solved to get the electromagnetic wave field (Jacobson et al., 2009).

The second (and more novel) phenomenon laid bare by Figure 3 is that the “east-west asymmetry” is much more pronounced for night than for day conditions. This is somewhat counter-intuitive, because the daytime reflection environment is lower in altitude—and hence more collisional—than is the nighttime reflection environment (Volland, 1995; Wait & Spies, 1964). Notwithstanding that intuition, the magnetic-westward attenuation is predicted in Figure 3 to be in daytime than in nighttime.

As noted above, several studies have observed an “east/west asymmetry” in the VLF path attenuation (Crombie, 1958; Hutchins et al., 2013; Taylor, 1960). These previous observations of anisotropic VLF attenuation based on broadband lightning signals did not treat the variation of the magnetic propagation azimuth along the Great Circle Path (from the lightning to the receiver). Moreover, those prior observations’ presentations did not include that the entire anisotropy is controlled by the magnetic dip angle. A path segment at dip angle 0 is not equivalent to a path segment at dip angle 45°, even if the magnetic propagation azimuth were the same. For a given path, the anisotropic transmission needs to be treated locally at each place along the path, and these local contributions must be integrated over the path. For paths of thousands of km, it is not meaningful to assert that there is a “magnetic azimuth” of that path. Only a local path differential segment has a single magnetic azimuth or a dip angle; the entire path, in general, does not.

3.4. Possible Relationship With Previous Work on D-Layer VLF Penetration

The model’s prediction of deep attenuation of magnetic-westward propagation at low dip angle and during nighttime might be consistent with an older observation involving lightning VLF signals recorded on the C/NOFS satellite (de La Beaujardiere, 2004) using the VEFI, or Vector Electric Field Instrument (Pfaff et al., 2010). The VLF signal arrives at the satellite only by penetrating the ionospheric D-layer and then continuing as a magnetospheric oblique whistler wave. The C/NOFS orbital inclination (13°) ensured that most of the recorded VLF waveforms were recorded at low magnetic latitude (Jacobson et al., 2011, 2018). Moreover, the VLF recordings almost all occurred when the satellite was in darkness, so that the ionospheric transmission was for a nighttime D-layer. The D-layer penetration process was inferred to be more efficient for westward-propagating than for eastward-propagating VLF signals, based on the statistical behavior of the VEFI recorded signals from lightning strokes that had been located by WWLLN (see Figure 4 in Burkholder et al., 2013). This was later seen more quantitatively (see the striking anisotropy in Figure 15a of Jacobson et al., 2018).

In the present instance we observe that the magnetic-westward propagation in the Earth-Ionosphere Waveguide is more attenuated than is eastward. Thus, we infer that the transmission in the waveguide, and the transmission upward from the waveguide into the ionosphere, have qualitatively opposite tendencies versus magnetic azimuth. This might be consistent. If a wave is attenuated due to D-layer effects within the Earth-Ionosphere Waveguide, the causes of the attenuation logically include (a) lossy collisional processes, and (b) upward penetration of wave energy through the D-layer. Either of these processes serves to reduce the forward transfer within the Earth-Ionosphere Waveguide. Hence the opposite tendencies versus magnetic propagation azimuth (see above) are compatible.

3.5. Adapting a Plane-Wave-Reflection Model for a Spherical-Shell Waveguide

VLF signals for the WWLLN system propagate in the Earth-ionosphere spherical-shell waveguide. Therefore, our use of a plane-wave-reflection model in the present application requires some care. To start with, propagation in a spherical-shell waveguide is subject to a lossless modulation of the signal amplitude due simply to the variation of the ray-tube cross-sectional area as a function of range (Wait & Spies, 1960). Even in the complete absence of loss (at either the ground or the ionosphere boundaries), the ray-tube cross-sectional area $A$ varies versus arc-distance $\rho$ according to

$$A(\rho) / A(\rho_0) = \sin(\rho / R_E) / \sin(\rho_0 / R_E)$$ (7)
where \( \rho_0 \) is a reference arc-distance and is \( R_E \) is the Earth’s radius (Wait & Spies, 1960). Thus, even with no lossy attenuation, we expect the electric field to vary versus arc-distance as

\[
E(\rho) / E(\rho_0) = \sqrt{\sin(\rho_0 / R_E) / \sin(\rho / R_E)}
\]

This ratio is the “C” factor in Equation 1 above. However, in the transition from Equations 4 to 5, we lose the effect of this factor because its effect is not time-dependent.

A more serious concern in using a plane-wave reflection model is that the plane-wave approach presents solutions for discrete, pre-ordained angles-of-incidence, whereas in the waveguide approach there are discrete waveguide modes rather than angles-of-incidence. The connection between these approaches has been discussed elsewhere (see, e.g., the instructive Section 2.1 in Cummer, 1997, 2000). Here, in this very approximate model, our approach is as follows: For a given arc-distance \( L \) from the lightning to the receiver, suppose that the wave undergoes \( n \) successive reflections at the ionosphere (so that the path is said to be “\( n \)-hop”). Then the path transmission factor for the plane wave will vary as \( R^n \), where \( R \) is the coefficient of amplitude reflection for a single reflection. Take \( \rho_0 = 1,000 \) km as a reference arc-distance. Then we shall leave as a free parameter the number of reflections in the reference distance \( \rho_0 = 1,000 \) km. Call that free parameter “\( r \).” Using the free parameter \( r \), we will adapt our single-reflection model (Figure 3) to distributed reflection over arbitrary arcdistances. Since \( r \) is the number of reflections in the reference arcdistance \( \rho_0 \), the number of reflections in the arcdistance \( \rho \) is greater by the ratio \( \rho/\rho_0 \).

We leave “\( r \)” as a free parameter to be fit by the comparison of model predictions with data. This also finessesthe problem, noted earlier, of our fixed choice of 85° angle-of-incidence. We have varied this angle, and found that the effect (on the reflection coefficient \( R \)) of varying the angle of incidence is indistinguishable from varying the free parameter “\( r \).” In the parameter fits later, we shall include \( r \) as a multiplier of \( g \) in all four places it appears on the rhs of Equation 5. Thus

\[
\ln(r_{\alpha,i,m}(t)) - \ln(r_{\alpha,i,m}(t_0)) = X - X_0
\]

where

\[
X = \frac{r}{\rho_0} \int_0^{L_{\alpha,i,m}} \ln\left[ R\left( Z_{\alpha,i,m}(t), \alpha_{\alpha,i,m}, I_{\alpha,i,m} \right) \right] ds_{\alpha,i,m} - \frac{r}{\rho_0} \int_0^{L_{\alpha,i,m}} \ln\left[ R\left( Z_{\alpha,i,m}(t_0), \alpha_{\alpha,i,m}, I_{\alpha,i,m} \right) \right] ds_{\alpha,i,m}
\]

and

\[
X_0 = \frac{r}{\rho_0} \int_0^{L_{\alpha,i,m}} \ln\left[ R\left( Z_{\alpha,i,m}(t_0), \alpha_{\alpha,i,m}, I_{\alpha,i,m} \right) \right] ds_{\alpha,i,m} - \frac{r}{\rho_0} \int_0^{L_{\alpha,i,m}} \ln\left[ R\left( Z_{\alpha,i,m}(t_0), \alpha_{\alpha,i,m}, I_{\alpha,i,m} \right) \right] ds_{\alpha,i,m}
\]

Note that \( R(Z, \alpha, I) \) is the single-reflection amplitude reflection coefficient as a function of solar zenith angle, propagation magnetic azimuth, and dip angle. Figure 3 above presents two special cases of \( R(Z, \alpha, I) \), for idealized daylight and idealized darkness ionospheric conditions.

### 3.6. Integrating the Solar Zenith Angle Into the Model

Consistent with the very approximate nature of our model and of our approach to comparison of the model with data, we now invoke a final simplification. In Equations 9a–9c, we strictly speaking would need to calculate realizations of the plane-wave reflectivity for a grid of different D-layer parameters. However, the exponential D-layer profile of electron density is by itself very much an idealization of the actual instantaneous state of the D-layer (see, e.g., the complexities in rocket-probe profiles in the compendium Friedrich & Rapp, 2009). Given the obvious fact that the exponential D-layer profile is by itself a gross simplification, we do not believe it is worthwhile to calculate a complete bank of such profiles (vs. solar zenith angle). Instead, we will use a weighted sum of a pure-day solution (the nominal case of Figure 3a) plus a pure night solution (the nominal case of Figure 3b). The weighting for this combination of pure-day and pure night is as follows: We hypothesize that the transition between day and night conditions is centered on some reference
solar zenith angle at or near the geometrical terminator, and occurs with a smooth taper to join “day” and “night,” in either direction and without hysteresis. We use a hyperbolic tangent function “f(t)” to taper this transition, as shown in Figure 4:

\[ f(t) = f(Z(t)) = 1 - \frac{1 + \tanh \frac{Z - Z_T}{w}}{2} \]  

(10)

where Z is the time-dependent zenith angle evaluated at each point on the Great Circle Path at the instant of the lightning, w is a halfwidth and Z_T is a transition zenith angle. We have found that the best timing agreement between model and data is gotten with a transition zenith angle Z_T = 96° and halfwidth w = 5°. We now replace the ln(R) function in the integrands in Equations 9a–9c, with a weighted linear combination of day and night solutions (see Figure 3 above) in the natural logarithm of local reflectivity according to

\[ \ln \left( R(Z(t), \alpha, I) \right) = f(t) \ln \left( R(0, \alpha, I) \right) + (1 - f(t)) \ln \left( R(180, \alpha, I) \right) \]  

(11)

The first ln(R) on the rhs of Equation 11 is for Z = 0°, to designate the natural logarithm of the day model from Figure 3a, and the second is for Z = 180°, to designate the natural logarithm of the night model from Figure 3b. The only thing that changes as a function of time in this recipe is the day-weighting factor f(t), while the R(0,α,I) and R(180,α,I) are independent of time, varying only versus propagation magnetic azimuth and magnetic dip angle. Using this linear combination of time-invariant models gives an efficient-to-implement transition between day and night conditions in the modeled logarithmic amplitude reflection. Hopefully this approach does no more violence to the physics than has already been done by use of an exponential profile of electron density. We emphasize that this is applied locally, to the local magnetic and local, instantaneous solar-zenith-angle conditions at each differential element along the path integrals.

4. Comparing the Model With Amplitude-Ratio Data

4.1. Single-Pair Parameter Fit

We now illustrate a parameter fit by comparing data and model for a single pair ratio. Figure 5a shows the location of the most prolific lightning cluster, in the western Atlantic (coinciding with the red-colored cluster in Figure 2a above) and the paths from that cluster to both Lisbon and St. Johns. Color indicates the absolute value of the dip angle, from 0° (blue) to 90° (red). Figure 5b shows the same paths, but with color indicating propagation magnetic azimuth as in the color wheel. This single-pair example samples only a very small portion of the dip-angle/magnetic-azimuth space. Figures 6a and 6b shows the loci of the two paths (cluster to Lisbon, and cluster to St. Johns) superposed on the display of model reflectivity solutions for (a) pure day and (b) pure night. The curves are parametrized by dip angle, and this allows the loci of azimuth/dip to be transferred to this azimuth/reflectivity plane. It is obvious that the single-pair example has zero coverage of the magnetic-westward half of each solution space. There is even incomplete coverage of the magnetic-eastward half. From Figures 6a and 6b alone, we can already see that the result of this parameter fit will not in any way sample the westward lobe in the model.

In Figure 6c, we vary the assumed reflections-per-Mm parameter (r) along the abscissa. Recall that this parameter now multiplies the ln(R) function in Equations 9a–9c. The ordinate shows the sum of the squares of residuals between the model (with the assumed r parameter) and the data. This is, in effect, a “penalty function.” The “best-fit” value of the parameter is where the penalty is minimum. That occurs at r ~ 2.7 in this single-pair case.
A word of caution on the model: As stated earlier in the discussion of Equation 5, the model as it is fitted to the data is capable of fitting only the excursions in the data, but not any constant baseline. During the fit, the model curve is rigidly adjusted up or down to constrain its temporal average to match the temporal average of the data. The only feature of the data that is, meaningfully fitted is the data's temporal excursion. The baseline is arbitrary.

Figure 7 shows the data (natural logarithm of sliding-median amplitude ratio) versus time (black squares). The best-fit model from Equations 9a–9c (at $r = 2.7$) is shown as corresponding teal squares. The solar zenith angle at the lightning cluster, at the Lisbon station, and at the St. Johns station are show in green, blue, and red respectively. The two halves of Figure 7 are the two transition periods found by the sorting process described earlier in Section 2. The left half of Figure 7 is the sunrise transient, while the right half is the sunset transient. The data in these two halves are natural logarithms of two tranches of the amplitude-ratio data in Figure 2b above.

The data/model comparison shown in Figure 7 already indicates a limitation of our model. While the sign and approximate magnitude of the transients are fitted adequately by the model, there are complications.
in the data that are not captured by the model. Note the overshoots near the end of the sunrise transient; these details are beyond the skill of our model.

We summarize the steps in the data preparation and analysis:

1. Choose a pair of stations and a lightning cluster to analyze.
2. Calculate the running-average time series of observed bin-median amplitude ratio.
3. Calculate the solar zenith angle versus time at the lightning cluster, at the two stations, and at a grid of points along each lightning-to-station Great-Circle Path.
4. Check to see if the time-series of amplitude ratio (from step b above) shows clearly identifiable transient excursions during times of day/night transitioning along the paths.
5. If there are clear amplitude-ratio excursions concurrent with the day/night transitioning, then snip the time series (from step b above) into pieces. Each retained piece will encompass one complete day/night transition.
6. These retained snippets, concurrent with day/night transitions, are now compared with the theory. The adjustable parameter is \( r \), the number of reflections per 1,000 km of path. During the fit of a snippet of data to the model, the time-averaged difference (between the snippet and the model of the snippet) is removed, so that all we are fitting is the temporal transient of the amplitude ratio, but not the offset of the amplitude ratio. For example, in Figure 7 above, there are two snippets, for each of the two day/night transitions. Each snippet is freely floated up or down to minimize the mean residual versus the model. The only effect contributing to the fit of the parameter \( r \) is the transient excursion within each snippet.

4.2. Multiple-Pair Parameter Fit

The same day as shown in Figures 5–7 above can provide a fit of the free parameter using all station-pairs that include Lisbon. Figure 8a indicates the path-pairs for Lisbon and the six other stations with which Lisbon has pair-ratio data satisfying the selection criteria described above in Section 2. In this case, there are three lightning clusters through which Lisbon has pairs amongst the other stations. These three clusters include the two in the western Atlantic, and one near the Aegean Sea. Color indicates the absolute value of the magnetic dip angle, from 0° (blue) to 90° (red). Figure 8b shows the propagation magnetic azimuth in color as shown in the color wheel. Now the sampling of dip angle/magnetic azimuth is much richer (compared to the single-pair example above). Figures 9a and 9b shows the multi-pair sampling, in the same format as Figure 6 above. The multi-pair sampling of dip angle/magnetic azimuth provides much better coverage of diverse magnetic propagation azimuths than had been the case with the single-pair case above. Regarding coverage of dip angle, the multi-pair coverage is still poor. It is true that the path to the Belem station crosses the Magnetic Equator and hence contains dip angle magnitudes down to zero, but this is done at a nearly magnetic southward azimuth and hence does not sample very deep into the lowest-reflectivity solutions, for example, \( R < 0.65 \). Those lowest-reflectivity conditions occur only in night and where the azimuth is westerly and where the dip angle is low.

Figure 9c shows the penalty function in fitting the \( r \) parameter for the multi-pair comparison of model with data. Compared to the single-pair penalty function (Figure 6c above), the contrast (between the heights at the wings and at the minimum) is degraded, though there is still a clear best-fit determination \( (r \sim 2.8) \). One of the data/model comparisons is shown in Figure 10, for Lisbon paired with Forks (Washington State, U.S.). The transition shown here is a mixed transition, due to the great separation between Forks and Lisbon in local time. In fact, the
time of sunrise at Lisbon (blue zenith curve) almost exactly coincides with the time of sunset at Forks (red zenith curve). The gross features of the transient in the data (black squares) are approximated by the model (teal squares), but the data’s “overshoot” near the end is not.

The parameter fits shown in Figures 6 and 9 are typical of what we see: fitted values of $r$ in the range $2 < r < 3.5$, although some path-pairs, due to their collapsed geometry, yield no convergent solution. It is important to caution that this parameter fit does not necessarily prove the underlying correctness of the model. Rather, we have merely shown that, if we apply the model, the gross features of the day/night transitions can be predicted with parameter fits in the range $2 < r < 3.5$.

### 4.3. A Fundamental Limitation of This Method

The “holy grail” of this section would have been to observationally test, by the amplitude-ratio method, the model’s prediction of the broad and deep westward, nighttime transmission minimum.

Our method requires identifying copiously-emitting clusters of lightning. Within a cluster, the strokes must occur often enough in time to provide good statistics in each 500-s-wide sliding average. The strokes within the cluster must occur quasi-continuously over enough of the day to permit us to track ionospheric changes associated with the passage of the solar terminator. That the cluster meeting these requirements exists, is not by itself enough. Additionally, the strokes in the cluster must be simultaneously detected in far-flung station pairs whose coverage in the solution plane (see Figure 3) rigorously tests the predictions of the model. In order to probe the effects of magnetic-westward propagation at low dip angle, we must detect copious strokes at a station which, according to the model, will receive only a highly attenuated signal. If the model is correct, that requirement is impossible to meet. Highly attenuated signals at this station will either (a) be lost in the competition against other stations to locate the stroke, or (b) not even trigger the station at all.

And there’s the rub. Despite inspection of hundreds of cases of clusters that are well detected by station pairs, no combinations of clusters and stations that we have found are able to test the model for lower reflectivity levels than about 0.6 in the solution space. That is, the cluster/stations combinations that are found do not provide magnetic-westward propagation at low dip angle. We note from Figure 3 that the dramatic prediction of the model occurs for nighttime conditions in the magnetic-westward sector at low magnetic latitudes. The predicted suppression of the local reflectivity there is to a level as low as 0.05. However, we have found no station pairs, for any copious-emitting clusters, with propagation paths dwelling for a significant fraction of their length anywhere below a local reflectivity of 0.6.

Thus the station-pair-ratio method is not able, so far, to provide a test of the predicted deep nighttime suppression of magnetic-westward transmission at low-to-moderate dip angles. Nor have we found observations contradicting the model in those conditions. Rather, there is just no data of sufficient quantity for addressing that part of the solutions space: $R < 0.6$.

This is not an accident or bad luck. Rather, it is inevitable that a method requiring reception of copious strokes will fail along paths where the transmission is deeply suppressed. We cannot make ratios of amplitudes from two stations if these are of strokes that are not even recorded at one of those stations.

### 5. Discussion and Conclusions

We have presented a method to study the behavior of the inter-station ratio of VLF stroke amplitudes, for strokes that are simultaneously recorded at multiple WWLLN stations. This approach combines numerous recurrent strokes from long-duration lightning clusters to build a time-series of the ratio for a major portion of the UT day.
The time variations of the sliding-averaged ratio are dominated by transient excursions coinciding temporally with those periods when the solar terminator is present along one or both of the paths. This strongly motivates a model incorporating significant control by the solar zenith angle.

We have adapted an existing full-wave theory of reflection from the D-layer to model transmission in the Earth-Ionosphere Waveguide at the frequencies (5–20 kHz) contributing to WWLLN signals. The model predicts that magnetic-westward propagation has less waveguide transmission than does magnetic-eastward propagation. This anisotropy is modulated by magnetic dip angle: The anisotropy is strongest at low dip angle, and weakest at large dip angle.

**Figure 8.** (a) All paths for ratios with Lisbon. This includes three lighting clusters and six other stations, plus Lisbon. Color indicates the absolute value of the magnetic dip angle, from 0° (blue) to 90° (red). (b) Color indicates magnetic propagation azimuth, from −180° (blue) to +180° (red) as shown in color wheel.
To account for solar-zenith-angle control on the waveguide transmission, our model takes a weighted combination of pure-day and pure-night solutions, determined locally for every path element along the Great Circle Path from the lightning to the WWLLN station, and for the exact Universal Time of the stroke.

The model solution based on the plane-wave-reflection theory successfully accounts for the gross features of the solar-terminator transients. However, small, residual time variations not obviously related to the solar-zenith-angle control are also observed, but are outside the scope of our model.

Our model predicts, counter-intuitively, that the magnetic-westward attenuation at low magnetic latitude will be much deeper during night than during day conditions. Unfortunately, this suppression of magnetic-westward propagation also largely eliminates the availability of recurrent recordings of those signals at our low-latitude stations. Thus the amplitude-ratio method is inherently unable to check on one of the model’s most intriguing predictions.

The present report is preliminary. A later paper will develop an alternative approach to testing the model prediction of deep attenuation in conditions of low dip angle and magnetic-westward propagation.

Figure 9. Same as Figure 6 above, but with the loci of reflectivity versus magnetic azimuth of the Great Circle Paths between the three lightning clusters, and Lisbon and the six other stations with which it is involved in ratios.

Figure 10. Similar to Figure 7 above, but for the pair Lisbon:Forks. Black squares: Data. Teal squares: Model with fitted “reflections per Mm” = 2.8. Solid colored curves show solar zenith angle at lightning cluster (solid green), Lisbon (solid blue), and Forks (solid red).

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Data Availability Statement

For sale to researchers who are not WWLLN participants, WWLLN data are available, at a nominal price to cover overhead costs of running the network, and archiving/distributing the data. To find out about such data access, see http://wwlln.net/

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