The virtual ionosphere reflection height variation is investigated temporally and spatially, with specific reference to the Met Office’s lightning detection network, the Arrival Time Difference Network (ATDnet). Data from this network, operating at 13.7 kHz, and a propagation model built by the Met Office based upon published theory were used to investigate this variation, specifically with regard to diurnal, seasonal, and 11-yr solar cycle variation. Variation over these temporal scales is chosen, since they correspond with variation in solar irradiance upon the earth’s atmosphere, something known to drive ionosphere height variation. The virtual ionosphere reflection height is found to vary diurnally from \(65\) km for the period 1000–1600 UTC to \(80\) km for the period 2200–0400 UTC, from 1 June to 31 August 2013 inclusive. A similar magnitude of variation is also observed seasonally, with the ionosphere height for daytime in August 2013 being \(64\) km and for December 2013 being \(76\) km. No significant variation is observed between the minimum and maximum of the last solar cycle, with a difference in ionosphere height of \(1\) km at most. The potential impacts of these results upon a very low-frequency (VLF) lightning detection network such as ATDnet are discussed, with solutions such as subnetting and wave-mode dominance analysis examined.

1. Introduction

The virtual ionosphere reflection height is fundamental to understanding the atmospheric propagation properties of very low-frequency (VLF) transverse electromagnetic (EM) waves with frequencies in the range of \(3–30\) kHz. Much work has been undertaken in this area, especially within the fields of communication and navigation technology.

The existence of the ionosphere, a region of the atmosphere containing ionized particles, was first postulated by Gauss in 1839. After Marconi successfully transmitted a signal across the Atlantic Ocean in 1901 (Marconi 1902), Kennelly and Heaviside postulated that the transmitted radio wave reflected off this region of the atmosphere (Heaviside 1902). Another key step in understanding ionospheric properties was the suggestion that this region of ionized particles was sustained by solar radiation (Eccles 1912). Experimentally, Appleton and Barnett (1925) and Breit and Tuve (1925, 1926) measured the height of this conducting layer at different frequencies and at different times of day. Appleton then developed significant theory describing the ionosphere (Appleton 1927), winning the 1947 Nobel Prize for his efforts.

Since then, much work has gone into understanding how electromagnetic waves propagate between the earth’s surface and the ionosphere, with significant contributions from Wait (e.g., Wait 1962) and Budden (e.g., Budden 1985).

This study investigates the temporal and spatial variation of this virtual ionosphere reflection height, using data from the Met Office’s lightning detection network, the Arrival Time Difference Network (ATDnet). It follows previous work undertaken by the Met Office (Bennett et al. 2010, 2011) investigating the diurnal variation of ionosphere height using a similar method to that implemented here. However, this paper includes...
analysis of potential seasonal and ∼11-yr solar cycle variation of the virtual ionosphere reflection height. Results are again included for diurnal variation, since it provides a consistent foundation for the comparison of diurnal, seasonal, and solar cycle variations of virtual ionosphere height and the related effects upon interference minima positions for a lightning detection system, something that has not previously been undertaken.

Further to this, a VLF propagation model has now been developed, and is briefly detailed in this paper, that provides additional insight into the location of these minima and can be used to estimate the ionosphere height variation from the observed interference minima locations. This model is herein referred to as the Met Office Lightning Propagation and Attenuation of Signals (Met LPAS) model.

ATDnet is an arrival time difference lightning network, where the time taken for an EM signal to reach individual receivers, or outstations, is used along with a propagation velocity to determine distance from each receiver and hence the location of the source. At the time of this study, the network has the operational geometry given in Fig. 1 and operated at a frequency of 13.7 kHz. A description of ATDnet can be found in Lee (1986) and Bennett et al. (2010, 2011).

The work described here is of direct importance to any arrival time difference lightning detection system operating in the VLF band. It is of importance because the value of virtual ionosphere reflection height at a given time and location dictates properties such as the signal-to-noise ratio of any signals from lightning events, and more fundamentally the propagation velocity of the dominant wave-mode associated with this signal. This has a direct effect upon location errors of lightning events. Minimizing location errors or ambiguities in the fix location calculation introduced by the effects mentioned above is of great importance to the users of ATDnet, since having confidence of how close a lightning event is to, for example, an offshore wind farm, is of great concern in order to ensure safe operation and to minimize the risk to human life.

a. Introduction of relevant theory

This paper is concerned with the vertical electric field, created by a lightning stroke, that propagates through an Earth–ionosphere waveguide. In meteorology this signal is referred to as an atmospheric, or sferic, and is emitted over a broad band of frequencies, although here only the 13.7-kHz component is investigated as it is the current operating frequency of ATDnet. The Earth–ionosphere waveguide is bounded by the earth at one limit and the ionosphere at the other. VLF signals reflect off the ionosphere at a height referred to as the virtual ionosphere reflection height. This is the height at which the electron density is sufficient to allow reflection at VLF frequencies, since the conductivity of the cold plasma created by ionization is dependent on the electron density and VLF waves reflect off the ionosphere above a certain conductivity (Wait and Spies 1964). The electron density is primarily driven by the solar irradiance incident upon the earth’s atmosphere, as photons of sufficient energy from the sun colliding with atoms or molecules in the atmosphere have a certain probability of ionizing them, often referred to as photoionization. The virtual ionosphere reflection height is herein referred to simply as “ionosphere height.”

Within the earth–ionosphere waveguide, there are various modes of propagation. First, there is a ground
wave, which travels along the earth’s surface, only interacting with this boundary. There are also sky wave modes that reflect once or multiple times off the ionosphere boundary. The first sky wave mode is defined as reflecting off the ionosphere once, the second mode is defined as reflecting off the ionosphere twice, and so on. Although this way of comprehending the physics of the system uses ray theory, it can aid one’s understanding of full wave-mode solutions (e.g., Volland 1995), such as the method of modeling the physical system described in this paper. Attenuation of the ground wave increases with distance and attenuation of the sky wave modes also increases with distance, and with every reflection off the ionosphere or the earth’s boundaries.

b. Overview of the propagation Met LPAS model

A VLF propagation model is used to provide an estimate of the ionosphere height for given observations. The Met LPAS model is based upon literature (collected in Volland 1995), and is applied in the form of a transfer function applied to an electric field signal and calculated over the spatial and temporal domains. The transfer function is applied to the electric field by

$$E_{z,\rho}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{E}_{0,\rho}(\omega) T(\omega) e^{-i\omega t} d\omega,$$

where $\omega$ is angular frequency, $t$ is the time, and $\hat{E}_{0,\rho}(\omega)$ and the transfer function $T(\omega)$ are given by

$$\hat{E}_{0,\rho}(\omega) = \frac{1}{c} \rho \int_{\text{location}} E_z(t) e^{i\omega t} dt,$$

$$T(\omega) = \frac{1}{h} \left( \frac{i\rho \lambda \Theta}{\sin \Theta} \right)^{1/2} \sum_n K_n e^{-A_n \rho + iB_n \rho + (1 + B_n) h / \rho} / 2a,$$

where $E_z(t)$ is the simulated electric field created by a lightning stroke at a given time perpendicular to the earth’s surface; $\rho$ is the propagation distance; $h$ is the ionosphere height; $\lambda$ is the wavelength of the EM wave; $k$ is the wavenumber, $a$ is the earth’s radius (~6371 km); $K_n$, $A_n$, and $B_n$ are amplitude, attenuation, and phase factors, respectively, for the $n$th sky wave mode; and $n$ equals zero is the ground wave mode. Polar distance $\Theta$ is given by

$$\Theta = \frac{\rho}{a}.$$

This model accounts for the Earth–ionosphere waveguide curvature and attenuation at the boundaries, and incorporates a number of sky wave modes to further improve the representation.

c. Method of investigating virtual ionosphere reflection height variation

Ionosphere height variation is investigated by using the time-averaged absolute signal-to-noise (ASN) ratio variation spatially to find the positions of interference minima. The ASN ratio effectively allows for measurement of the quality of a lightning event signal temporally and spatially, and if it is assumed that on average a lightning event signal will have a particular ASN ratio, then the underlying patterns in the ASN ratio data are likely induced by variation in the propagation of that signal. Behaviors seen in the ASN data can therefore be used to investigate temporal and spatial variation in the earth–ionosphere waveguide properties. The Met LPAS model can predict the position of these minima for a given ionosphere height by calculating the transfer function amplitude with distance from a simulated lightning event. Comparison of the position of the interference minima found via experiment and the predictions given via the Met LPAS model then allow for an estimation of the average ionosphere height over the given period. Data from the model that allow for an estimation of the average ionosphere height over a given period, along with a more in-depth explanation of how these data are used, are provided in the results and discussion section.

Before undertaking this analysis, calibration of the Met LPAS model was carried out, using data from NASA’s International Reference Ionosphere (IRI) model (Bilitza et al. 2011), which predicts the ion density, and hence the electron density, that can then be used to determine the ionosphere height for a given location and time. The IRI model has limitations in that the ion density values obtained from the model are not instantaneous, but a source of more appropriate ion density values for this study is not known. Therefore, in the absence of more appropriate estimates, the lightning data are averaged over a 3-month period. As the data are used only to approximately verify that the Met LPAS model provides a realistic estimate for ionosphere height, use of the IRI model for calibration is deemed appropriate in this situation. Details of this calibration are not included in this paper, but they could be undertaken independently by referring to the literature behind the Met LPAS model (Volland 1995) and the IRI model data at the locations of the outstations used in this paper.

The primary outstation used in this investigation is Payerne, Switzerland (46.8ºN, 6.9ºE), although some data for Norderney, Germany (53.7ºN, 7.2ºE), and Exeter, United Kingdom (50.7ºN, 3.5ºW) are included. Where the Met LPAS model is plotted with experimental data, the ionosphere height input into the model...
is referenced by using NASA’s IRI model to find the ion density, the corresponding electron density, and therefore the conductivity at which reflection of VLF waves occurs. According to literature (Wait and Spies 1964; Volland 1995) a reasonable approximation for VLF radiation is to assume reflection at a conductivity of $2.2 \times 10^{-6} \text{ S m}^{-1}$, and it can be calculated using

$$\sigma = \left( \frac{N e^2}{m} \right)^{1/2},$$  \hspace{1cm}(5)$$

where $N$ is the electron density at a given height (from NASA’s IRI model), $e$ is the charge of an electron, $e_0$ is the permittivity of free space, and $m$ is the electron rest mass. The height associated with this conductivity is then used to obtain a prediction of ASN ratio from the Met LPAS model for comparison with data, as given in Figs. 2 and 3. The associated virtual ionosphere reflection heights calculated from Eq. (5) using NASA’s IRI model at the correct geographic location of the station Payerne are found to be approximately 60 and 83 km over the period studied for daytime and nighttime, respectively.

As the current operating frequency of ATDnet is 13.7 kHz, all data in this paper are measured at this frequency and model data are therefore also calculated for a frequency of 13.7 kHz. The height of reflection of VLF waves off the ionosphere is proportional to frequency, with a higher-frequency electromagnetic wave reflecting off a greater ionosphere height (e.g., Booker and Seaton 1940). In a plasma such as the ionosphere, the transmission and reflection properties are dictated by the plasma frequency $\omega_p$, given by Kittel (2004),

$$\omega_p = \left( \frac{N e^2}{m e_0} \right)^{1/2}. \hspace{1cm}(6)$$

The conductivity of the ionosphere $\sigma$ and the plasma frequency $\omega_p$ are therefore related to one another, and since $\omega_p = 2\pi f$, the frequency of an electromagnetic wave transmitted through a plasma, $f$, is therefore related to conductivity by

$$\sigma \propto 2\pi e_0 f. \hspace{1cm}(7)$$

As this is a linear relationship and the conductivity of the ionosphere defines the virtual reflection height of the ionosphere, one would expect the ionosphere height to vary linearly with frequency. The conductivity of the ionosphere increases with height; therefore, a higher frequency would result in a higher virtual ionosphere reflection height. This relationship can be used to predict how the data and model results in this paper are relevant at other VLF frequencies, although this is not undertaken here as no supporting data can be provided.

The lightning event data presented in this paper are temporally averaged over a period of 3 months, within a given time frame each day, unless otherwise specified. Much variation is observed in the approximately
instantaneous data for a given time on a given day. Averaging is therefore undertaken to minimize the effects of temporal perturbations of the order of seconds to days, caused by varying weather conditions or brief solar events, biasing the general trends observed that vary diurnally, seasonally, or with the solar cycle. Although the impacts of varying weather conditions or brief solar events on lightning location detection could be of great interest, they are not discussed here, partially because of the technological challenges that would be faced if trying to optimize a lightning detection network to account for these effects. The temporally averaged data given in this paper is intended to guide decisions about where more robust corrections for diurnal, seasonal, and solar cycle can be made in order to provide finer tuning for a VLF lightning detection system, especially a network using a comparably narrow frequency band to that of ATDnet.

2. Results and discussion

a. Diurnal variation and introduction of Met LPAS model results

ASN ratio data are provided for lightning events detected by ATDnet over the periods of 1000–1600 UTC and 2200–0400 UTC 1 June to 31 August inclusive. Data over this period for two other ATDnet outstations and for Payerne are provided. The stations Norderney and Exeter are included to verify that the data from the outstation at Payerne are broadly representative of the behavior observed for a given outstation in ATDnet. Figures 2 and 3 present this ASN data over the two periods, daytime and nighttime, respectively, being plotted separately for clarity. The corresponding results from the Met LPAS model are also plotted for comparison in these figures, with the ionosphere height used to produce the Met LPAS model plots in Figs. 2 and 3 derived from IRI model data for the location of the ATDnet station at Payerne for the durations for which the real lightning event data are plotted. Here, and throughout the rest of this paper, the Met LPAS model’s results are for a ground waveguide mode \( n = 0 \) in Eq. (3) and four sky waveguide modes \( n = 1 \) to \( n = 4 \) in Eq. (3), since for this number of contributing waveguide modes the model’s predictions approximately converge. No more waveguide modes are therefore needed and would increase computational cost for negligible gain. This comparison also indicates how well the model represents the physical behavior observed.

The data for the three outstations mentioned above over the summer of 2013 show several interference minima associated with daytime and nighttime conditions, defined for the purposes of this paper as 1000–1600 UTC and 2200–0400 UTC, respectively. These periods are therefore referred to as daytime and nighttime, respectively.

The data given in Fig. 4 are provided to show the Met LPAS model’s response of the position of the interference minimum with variation of ionosphere height. The data are obtained by varying the ionosphere height input used by the model and finding the positions of the first daytime minimum and the first two nighttime minima.
The errors given in Fig. 4 are likely to be overestimates because of the half-width maximum method used. Errors could be further constrained and confirmed by using data from a greater number of years. Data such as these outputs by the model allow for estimation of the variation in ionosphere height when compared to the measured positions of interference minima in the observed lightning event data.

For daytime, Fig. 2, one interference minimum can clearly be seen at ~400 km, with another less clear minimum at ~2600 km, which is observed only in the Payerne and Norderney data. At the first minimum, the drop in ASN is greater than 50%. For nighttime, Fig. 3, there are two minima below 1000 km, and for Norderney and Exeter there is also a clear minimum at ~2000 km. The first nighttime minimum is indicated by a drop in average ASN of 40%, the second minimum is indicated by a greater drop of more than 50%, and the third minimum is characterized by a drop of ~50%.

Determining which of the significant nighttime minima less than 1000 km corresponds to the significant daytime minimum within this range can be undertaken using the Met LPAS model. If the Met LPAS model’s ionosphere height is varied and the results are compared to that of the experimental diurnally varying data, it can be seen that the second significant interference minimum at night corresponds with the first significant interference minimum during the day (see Fig. 4). When the experimental data in Figs. 2 and 3 are then compared to the Met LPAS model output, it is made clear that as the ionosphere changes from the daytime regime to the nighttime regime, the distance of the observed interference minimum in the daytime increases in distance from the source while a closer interference minimum to the source becomes significant at this greater ionosphere height.

The Met LPAS model’s results plotted in Figs. 2 and 3, which are correlated to the position of the greatest minimum, show agreement with the positions of minima for both day and night for distances less than ~1000 km. However, at night there is also clear agreement of the Met LPAS model with the data for Norderney and Exeter at 2000 km, suggesting that the minimum at this distance for Payerne is suppressed for some reason. This difference is likely due to the proportion of land and sea surrounding the outstation and/or the topography of the land.

First, Payerne is surrounded for hundreds of kilometers by land. The Met LPAS model assumes a land conductivity of the propagation of the ground wave, since the model is run with parameters most relevant to Payerne. However, there is the possibility that the attenuation coefficients for the sky waveguide modes, which are likely dominant at 2000 km (Volland 1995), may be more representative of at least some propagation over water, which has greater conductivity and therefore would result in different attenuation characteristics. Literature also suggests that lightning events may have higher signal amplitude over sea than land (e.g., Said et al. 2013; Zoghzoghy et al. 2015), which would influence the signal-to-noise ratio of detected events at angles from the stations where seas or oceans are located. Furthermore, data from satellite observations suggest lightning occurrence rates differ over land and sea (Blakeslee et al. 2014), potentially biasing the number of events observed on average at the various stations.

Second, the topography of the land surrounding Payerne is more varied compared to that of Norderney and Exeter. Figures 5 and 6 give plots of the two-dimensional spatial variation of the average ASN ratio for Payerne for daytime and nighttime, respectively. The interference rings observed vary in width and intensity with angle. If there are no data for a certain area, then it is simply because no lightning events were detected in those regions. However, where there are data over a certain area, then it is likely the higher or lower ASN ratios are either due to a greater number of events, since mountainous regions are closer to the cloud base and therefore potentially increasing the likelihood of lightning events, or due to underlying geophysical phenomena associated with mountains that potentially perturb the ionosphere (Grocott et al. 2013; Lastovicka 2006) and potentially inhibit certain ground wave propagation. Plotting event number density variation spatially, as
given in Fig. 7, likely rules out the number of events causing this spatial variation with angle from the outstation, since there is no correlation between the data in Fig. 7 and the data in Fig. 5. Geophysical features and the topography therefore cause this variation of ASN ratio with angle and are a likely cause of the disagreement between Payerne and Norderney or Exeter.

The spatial variation of the ASN ratio with angle from the outstation discussed above is therefore also of importance when considering interference minima generally, since 2D spatial effects could be hidden in the 360° averaging method used for the analysis of all the ASN ratio data against the distance from source plots included in this paper. As these effects seem to become

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FIG. 5. Plot of average ASN ratio with latitude and longitude (0.1° × 0.1° bins) over Europe, for 1000–1600 UTC 1 Jun to 31 Aug 2013 inclusive, for the ATDnet outstation at Payerne.

FIG. 6. Plot of average ASN ratio with latitude and longitude (0.1° × 0.1° bins) over Europe, for 2200–0400 UTC 1 Jun to 31 Aug 2013 inclusive, for the ATDnet outstation at Payerne.
prominent only at distances of greater than 1000 km, detailed analyses, to find corresponding ionosphere heights using the Met LPAS model, are restricted to distances below 1000 km.

Table 1 provides a summary of the interference minima positions for daytime and nighttime, and the corresponding estimated ionosphere heights using the Met LPAS model. The errors are likely overestimated, as discussed earlier. The observed variation in ionosphere height between daytime and nighttime is 15 km. This difference is significant, with a greater than 20% increase in height at night that inevitably leads to the variation in propagation characteristics observed in the data presented in Figs. 2 and 3 specifically. There is a deviation in the estimate using the nighttime minima, with a 2-km discrepancy. This indicates that the Met LPAS model still has room for improvement and its estimates of ionosphere height are accurate only to within the order of several kilometers.

b. Seasonal variation

Figure 8 gives a plot of average ASN ratio variation with distance from the source, over daytime for every day in each month of the year 2013. The data are plotted only to a distance of 1000 km from the source, since the interference minimum variation, and other general signal trends, are clearer over this length scale. The behavior seen in this region is representative of that up to 3000 km and likely further apart from an obvious reduction in signal amplitude with distance. It can be seen that, generally, the summer months have less ASN signal fluctuation than the winter months, with July having the least ASN signal variation and December having the most. A key observation from these results is the trend of interference minimum with month. The farthest interference minimum position occurs in winter, at a distance of ~520 km from the source for the month of December, while the closest minimum position occurs at a distance of ~380 km from the source for the month of August. September has a minimum that occurs closer again than August’s, but it is not clearly defined, with another local minimum within 50 km, and so is not used. According to the Met LPAS model’s predictions, see Fig. 4, the virtual ionosphere reflection height therefore varies, on average, from ~76 km in December to ~64 km in August. This difference of ~12 km is significant, a
15% variation in the ionosphere height that will inevitably vary the group velocity of sky-waveguide modes.

The lower fluctuation in ASN in summer suggests that the ionosphere is more stable during this season. Data have also been analyzed for other ATDnet outstations, the results of which prove consistent with Payerne’s, suggesting that it is not due to a physical anomaly regarding the setup of the outstation at Payerne. However, there are reasons other than the stability of the ionosphere that could be the cause of this apparent variation. One possibility is that the amplitude of the signal from the average lightning stroke may be greater in summer than in winter, which would cause the absolute signal-to-noise ratio to increase and therefore reduce the effects of any noise in the VLF band on the detected signal. However, this is unlikely since there is no conclusive evidence of a seasonal variation in lightning amplitude (Miyake et al. 1992; Goto and Narita 1995) and the amplitude of detected winter lightning strokes appears comparable to that of summer lightning strokes (Guimaraes et al. 2014). Another reason could be due to a greater number of events over which to average, which reduces the effect of noise. It is known that lightning over Europe is more prevalent in the summer than in the winter, and so this could feasibly account for the reduction in variation, or noise, seen in the July data over the January data.

The shift in the interference position, whereby it moves closer to the source in the summer, suggests that the ionosphere height is reduced during the daytime in summer. One might expect this, since the ionosphere height variation is primarily driven by solar radiation intensity incident on the atmosphere, which is greater in summer than in winter for the Northern Hemisphere.

The greater flux of photon incidents upon the atmosphere results in a greater probability of photons penetrating further and ionizing particles at a lower height in the atmosphere.

Since the data in Fig. 8 are for daytime, it is worth considering whether the seasonal variation has any effect at nighttime, since one might conceive that this could have an impact after the day–night terminator, caused by a lag in the seasonal effects. The plot given in Fig. 9 clearly refutes this idea, showing similar results for nighttime data averaged over the months of January and July 2013 separately.

c. Variation with the 11-yr solar cycle

Figure 10 gives average ASN ratio data for daytime over the summers of the years 2008 and 2013, corresponding approximately with summers closest to the most recent solar minimum and maximum, respectively (Yeo et al. 2014). First, the interference minimum position at ~400 km does not move significantly toward the source, with a shift of ~20 km closer to the source for the 2013 data, corresponding with the solar maximum. According to the Met LPAS model, see Fig. 4, this would suggest a difference in ionosphere height of ~1 km. This suggests that the ionosphere height does not vary significantly with the solar cycle variation, or at least not sufficiently with regard to a system such as ATDnet. Although at first sight this result suggests that the ~11-yr solar cycle has little effect, solar cycles over this temporal scale are not necessarily consistent. For example, the solar minimum used in this investigation was lower and occurred for longer than the previous minimum
(Solomon et al. 2010), which occurred in 1996. This lack of consistency and therefore predictability means that although these results are reliable for the period measured, they may not be representative of other solar minima.

Second, the ASN ratio is generally higher for the 2013 data, allowing for more distinct minima after 1000 km to be seen that is not observed clearly in the 2008 data. This is likely to be due to an alteration of equipment at the receiver site between these dates, resulting in reduced noise but also an apparent increase in the standard deviation of the data. Unfortunately, when observing effects over this temporal scale, the improvement of detection equipment is largely unavoidable as it is driven by other factors. Fortunately, no changes have been made that would have affected the minimum position.

d. Implications for ATDnet, or a similar VLF lightning detection system

The results of this study, specifically how the ionosphere height and therefore the locations of interference minima vary diurnally, seasonally, and over an ~11-yr solar cycle, have implications for ATDnet or a similar lightning detection system. These results are primarily in minimizing areas of relative poor performance in interference minimum regions and in selecting the propagation velocity for the dominant wave-mode correctly.

The presence of interference minima in ATDnet data results in either a lightning event not being detected by the given outstation associated with the interference minimum region within which that event occurred or, more detrimentally, the outstation cannot discriminate between several events that have similar apparent waveforms. The reason is that the signal-to-noise ratio is lower for each waveform, causing ambiguity and potentially incorrect correlation of one event detected in the outstation’s interference minima regions and that of another event detected by the other outstations in the network.

The methods of compensating for the relatively poor performance in this interference minima region are broadly similar in that the effective geometry of the detectors used to locate a lightning event must be varied, independently of the causes of an interference minimum band, whether it be a diurnal fluctuation or one over an ~11-yr solar cycle. One method is discussed in previous work (Bennett et al. 2011), whereby additional stations are added that are sufficiently far from the event that their interference minima are insignificant and therefore improve the performance in these regions.

Another method that also potentially mitigates this issue is dynamic subnetting, where stations are switched in and out of a system depending upon whether an event falls in an interference minimum region. An event that occurs within a station’s interference minima regions may be discounted, or weighted to mitigate its detrimental effects on the location accuracy, thereby increasing the location accuracy and the number of events positively identified by ATDnet. The concept of dynamic subnetting as a solution is feasible only if sufficient outstations are available to maintain a minimum number of contributors necessary to locate a particular lightning event.

For dynamic subnetting to be implemented, the interference regions have to be known either in real time.
or in advance, since there can be much temporal variability from day to day in ionosphere height, with variations of the order of kilometers observed (Maurya et al. 2012). Currently, real-time calculations, although the most desirable solution theoretically, are not possible since there is currently no reliable source or method of measuring the virtual ionosphere reflection height at VLF frequencies in real time on a global scale. However, data such as those provided here, combined with the predictions of the computational Met LPAS model used in this study, could provide an estimate as to where these interference minima regions are located for a given time, which could then be used as a reference for an ATDnet subnetting mechanism.

It is suggested that seasonal data for a greater number of years could be used to further constrain these estimates. If the dynamic subnetting approach were applied seasonally, then it is also suggested that further analysis is undertaken to establish whether averages would be most representative if taken over 1, 3, or 6 months. As the data given in Fig. 8 suggest a relatively consistent variation in interference minima location month by month, a 6-month average could be discounted, with a month-by-month comparison favored, as long as any annual discrepancy in solar intensity or atmospheric conditions was considered.

Since the variation of interference minima region location is $\sim 20$ km or less over an $\sim 11$-yr solar cycle, the effectiveness of correction via dynamic subnetting is uncertain. Based on the results from this study, subnetting to correct for such a small spatial fluctuation over such a long time scale is not recommended.

One further method of compensating for the negative impacts of interference minima could be to measure different frequency VLF signals, which would reduce the interference minima effects because a different VLF frequency would reflect at a different height and so have a different interference minima pattern to that observed in the data presented in this paper. However, this has been considered for ATDnet; but, although this is a theoretically simple solution, it is a production system, which therefore means that such changes currently cannot be accommodated and therefore no supporting data can be produced.

As well as addressing the negative effects of the interference minima upon a lightning detection network, the results of this study could also aid improved network geometry decisions for a future network. A geometry could be designed such that it minimized the effects of diurnal variation, seasonal variation, or potentially both, depending upon operational requirements.

The second implication of this study for ATDnet is the correct selection of the propagation velocity associated with the dominant wave mode at a given distance. This is an important consideration for any arrival time difference lightning detection system, since the propagation velocity directly affects the location error of the solution. A signal received at an ATDnet outstation may be composed of a number of different modes, with the mode of greatest amplitude being used to determine the timing difference of that event from the reference signal from another detector. The greatest amplitude component of this waveform will be associated with the dominant wave mode at the distance of the detector from the event.

The distance over which the ground waveguide and sky waveguide modes are dominant is briefly discussed in literature (e.g., Volland 1995) but experimental calibration of this for a particular network, over varying topography, would be invaluable in the minimization of location error for an arrival time difference lightning detection system.

The propagation velocity for the $n$th mode, the group velocity, is given by Griffiths (2013) as

$$v_g = \frac{\partial \omega}{\partial k}$$

which for the Met LPAS model is given by Volland (1995) as

$$v_{g,n} = \frac{c}{\left(1 + \frac{h}{2a}\right)^2 \left(1 + \frac{(2n - 1)^2 \pi^2 c^2}{8h^2 \omega^2} + \frac{c}{4h} \left(\frac{2e_0}{\sigma_e \omega}\right)^{1/2}\right)}$$

where $c$ is the velocity of light in the medium and $\sigma_e$ is the ground conductivity.

This velocity, which is calculated by the Met LPAS model for given wave modes, is directly dependent upon the ionosphere height. If the positions of the interference minima for an outstation were found, the ionosphere height and hence the propagation velocity of each wave mode can be inferred using the Met LPAS model.

Wave-mode dominance analysis can be undertaken using the results of this study by using the Met LPAS model to assess each mode’s effect on the ionosphere height. Then this could be verified experimentally by using lightning event data that occurred at a known time and location, and then investigating the time of arrival of the associated signal with various outstations at various distances from the event. Although it can prove challenging to know the exact location and time of a lightning event, it is possible to a sufficient level of accuracy. Locations such as Säntis Tower, Switzerland (Romero
et al. 2013b), have lightning event data available (Romero et al. 2013a), sufficiently constrained to potentially identify the signal as detected by a system such as ATDnet.

e. Wider implications and potential applications

The results given in this paper are also applicable to VLF propagation generally. For example, in the field of communications, knowing where the interference minima regions occur and how they vary with season could prove valuable when designing a static communication network or where vulnerabilities may lie in a dynamic network with moving transmitters or receivers.

A wealth of information regarding the influence of solar irradiance on the earth’s atmosphere is encapsulated within lightning data. It is accepted that the sun influences the earth’s climate system on seasonal, decadal, and longer time scales (e.g., Gray et al. 2010; Haigh et al. 2010). Temporal variation in the data presented here clearly indicates that data of this sort have the potential to be used to investigate climate variation, over time scales up to decades in the case of Met Office data.

3. Conclusions

Clear diurnal variation of ionosphere height is measured, confirming previous work in this area. A variation of ~15 km is observed between day and night virtual ionosphere reflection heights of ~65 and ~80 km, respectively, with the Met LPAS model approximately representing the physical behaviors observed. Seasonal variation is observed, with a gradual change month by month, and the maximum variation occurring between the months of December and August, with ionosphere heights of ~76 and ~64 km, respectively. This ~12-km variation is similar in magnitude to that of diurnal variation and so should be considered important when attempting to account for ionosphere height variation for a lightning detection system such as ATDnet. An 11-yr solar cycle variation is addressed, with an ionosphere height variation of ~1 km observed. The effect of this variation would be minimal compared to diurnal and seasonal effects; thus, for current lightning detection network technology, it is suggested that 11-yr solar cycle correction is not necessary. However, because of the variation of individual solar cycles, it is recommended that an investigation similar to this be repeated over a greater number of solar cycles, if such data become available.

Methods of mitigating the effects of spatial and temporal variation of interference minima regions discussed include dynamic subnetting, to switch in and out contributing outstations for locations where the interference minima regions occur; and wave-front dominance analysis, to provide a known reference for the distance at which a given wave mode is dominant for a particular location and time. Wider implications of the results presented in this paper include improved identification methods of potential communication system vulnerabilities and applications of lightning event data for the analysis of how solar irradiance variation affects Earth’s climate system.

Acknowledgments. Thanks go to S. Matthews, P. Taylor, P. Odams, and R. Smout (Met Office) for valuable their insight and contributions in the area of the technical operation of ATDnet. Thanks also to G. Anderson for developing some of the Python code used to analyze and plot the observational data. Thanks also go to M. Fullekrug (University of Bath) for his contributions aiding the development of the theoretical Met LPAS model. Finally, thank you to the anonymous reviewers for the constructive feedback, especially with respect to guidance on additional relevant literature.

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