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# The Effect of Changes in Lightning Waveform Propagation Characteristics on the UK Met Office Long Range Lightning Location Network (ATDnet)

Alec Bennett[1], Greg Callaghan, Catherine Gaffard, John Nash and Richard Smout

*Met Office, FitzRoy Road, Exeter, EX1 3PB, United Kingdom*

## 1. Introduction

The UK Met Office owns and operates a long-range Very Low Frequency (VLF) lightning location network called ATDnet. The network of 10 operational sensors, located mostly in Europe, continually monitors a narrow electromagnetic frequency band centred at 13.7kHz in the VLF for short bursts of activity associated with lightning strokes. An overview of the ATDnet system is described by Gaffard et al. (2008). Once a stroke is detected at a sensor site the waveform is recorded and sent to the Met Office headquarters in Exeter, UK for processing. Accurate timekeeping (down to a few nanoseconds) is essential as it is the Arrival Time Difference (ATD) between waveform arrivals at different sensor sites which is used to locate the origin of the stroke. Once the arrival time differences are calculated for a lightning stroke, the location is estimated using a waveform propagation algorithm. Since ATDnet determines arrival time differences using waveform correlation, any changes to the waveform shape need to be considered for accurate location estimates. The VLF signal emitted from the lightning stroke is trapped between the surface and upper atmosphere in the Earth-Ionosphere waveguide. As the signal propagates it undergoes dispersion, so the individual phases of the waveform propagate faster than the position of maximum amplitude, which travels slightly slower than the speed of light at the group velocity. The difference between group and phase velocity needs to be accounted for by the stroke location algorithms in order that the waveforms from each sensor site can be properly correlated. The values of phase and group velocities are dependent on the waveguide cut-off frequency and the frequency of the signal being received (equation 1). The waveguide cut-off frequency represents the lowest frequency that can propagate in a given mode along the waveguide without severe attenuation and is a function of the waveguide height, which in this case is the height of the ionosphere (equation 2).

$$V_g = c\sqrt{1-\left(\frac{\omega_0}{\omega}\right)^2} \quad (1),$$

[1] Corresponding Author contact email: alec.bennett@metoffice.gov.uk

*where $V_g$ is group velocity, c is speed of light in a vacuum, $\omega$ is angular frequency of received signal and $\omega_0$ is the cut-off angular frequency of the waveguide.*

$$\omega_0 = \frac{\pi c\left(n - \frac{1}{2}\right)}{h} \qquad (2),$$

*where n is the mode number and h is the waveguide height (i.e. ionospheric height).*

Equation 2 assumes the waveguide sides are uniformly conducting with no spatial variability of h, so is a simplified approximation of the real Earth-Ionosphere waveguide (Hunsucker and Hargreaves, 2002), which possesses spatial variability in both ionospheric and surface conductivities. From these equations it is evident that variation of the ionospheric height will produce a corresponding variation in group velocity of opposite sign. In reality, the ionospheric height is not constant but varies according to the ionisation profile. In the absence of geomagnetic storms, the most pronounced variability is the diurnal, where photoionisation from solar UV lowers the effective ionospheric height for VLF from approximately 85km at night to 70km during the day over mid-latitudes e.g. Wait and Spies (1964), Kikuchi (1986). Accounting for such ionospheric variability in long-range VLF lightning location networks propagation algorithms has shown an improvement in location error and detection efficiency (Chronis and Anagnostou, 2003), although such re-processing will increase computation time and an initial general location of lightning strokes will need to be identified before the relevant corrections to propagation paths could be implemented in real time.

ATDnet locates lightning strokes over a broad geographical region (Figure 1) using algorithms that do not currently account for ionospheric variability, making it possible to analyse the effect of such variability over different spatial and temporal scales. The effects of changes to ATDnet lightning location parameters resulting from a change in these propagation characteristics are discussed in subsequent sections, categorised by their observed spatial and temporal influence.

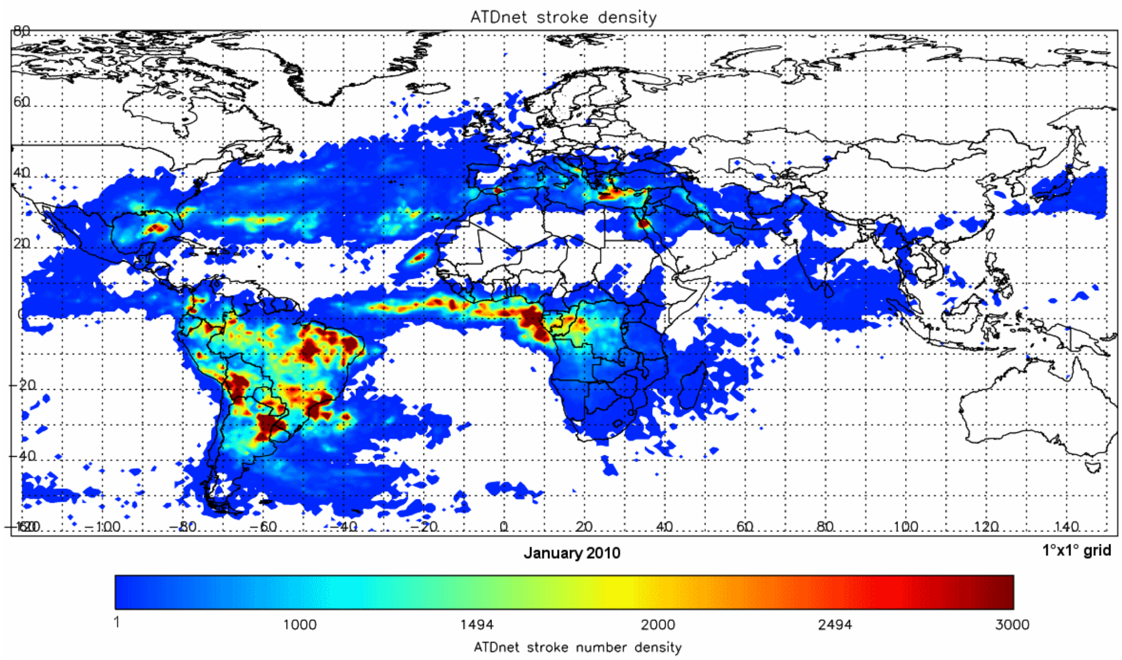


Figure 1: Stroke number density for one degree grid boxes located by ATDnet during January 2010. Only European sensors were active during this period.

## 2. Short period random variability of stroke location uncertainty

Random, short-period variability of phase and group velocities for a propagation path occur continuously and are most pronounced at long range. The effect of such variations is to broaden the distribution of lightning location errors, the magnitude and orientation of which also depends on the network geometry. Although individual variations can not be modelled, the general effects on the location error distribution can be theoretically modelled and mitigated against by appropriate network geometry.

ATDnet locates lightning strokes by minimising the cost function between observed and theoretical arrival time differences for an initial location estimate (Lee, 1986). The sensitivity of arrival time difference hyperbola locations between different sensor sites to arrival time errors can be calculated for any stroke location and assumed time difference variance caused by random variations in propagation velocities. Combining the hyperbolae location sensitivities for all active sensor sites allows the typical rms location error to be mapped. The spatial variability of location error is strongly dependent on the network geometry, especially the locations of the outer sensors which mark the network boundary as location uncertainty is lowest within the network.

The effect of such variability and validity of theoretical location error estimations has been assessed for long (~9,000km) propagation paths between Europe and southern Brazil. Figure 2 shows a map of theoretical location error magnitude and direction for South America, calculated assuming an arrival time difference variance of 10 microseconds and the participation of all sensors in the lightning location. Assessment of the validity of this theoretical model was achieved by comparing ATDnet lightning stroke locations to cloud-to-ground strokes detected by a local network covering southern Brazil. The network (BrasilDAT) is highly accurate (typical error <1km) and was used as an indicator of actual stroke locations. Strokes coincident in time (<1ms) between ATDnet and BrasilDAT were collected during 1-10 January 2008 and their vector differences in location calculated. The results of the comparison are shown in Figure 3, with the theoretical location error ellipse superimposed. As short-period random variability is being assessed, the observed small location offset in the modal range is used as the centre of the error ellipse rather than the zero-difference position, for ease of comparison. The offset is smaller than the standard deviation of latitude and longitude error distributions, so is not considered statistically significant, although it is possible that such offsets are produced by the diurnal variation of ionospheric height, as discussed in the next section. Similar minor offsets have been observed for other long-range lightning location networks (Roger et al., 2005).

It can be seen that the distribution of observed location errors are in close agreement with the theoretical ellipse, which would represent the area enclosing ~70% of data. Minor deviations in the orientation of observed location error long axis are due to the use of different sensor sites by the ATDnet algorithms. Similar agreement between simulated and observed location errors for long ranges were obtained by Chronis and Anagnostou (2003) using the ZEUS network, which uses the same general location technique and error estimation as ATDnet. The close agreement between observed and modelled location error distribution also implies that the 10μs variance assigned to the typical random timing errors due to variability in propagation velocities, waveform correlation and timekeeping is appropriate. 10μs was also shown to be appropriate for the World-Wide Lightning Location (WWLL) network in a similar study by Roger et al. (2005).

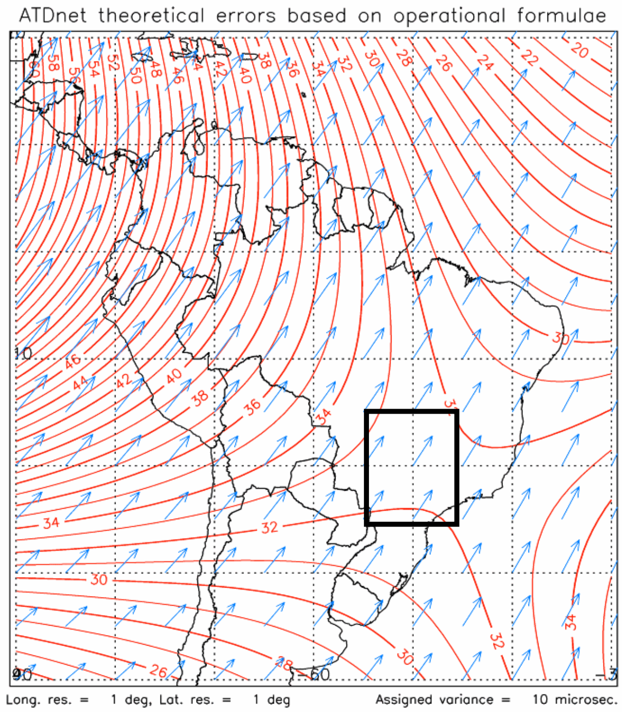


Figure 2: ATDnet theoretical location error (red contours) in kilometres and error ellipse orientation (blue arrows) for South America, for a 10 microsecond arrival time difference variance and participation of all ATDnet sensor sites in the lightning location. The rectangle indicates the region used for ATDnet and BrasilDAT cloud-to-ground lightning location comparison.

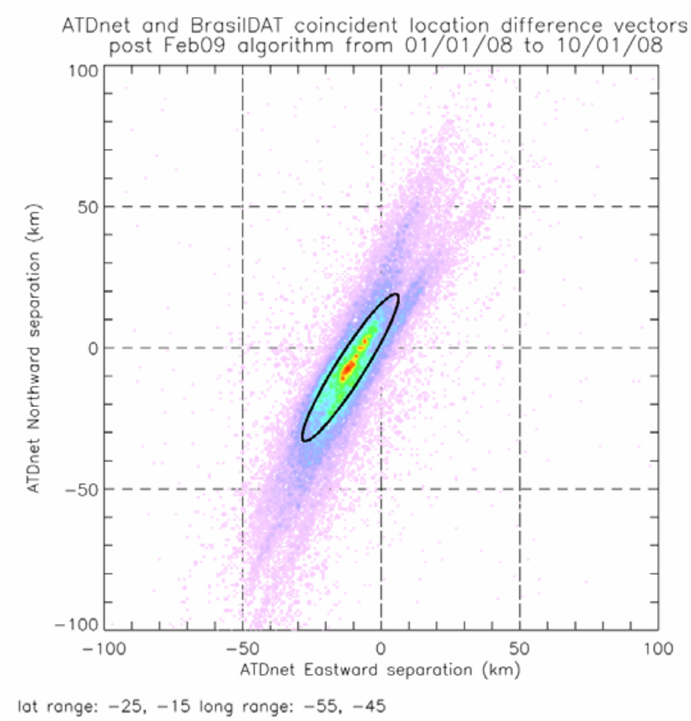


Figure 3: Observed ATDnet location error (derived using coincident strokes with the BrasilDAT network), with the theoretical error ellipse for Southern Brazil superimposed. The ellipse is

centred on the modal location error. Data collected during 1-10 January 2008, rerun using an ATDnet location algorithm update during early 2009. The scatter plot is coloured according to event density (red being most dense).

## 3. Diurnal variability of medium range stroke location uncertainty

Propagation of VLF can be considered to be in the form of several modes following the Earth-Ionosphere waveguide. The primary mode (mode 1) is characterised by the lowest cut-off frequency and hence fastest group velocity as indicated by equation 2 compared to higher order modes. The lower cut-off frequency of the primary mode also means this mode is less attenuated with distance compared to higher modes (Kikuchi, 1986). As the different modes travel at different speeds, their phase relative to each other will be a function of propagation distance. This effect will therefore produce a spatial distribution of modal interference (e.g. Lynn, 1977), with significant attenuation expected when two modes are in anti-phase, producing a reduced wave amplitude and waveform distortion. As ATDnet relies on the correlation of waveforms received by different sensor sites, modal interference has the potential to produce significant, but predictable, degradations of performance.

Initial studies on the effect of modal interference on ATDnet performance was summarised by Gaffard et al. (2008), and identified distinctly different patterns of modal interference with propagation distance between night and day. In the ATDnet correlation algorithm, signal-to-noise ratio of the waveform correlation is measured and logged for each sensor site used to locate every stroke detected. During the day, there was a reduction in waveform correlation signal-to-noise centred ~450km from the sensor site, with progressively shallower minima at ~1300km and ~2100km. During the night however, the minima were more pronounced and broader, with the two most prominent signal-to-noise reductions centred about ~600km and ~2000km, with a more shallow dip at ~3600km.

These patterns can be explained by calculating the group velocities for the first two modes as a function of ionospheric height, using the first-order propagation approximations given by equations 1 and 2. Higher order modes also exist, as does a ground-wave, but these propagation varieties are only significant over distances of a few hundred kilometres. Once the difference in group velocities between modes 1 and 2 are calculated (~2%) it is possible to suggest the propagation distance where destructive modal interference (anti-phase) will occur for a given ionospheric height. From Figure 4 it can be seen that during the day when the ionospheric height is approximately 70km, the first interference zone from modes 1 and 2 will be centred approximately 440km from the source and 650km when the ionosphere rises to ~85km at night. Successive anti-phases will be therefore be encountered at intervals of approximately 880km and 1300km thereafter. These simple theoretical predictions are in close agreement to the observed interference patterns for day and night. Short-distance fluctuations in signal-to-noise can therefore be attributed to higher-order modes (which attenuate rapidly) and interference with the ground-wave propagation component, which is strong at short-range. For example, interference bands would be expected between modes 1, 2 and 3 150-300km from the source from Figure 4.

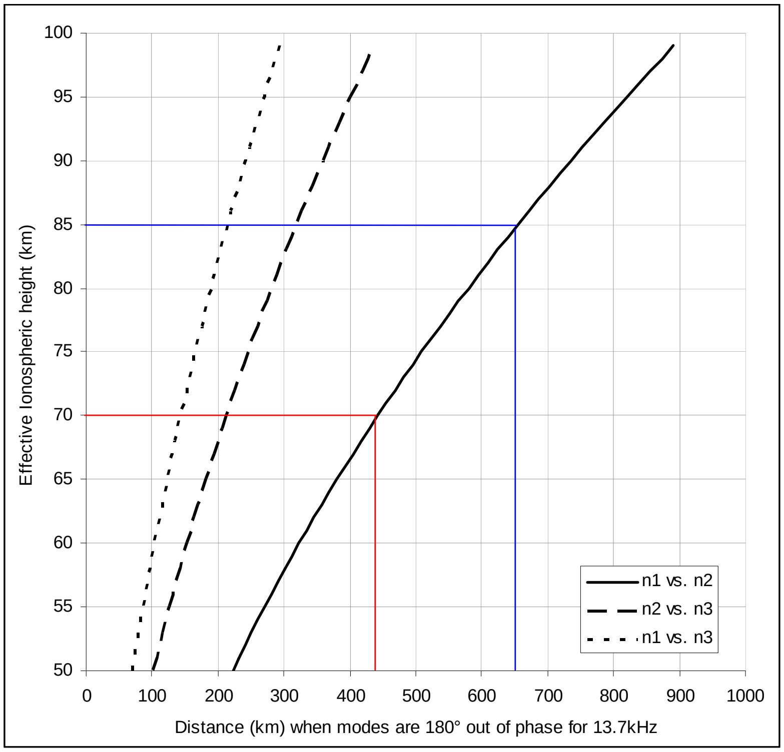


Figure 4: Relationship between the ionospheric height and distance of maximum modal interference for modes 1-3 (denoted by n) at 13.7kHz. The red and blue lines indicate typical day and night conditions, respectively.

Differences in severity of the interference zones are expected to be due to the relative strengths of modes 1 and 2 as mode 2 attenuates at a grater rate than mode 1. This explains the dominance of the first interference zone during the day when attenuation is maximum, and the similarity of the first and second interference bands during the night when mode 2 can propagate several hundred kilometres with little attenuation relative to mode 1. Even during the night however, the effect of modal interference is limited to propagation paths less than ~3,000km.

Analysis of the correlation signal-to-noise from lightning strokes around an ATDnet sensor located in Norderney, NW Germany, over the period of a month identifies the spatial distribution of modal interference. The first band of interference generated by interaction of modes 1 and 2 is dominant during the day and can be clearly seen in Figure 5. A significantly weaker secondary interference ring can also be seen (radius from sensor site to French-Spanish border). This secondary band is stronger during the night when attenuation of mode 2 is reduced, with changes in modal interference scale and intensity considered to be the main factor in producing a reduction of ATDnet detection efficiency in Europe during the night, as most sensor sites are within 3,000km of the European region. Further investigation on the spatial distribution of modal interference is envisaged to identify any seasonal variability and effects of ionospheric anisotropy.

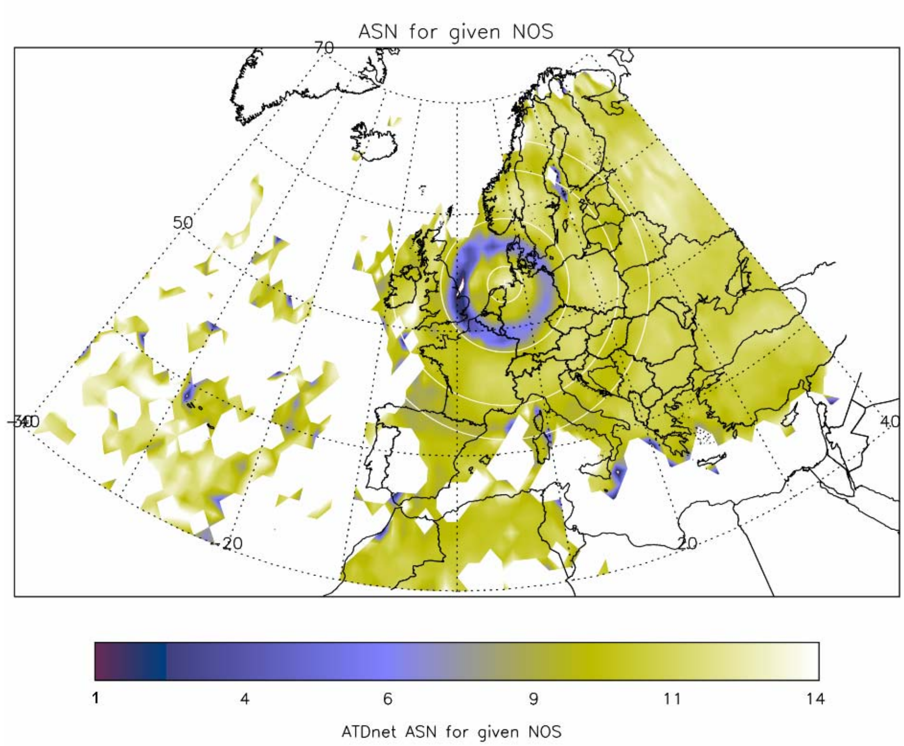


Figure 5: Map of median correlation absolute signal-to-noise ratio for waveform correlations near to an ATDnet sensor site located in Norderney, Germany during the day (defined as 08-17 UTC) for July 2009. Two concentric bands outlined in white represent theoretical zones of modal interference.

## 4. Diurnal variability of long range stroke location uncertainty

Diurnal variability of ATDnet stroke location uncertainty and detection efficiency is evident even further from the effects of mode 1 and mode 2 interference. The diurnal variation of time difference residuals (modified by variance) remaining from the minimisation process used for stroke location are shown in Figure 6a, for propagation paths between Europe and southern Brazil (~9,000km). The increased residuals during the day correspond to an increase in location error (Figure 6b), as expected due to the uncertainty in the minimisation outcome.

The diurnal variation of long-range performance can be explained by variation of ionospheric height. As the propagation algorithms used by ATDnet currently assume a fixed phase and group velocity (tuned for the night time ionosphere), then the increase of group velocity resulting from a daytime reduction in ionospheric height is sufficient to introduce location ambiguities, despite the velocity difference being only ~0.05% for mode 1.

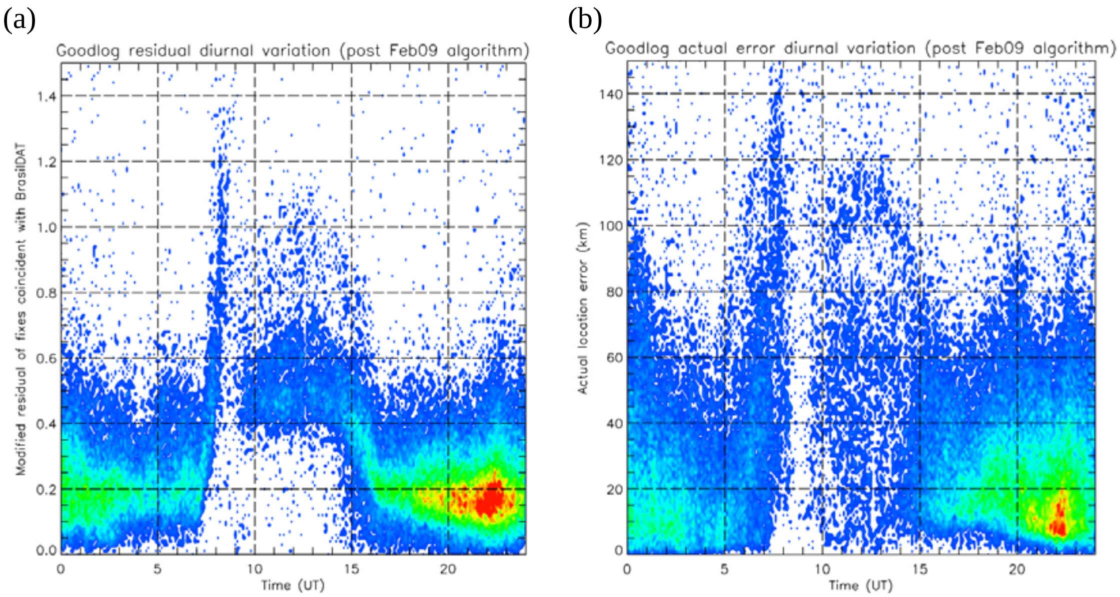


Figure 6: (a) Diurnal variation of time difference residuals of ATDnet location minimisation process for strokes coincident with BrasilDAT in southern Brazil. (b) Diurnal variation of ATDnet location error for BrasilDAT coincident strokes. Data collected during 1-10 January 2008, rerun using an ATDnet algorithm update during early 2009. The scatter plot is coloured according to event density (red being most dense).

Arrival time differences between two ATDnet sensors (UK and Finland) have been calculated and the change mapped for a 0.1% increase in group velocity (Figure 7). Such maps are useful for identifying areas most sensitive to changes in ionospheric height when different sensor sites are used in the lightning stroke location and provide a first-order estimate of the relative amplitude of residual and location error diurnal variations if a uniform velocity algorithm is used, for any given network geometry.

Once the change in arrival time difference is found, it can be converted to a location error of the arrival time difference hyperbola between the two sites by dividing by the arrival time difference gradient. A map of hyperbolae location error for a 0.1% change in group velocity is presented in Figure 8, showing that large (>100km) location errors can be introduced in some regions. These findings highlight the consequences of not accounting for the diurnal variation of ionospheric height, even for long distances outside of the influence of mode 1 and 2 interference. However, such corrections are non-trivial to implement in a real-time operational lightning location network such as ATDnet due to the increased computing requirements and need to know the approximate location of the stroke before a propagation path correction can be applied.

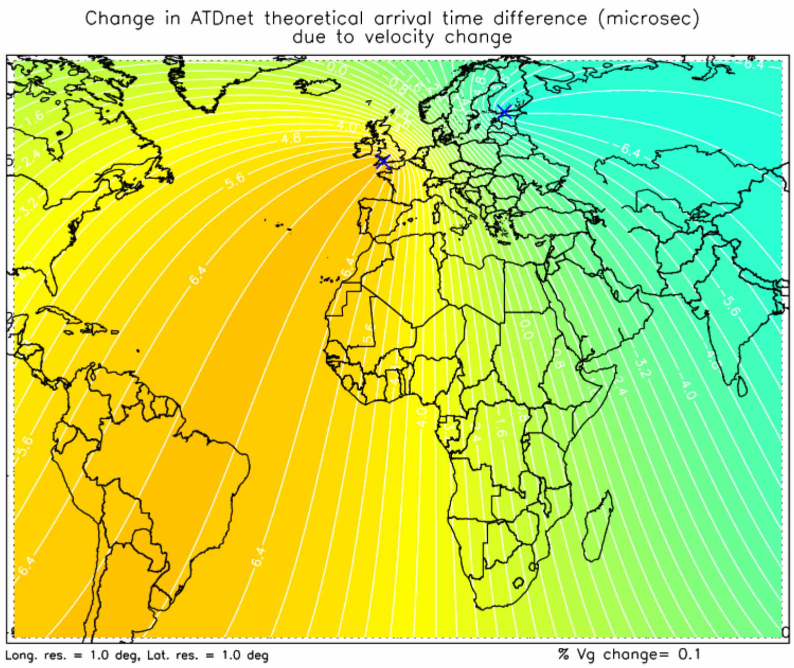


Figure 7: Theoretical change in arrival time differences between signals received at two sites in the UK and Finland respectively if the group velocity was increased by 0.1%.

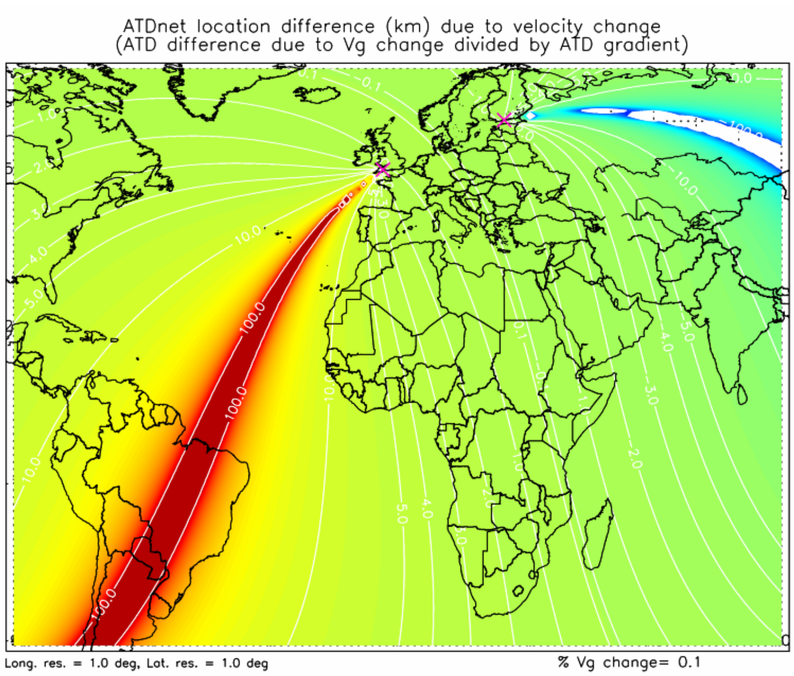


Figure 8: Theoretical change in location of ATD hyperbola (in km) between signals received at two sites in the UK and Finland respectively if the group velocity was increased by 0.1%.

Another feature noticeable in Figure 6a and Figure 6b is the temporary reduction in detection efficiency and increase in location error around sunrise (~08-09 UTC). If the sunrise terminator is located within a few hundred kilometres of the lightning activity and to the west of the VLF receivers, a second-order mode is excited in the night side, which in turn generates a first order mode at the terminator (Kikuchi, 1986). This first order mode from the conversion at the terminator interferes with the first order mode that propagated directly from the lightning activity and produces significant attenuation and waveform distortion, leading to the temporary reduction in detection efficiency and increase in location error seen around sunrise in Figure 6b. This feature is in addition to the observed increase of long-range detection efficiency at night due to the more favourable propagation conditions.

## 5. Mitigation of diurnal variation in location uncertainty

The diurnal variation of location uncertainty is due to the regular variation of ionospheric height. ATDnet currently does not include this diurnal change in waveguide properties in the location algorithms, so tends to have larger correlation residuals during the day, with associated increases in location uncertainty. Incorporating time-dependent changes to phase and group velocities will therefore be advantageous, as demonstrated by Chronis and Anagnostou (2003).

For propagation paths <3,000km, knowledge of modal interference patterns can be used to optimise VLF lightning location networks. Although interference from propagation modes 1 and 2 can cause significant degradation in waveform correlation for an individual sensor site, adverse effects on the complete network can be mitigated against by network redundancy and careful site selection to avoid overlapping interference bands. Therefore it will be advantageous to install additional sensor sites (ideally more than four) at distances greater than approximately 3000km from western Europe which will be beyond the significant modal interference bands, to ensure good correlations for stroke locations in this region during the night. Planned future ATDnet expansion will take account of the modal interference patterns.

Currently the ATDnet system defines the reference site (used by all the other sites in waveform correlation) as having the tightest waveform with a well-defined peak amplitude. However, the advantage of long-range lightning detection techniques using waveform correlation is that the actual shape of the waveform is not important; rather the similarity between waveforms received at different sites is the key to achieving unambiguous arrival time differences used for stroke locations. Therefore, the ideal method of reference site selection is determining for each event which of the sites received a waveform which correlates best with the other waveforms, rather than simply which waveform is “cleanest”. This would imply that even if all the sites were subject to modal interference (from the same band), a good quality stroke location could still be determined providing all the waveforms were subject to the same deformation. The problem with this approach is that waveform correlation is the most computationally expensive part of the stroke location software, and the computation time would increase rapidly with the number of sites reporting waveforms. Another approach would be, having calculated an approximate position for the stroke, to evaluate potential sensor sites expected to suffer least from modal interference for the stroke location according to the assumed distribution of modal interference bands for that time.

## 6. Summary and conclusions

Three general sources of variability in lightning stroke waveform propagation characteristics affecting ATDnet have been discussed and methods of mitigating their effects on ATDnet performance suggested.

Short-period random variability is inevitable over long propagation distances due to timing and waveform correlation errors and natural variations in ionospheric height and conductivity as well as differing surface properties. Such random variability can not be prevented but the effects on the location error distribution can be adequately represented once network geometry in relation to the lightning location is considered.

Modal interference, especially between modes 1 and 2, produces substantial degradation in waveform correlation in distinct circular bands, which vary in size and intensity from day to night. Although individual sites are effected by such interference, current network redundancy in ATDnet allows at least the minimum of four sensors required for an unambiguous location to be unaffected by the interference and therefore limit the effects on overall network performance. Consequently, modal interference is not usually a problem for ATDnet during the day, but does cause a degradation of performance over Europe at night, where most sensors are within range of mode 2 propagation. The planned expansion of the network during 2010/11 to include several sensors >3,000km from Europe is a suggested remedy to this night time degradation, as well as modifications to the selection criteria of the reference waveform for correlation.

Long range variability in performance is due to either attenuation of waveform over long propagation paths, including modification of waveform shape e.g. from phase velocity inhomogeneities or interfering primary modes excited near the sunrise terminator, or changes in ionospheric height. The latter can in principle be accounted for using time dependent propagation algorithms, but increases in computational time, complexity and requirement for an initial location estimate would need to be considered if implemented on an operational lightning location system. Waveguide conductivity inhomogeneities could be accounted for using an ionospheric/surface conductivity model, but the same considerations to algorithm complexity will also apply. The most appropriate mitigation remedies shall therefore be based upon the expected performance improvements in relation to the inherent resource and compromises required for their implementation.

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