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Observing Lightning Around the Globe from the Surface

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1. Introduction

The UK Met Office VLF arrival time difference (ATD) long range lightning location network has been operating successfully for nearly 20 years. The range includes all of Europe, North Africa, the North Atlantic and most of South America. Recent expansions and improvements to the network have increased the range of detectable lightning to now include all of South America, Africa and central Asia. The improved network (now called ATDnet) has been operating offline in parallel to the original system for testing, but has now replaced the current operational system since December 2007.

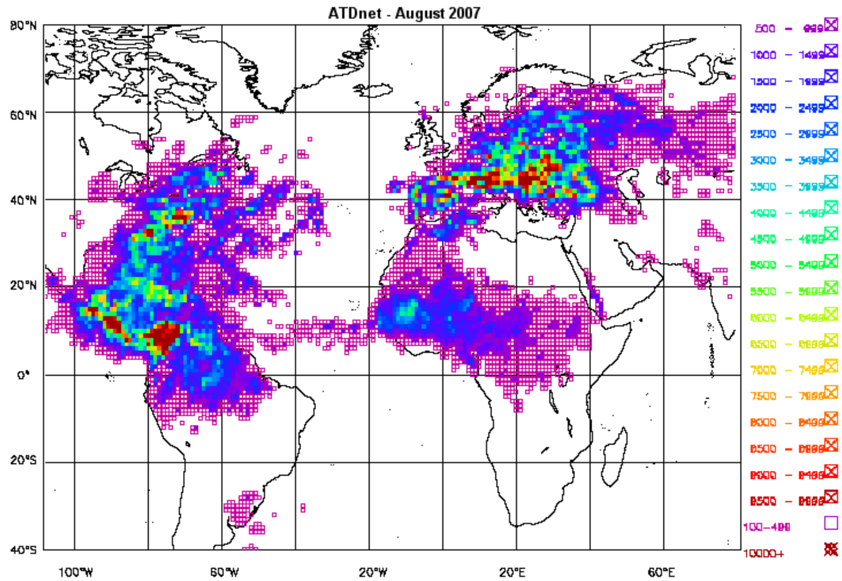
The increased coverage and new receiver instrumentation for the ATDnet network will be discussed. The network is compared to other European lightning detection systems to assess the accuracy and detection efficiency over Europe. A significant diurnal variation in the detection efficiency of ATDnet is observed over Europe, which is suggested to be due to a nocturnal enhancement of wave guide modal interference.

2. ATDnet Network

The ATDnet system is the upgraded version of the original ATD network. Like the original, ATDnet uses a surface-based network of VLF (Very Low Frequency) radio receivers across Europe which record the absolute arrival time of lightning emissions. By comparing the arrival time differences between several stations, the position of the lightning stroke is found. Details of the original ATD system, including estimated location errors, are discussed by Lee (1990). Recent improvements to the system have extended the detectable range to cover all of South America, Africa and central Asia (Figure 1) reported by Nash et al. (2006), although the network is tuned to provide greatest detection and spatial location accuracy over Europe. The improved network (now called ATDnet) currently has 14 detectors (called NOS (New OutStation), with 11 in full operational use) and records about 6-8 times more flashes than the original ATD during the Northern hemisphere summer. The detection frequency has been increased from 9.76kHz to 13.7kHz to avoid a persistent band of man-made noise. Figure 2 displays the locations of the 11 operational NOS. These locations were chosen to provide maximum coverage over Europe (ATDnet's primary region) with minimum stroke location errors. An example of the NOS VLF antenna and PC interface are shown in Figure 3.

The NOS uses a Rubidium oscillator for accurate timekeeping, calibrated using the GPS signal. Advances in the signal processing software allow spurious noise near the detector frequency to be reduced by notch filtering. Unlike the original ATD system, the detector frequency of the new network can be changed by software, without the need to modify any hardware.

(a)



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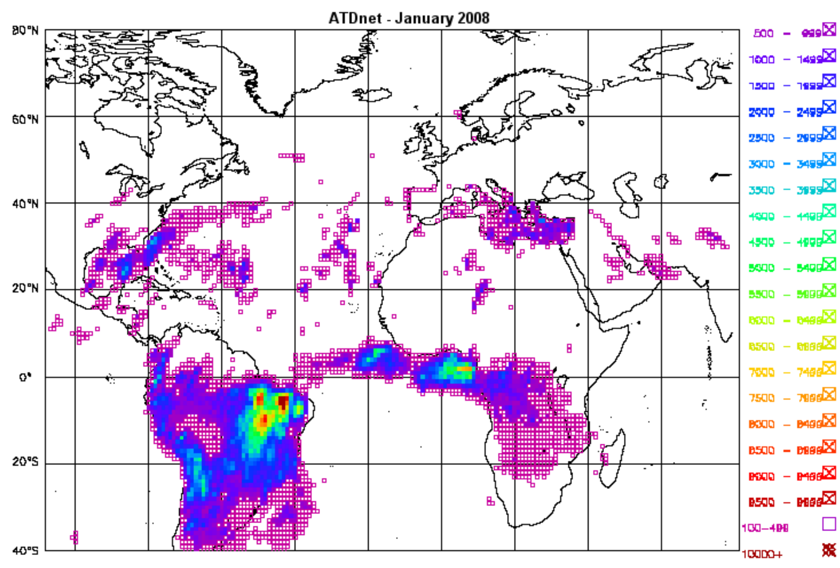

Figure 1 – Climatology of ATDnet lightning stroke density for (a) August 2007 and (b) January 2008. The scale represents the number of strokes in the one degree grid boxes during the month.

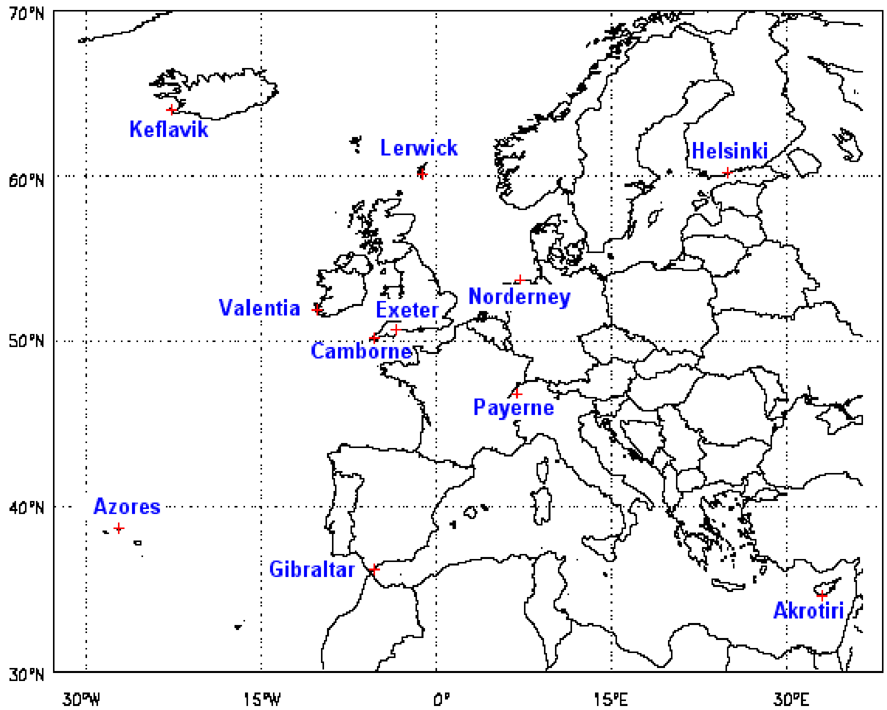

Figure 2 – ATDnet NOS (New OutStation) locations. Additionally, there is a NOS at La Réunion in the southern Indian Ocean (although not used operationally at present), one soon to be installed at Upington, South Africa and an additional NOS used for development at Exeter.

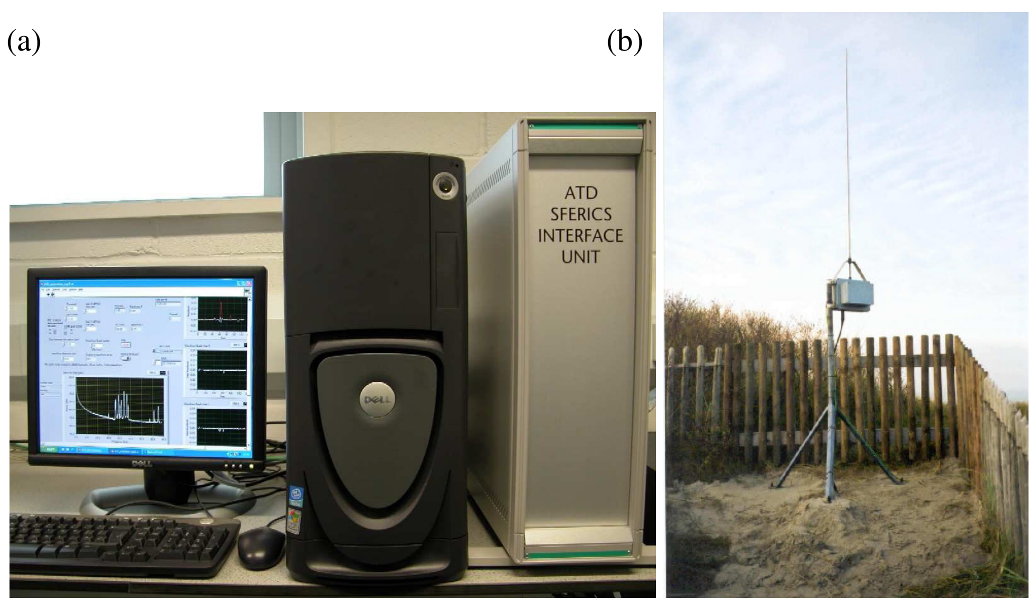

Figure 3 – ATDnet NOS (Norderney), comprising of a PC interface unit (a) attached to the VLF antenna module (b).

The arrival time differences are found by correlation of the entire waveform received by each active NOS to one which is selected as the “reference station” for that event. The criteria for reference station selection takes into consideration the initial estimated distance of the NOS from the fix, the position of the NOS within the network and the quality of the received waveform.

3. Comparison with other lightning detection systems

Seven days of detected strokes by ATDnet over France and over Austria have been respectively compared with the French and Austrian lightning detection systems. The French and Austrian systems use broadband VLF/LF (~1-350 KHz) lightning emission. They observe the arrival time difference of the maximum of the electro-magnetic discharge from the cloud to ground discharge and the angle from which the discharge is coming to measure the lightning location. This technique relies on ground wave propagation. The attenuation of broadband VLF/LF ground wave propagation is such that these systems detect strokes only within the area defined by the sensor network and at relatively low range outside the network (400km). Unlike these systems, ATDnet also incorporates the sky wave signals and is therefore sensitive to sources over a considerably longer range. Both the French and Austrian systems use IMPACT sensors developed by Vaisala and the same software developed by Météorage. For these systems, the location accuracy of lightning is claimed to be better than 1km (of the order of 500m) within the network, with a flash detection efficiency of 90%.

3.1 ATDnet compared to Meteo-France system

On a daily basis, an initial examination of the data reveals that the two systems detect about the same number of events. In the particular example shown on Figure 4, the general pattern of storm location was similar, except for the ATDnet distribution of stroke being slightly more spatially spread than for Meteo-France. On average over the week, ATDnet detected 6% more strokes than Meteo-France. When looking at the diurnal variation of the detected events (Figure 5) a diurnal pattern is clearly noticeable, with more events detected by ATDnet in the day time and less in the night time than from Meteo-France.

(a)

(b)

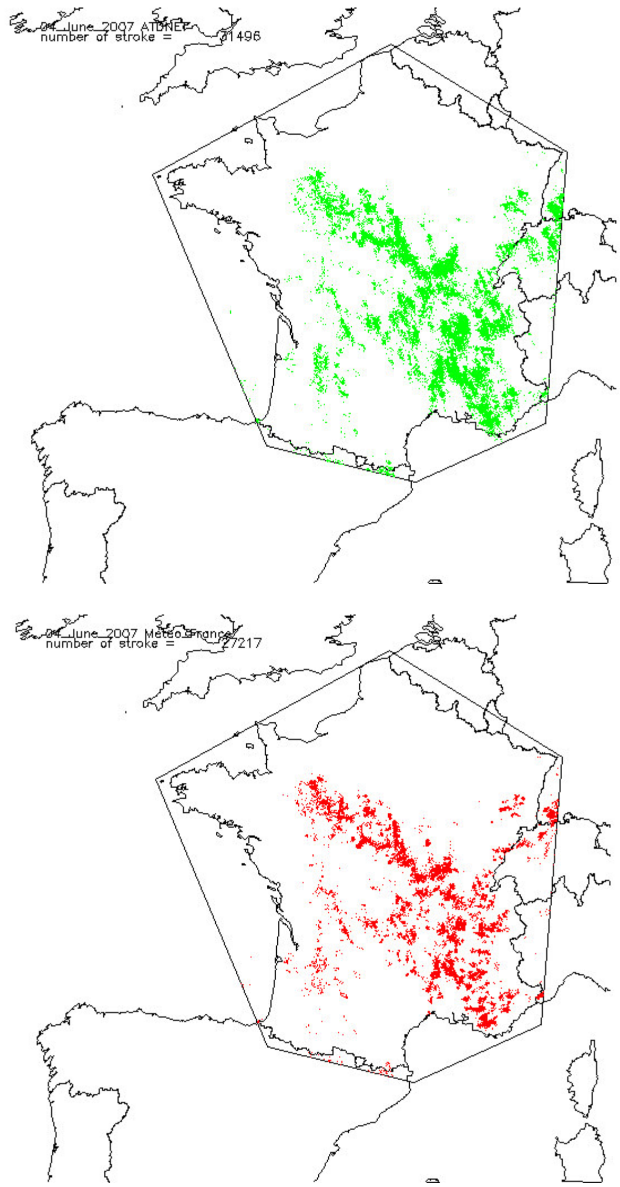

Figure 4 - lightning detected on the 04 June 2007 by (a) ATDnet and (b) Meteo-France.

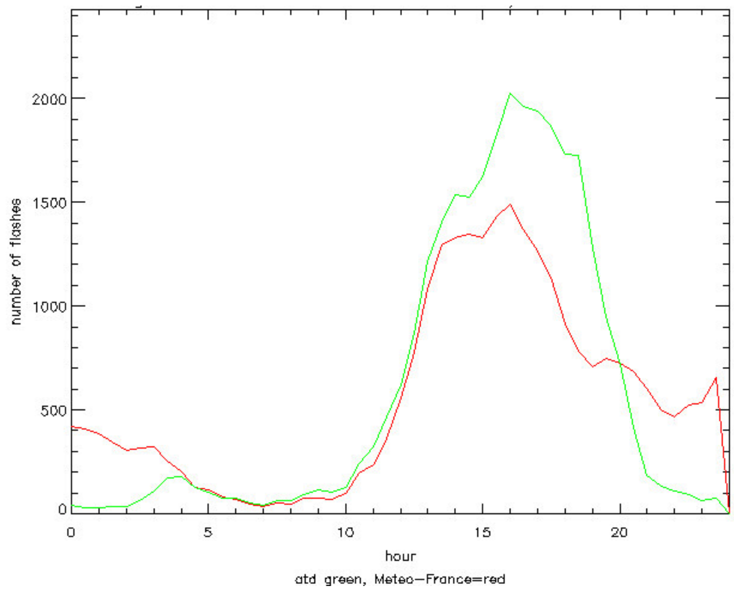

Figure 5 – Diurnal variation of number of strokes detected in 30-minute intervals by ATDnet (green) and Meteo-France (red), averaged over a week. Time in UTC.

3.1.1 Stroke by stroke comparisons

Overall the two systems detected the same thunderstorm events; however they don't necessarily see the same lightning at the same location in space and in time. A mismatch in space and in time could result from several causes: errors in the intrinsic accuracy of the time stamps for the two systems, differences in computer clocks, erroneous detection of wave forms, or failure to detect the wave form at enough sensor sites to derive a location.

A previous comparison between the original ATD and Euclid (a cooperative agreement between operators of Vaisala systems in Europe including the Meteo-France system) was made by Daley et al. (2000), who discovered that the PC clocks themselves were time shifted by ~12 seconds, with the error in the ATD system. Now, Meteo-France and ATDnet both use a GPS based time clock, so the two systems should have the same time.

To compare the clocks we first looked at the detection of strokes in both systems by step of 100s, 50s, 10 s, 5s then 1s to check than no gross time shift existed in the two systems. Then an area with thunderstorm activity was selected. The events are co-located second by second, and for all co-located events the minimum difference time with the other system is recorded. The plot of the minimum time difference (Figure 6) shows that the majority of the data have a bias of 110us. An iterative 3 standard deviation (sigma) test converges to a standard deviation of 32us and a bias of 114us.

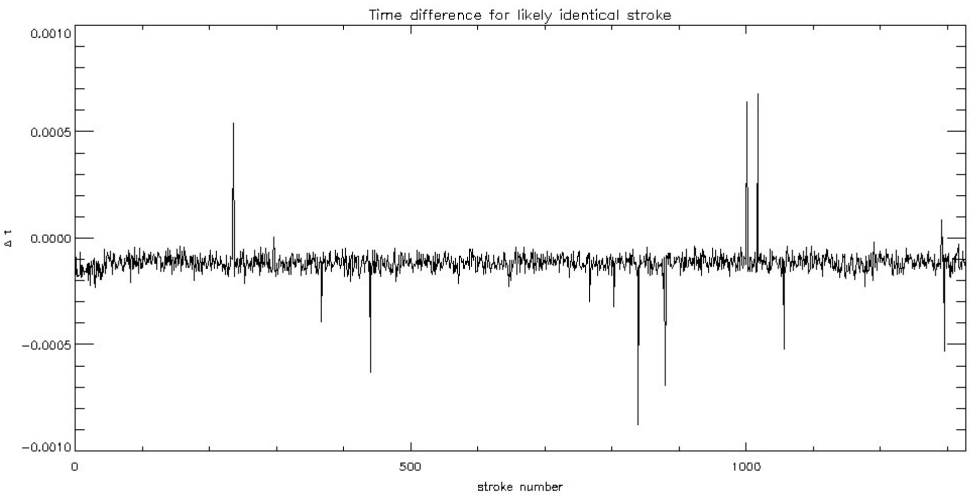

Figure 6 - Time difference between strokes detected by ATDnet and Meteo-France.

In the rest of the comparison we have assumed that once the bias is removed, strokes with a difference in time lower than three standard deviations were the same event detected by the two systems. Using this time window criterion, both systems saw ~45% of the same strokes over the whole period (ie 85197 co-located strokes).

The distribution of the difference in location is shown in Figure 7. The black curve corresponds to measured difference and the red curve to the theoretical error computed by the ATDnet system itself.

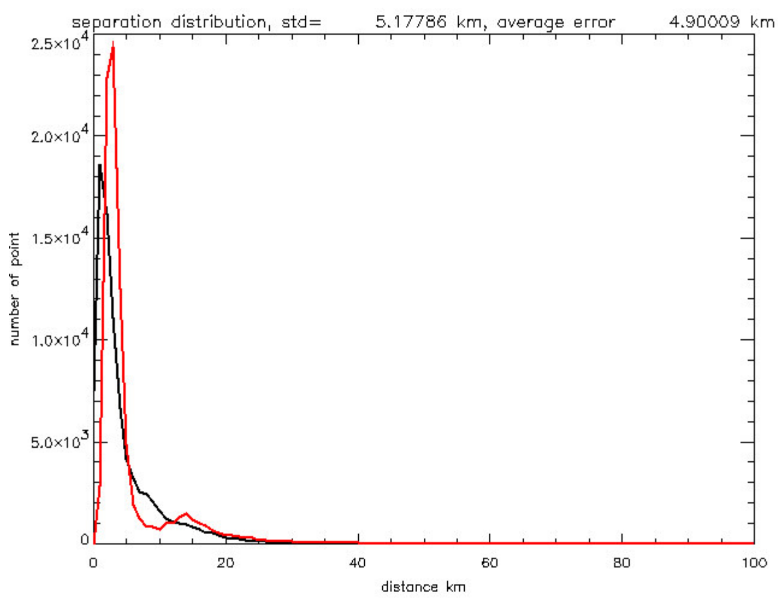

Figure 7 - Distribution of the difference between ATDnet and Meteo-France. The black curve corresponds to measured differences, and the red curve to the theoretical error computed by the ATDnet system itself.

The mean measured difference is 4.9km with a standard deviation of 5.1km. The estimated error is slightly higher with a value of 5.7km for the mean difference and 6.0km for the standard deviation. The good agreement between the two values indicates that the estimated error is, on average, correct. Examination of the tail of the distributions indicates that there is a tendency for large (i.e. exceeding ~15km) errors to be overestimated theoretically. This is likely to be a consequence of using an error quality control threshold that is proportional to the distance between the network and stroke. Differences are also observed between the diurnal variations of measured and theoretical error, with an underestimation of the theoretical error during the night (Figure 8).

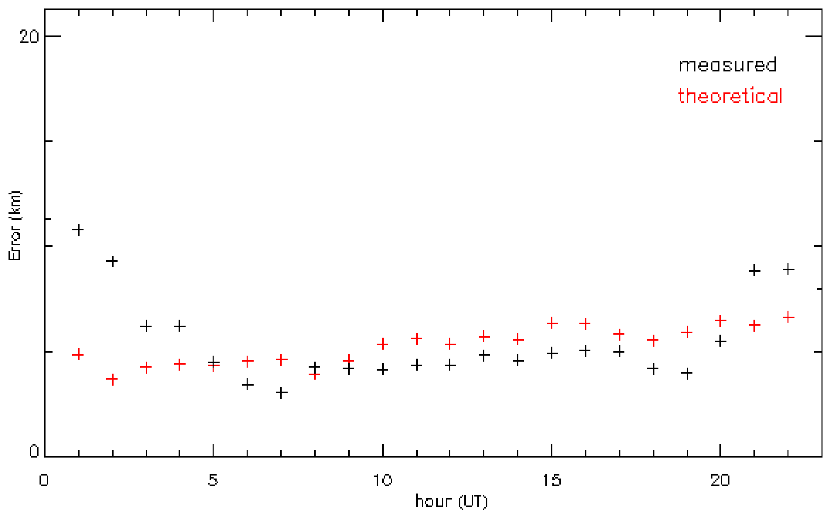

Figure 8 – Diurnal variation of measured (black) and theoretical (red) ATDnet location error for co-located events over France.

*3.2 ATDnet compared to the **A**ustrian **L**ightning **D**etection and **I**nformation **S**ystem (ALDIS)*

The same method of comparison between ATDnet and the Meteo-France system (subsection 3.1) was used to compare ATDnet with the Austrian ALDIS lightning detection system. It was found that the time differences between ATDnet and ALDIS were similar to that of Meteo-France, with a mean bias of 140us and a standard deviation of 37us. However, unlike the comparison with Meteo-France, ALDIS recorded approximately twice as many lightning strokes than ATDnet (with ~50% of the ATDnet fixes co-located with those of ALDIS). Reasons for the higher number of detected events by ALDIS are unclear, although this could be due to ALDIS recording more low peak current lighting activity than ATDnet, which mainly registers cloud-to-ground activity for higher peak currents, especially at longer range.

A comparison was made between the lightning stroke amplitude distribution detected by ALDIS for the complete dataset and the distribution of strokes that were also detected by ATDnet (Figure 9a). From this analysis, it is apparent that the co-located distribution is shifted towards higher amplitudes, suggesting that the weakest amplitude strokes detected by ALDIS were not detected by ATDnet. However, the comparison of complete dataset and co-located stroke amplitude distributions between ATDnet and Meteo-France (Figure 9b) showed no significant difference. The source of these low amplitude events detected by ALDIS is uncertain.

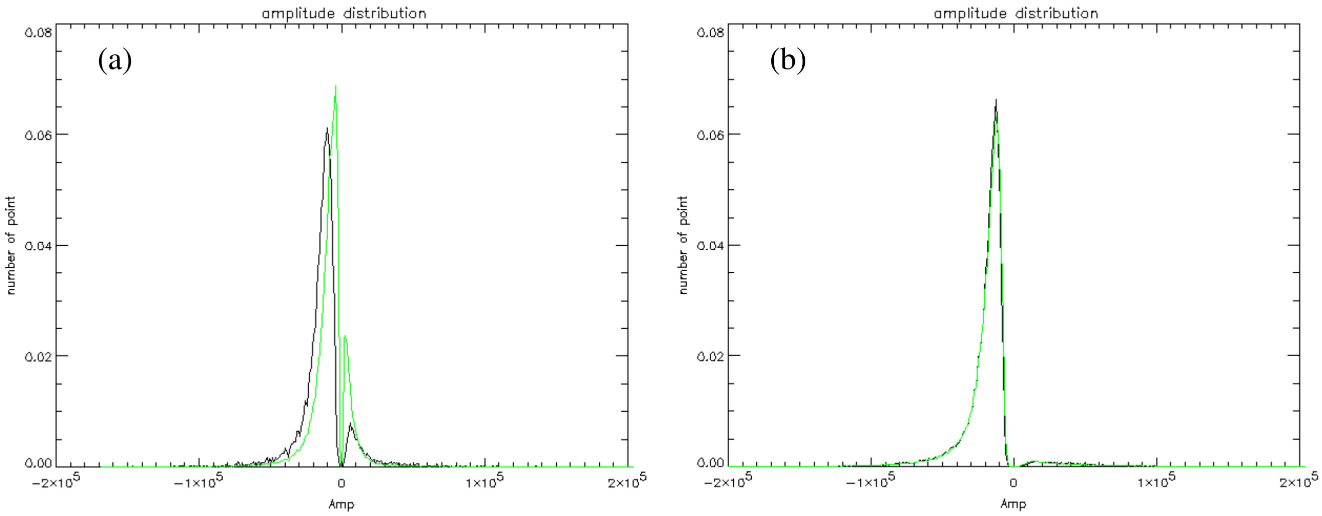

Figure 9 – Stroke amplitude distribution (relative to total strokes for each dataset) for (a) ALDIS and (b) Meteo-France, with green denoting all strokes measured by the respective systems and black being strokes which were also detected by ATDnet.

Measured and theoretical errors for the ATDnet and ALDIS comparison were similar, in accordance with that found during the Meteo-France strike. However, there were insufficient nocturnal thunderstorms during the ALDIS test to confirm any underestimation of theoretical error by ATDnet, as found in the comparison with Meteo-France.

4. Diurnal variation of ATDnet stroke location uncertainty

Once the location of a lightning stroke is calculated by ATDnet, a quality control algorithm is automatically initiated and the stroke is stored in one of two different groups. If the stroke location is considered to be of high quality (i.e. the residual from the waveform correlation-based location calculations is below a given value and the theoretical location error is below a threshold proportional to the distance between the stroke and centre of the network), then the stroke location is stored in a collection called the “goodlog”. It is only stroke locations in the goodlog that are reported operationally. Stroke locations with a residual or error exceeding these quality control thresholds (indicative of a more ambiguous stroke location) are placed in a collection called the “poorlog”. By examining the fraction of poorlog counts to those in the goodlog, it is possible to assess the relative uncertainty of stroke locations as a function of time. Furthermore, this fraction can be subdivided into broad geographical regions to evaluate the spatial, as well as temporal variation of stroke location uncertainty. An example of this regional diurnal variation is given for September 2007 in Figure 10.

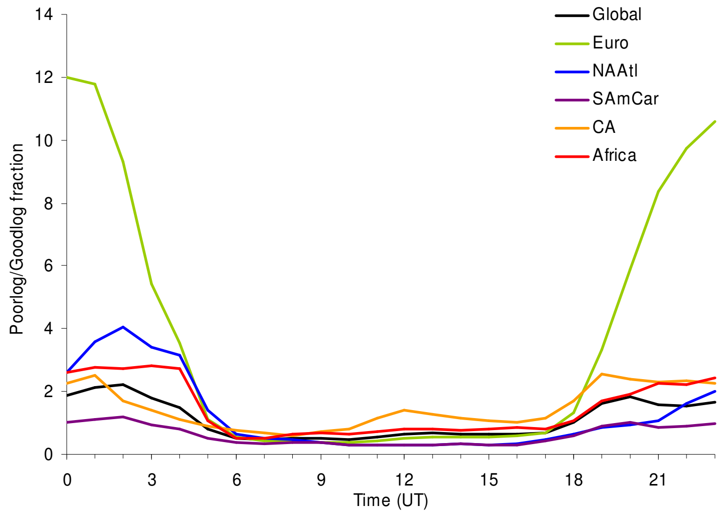

Figure 10 – Fraction of ATDnet regional poorlog over goodlog fix numbers during each hour, averaged over September 2007. Regions are Global (all fixes), Euro (European region), NAAtl (North America and North Atlantic), SAmCar (South America and Caribbean), CA (Central Asia) and Africa.

From Figure 10 it can be seen that all regions tend to have a greater fraction of stroke locations in the poorlog compared to goodlog between approximately 18-05UT, corresponding to the European night. The source of this diurnal variability is expected to be due to effects within the vicinity of the ATDnet network, as the network is currently confined to Europe (Figure 2) and there is no evidence of any time shift of diurnal variation between regions of differing longitude (expected if the fraction was related to local thunderstorm activity or ionospheric conditions). Consequently, the diurnal variation is most pronounced for the European region. Additionally, as the theoretical error threshold is a function of distance from the stroke to the network, this may also be a contributing factor to the regional variation of diurnal poorlog/goodlog amplitude.

The source of increased uncertainty in ATDnet flash location during the European night is expected to be a result of increased modal interference in the Earth-ionosphere waveguide (Lynn, 1977), which causes a reduction in the correlation between the NOS waveforms with the reference. The increased "noise" in the correlation results in more uncertainty in arrival time difference calculations, which corresponds to an increased proportion of stroke location residuals exceeding the limit defined by quality control and being placed in the poorlog.

The zones of greatest modal interference during both European day and night were investigated using the absolute signal to noise (ASN) ratio of ATDnet stroke locations reported in the goodlog. The ASN is a function of the correlation between the waveform of a particular NOS with the reference. The Norderney (Germany) NOS was chosen for this investigation due to its high reliability and central location within the network (Figure 2). The mean ASN was plotted as a function of distance between the NOS and stroke location for both night (21-02UT) and day (08-17UT) between July and September 2007. The results are presented in Figure 11. From these results it can be seen that there are certain distances from the NOS where the ASN drops considerably relative to the mean. For the day this occurs in a region centred ~450km from the NOS, with progressively shallower minima at ~1300km and ~2100km. During the night however, the minima are more pronounced and broader, with the two most prominent ASN drops centred about ~600km and ~2000km, with a more shallow dip at ~3600km. The locations of these modal interference regions during the night correspond closely to those of Kikuchi (1986), who observed nocturnal modal interference patterns using the Omega VLF signal at 13.6kHz (close to the frequency of ATDnet at 13.7kHz).

The daytime modal interference patterns during the day are related to those of the night by the relative decrease in ionospheric height resulting from photo-ionisation by solar ultraviolet radiation (e.g. Hunsucker and Hargreaves, 2002). This decrease in the height of the Earth-ionosphere waveguide alters the modal interference pattern, both in terms of amplitude and separation between regions of high interference, as seen in Figure 11. The variable ASN at short range (<300km) may incorporate additional ground wave interference.

The typical length scale and increased amplitude and width of the modal interference zones surrounding the European NOS network during the night causes the general degradation of correlation for European lightning stroke locations, although all locations are affected as their sky wave propagates through the interference zones as it nears the NOS receiver.

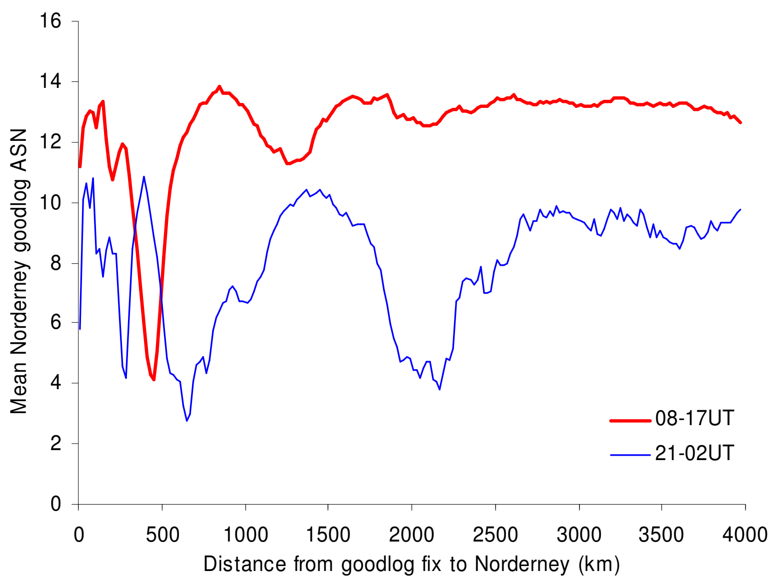

Figure 11 – Mean absolute signal to noise ratio (ASN) with distance from lightning fix location during the day (08-17UT) and night (21-02UT) for the Norderney (Germany) ATDnet receiver, averaged over July to September 2007.

5. Future developments

Although ATDnet is now a successful operational system within the UK Met Office, the network is still subject to continued improvement. Future developments include modification of the quality control and stroke location algorithms to account for the diurnal variation of correlation signal-to-noise as a result of modal interference. A further expansion of the ATDnet network to allow global coverage is envisaged, especially the inclusion of the SE Asia and Australian regions. With the increased number and distance between outstations (some of which are in remote areas), improvements to the network communications will be made, allowing maximum data transfer rates and a reduction in communication costs.

6. Conclusions

The ATDnet long range thunderstorm detection system is an upgraded version of the original ATD system, and has now replaced ATD as the operational system of the UK Met Office. ATDnet has coverage spanning much of the world using only 11 operational outstations in Europe. East Asia and Australia as well as west and mid-west of North America being land regions currently not within range, although an expansion of the ATDnet network is planned for the future.

The number of strokes detected over France by ATDnet and Meteo-France are similar, as were the stroke locations. ATDnet detection drops by a factor of 2 relative to the Austrian system (ALDIS) over Austria, as very low amplitude events are detected by ALDIS but not ATDnet. However, this discrepancy was not apparent in the comparison between ATDnet and Meteo-France. Reasons for this difference between ATDnet and ALDIS are unclear at present, but may be due to differences in processing software between ALDIS and Meteo-France. This finding demonstrates the advantage of using ATDnet as a cross-check between these two shorter-range systems. Approximately 50% of ATDnet data co-locates in time with both Meteo-France and ALDIS, with estimated ATDnet theoretical location error approximately equal to measured error, except during the night over France.

The diurnal variation of strokes detected by ATDnet over France compared to those of Meteo-France indicate that ATDnet detects more events during the day, but less at night. This difference is suggested to be due to modal interference, as ATDnet relies on the sky wave for long range (>400km) detection, unlike Meteo-France which only uses the ground wave component. However, the nocturnal events are likely to be detected by ATDnet, although they are currently removed from the operational database by quality control.

References

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