ATDNet network redesign feasibility study.

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Executive summary

ATDnet is the Met Office's (UK's national weather and climate service) operational lightning detection network. It operates by detecting the Very Low Frequency (VLF) radio waves transmitted by a lighting stroke, called "atmospherics" or simply "sferics". The propagation of the sferics can be several thousand kilometres allowing for a relatively dispersed network to have some detection capabilities over a very large area. The accuracy of the location of lightning strokes is not only a function of detection of the sferics but of the relative network geometry.

A review of the literature has been conducted and included alongside some new results to investigate ATDnet's current performance, in terms of relative detection efficiency (DE) and location accuracy (LA). The review used data from a range of sources, including long- and short-range ground-based networks and space based lightning location instruments. It was concluded that the network is effective over Europe with a DE of 80-90% of CG flashes and 40-60% CG strokes. ATDnet median location accuracy relative to reference systems was in the order of 1-3 km. The network also shows some coverage in other areas; 10-15% DE of TRMM-LIS flashes over the West Atlantic, 5-10% in northern and western Africa and approximately 5% in more distant regions like South America and the South Atlantic. The Long Wave Propagation Code (LWPC) was used along with a location accuracy model to model the operational ATDnet results for both a DE proxy and LA.

Meteosat Third Generation (MTG) will include a lightning imager (LI) instrument. This new instrument will provide lightning data over a substantial part of the Earth including Europe, Africa, Atlantic Ocean and parts of south America. To enable validation and calibration it may be useful to have a near consistent conventional ground-based network. A first order modelling feasibility assessment has been conducted by modelling different scenarios of network, until coverage over the MTG LI domain is comparable to ATDnet in Europe.

To model a potential network to cover the MTG LI domain the domain was first splint into five regions (excluding ATDnet region). Each region was modelled first using the LWPC increasing the number of receivers until the assumed DE proxy was acceptable over the whole domain. The location accuracy model was then run to ensure that the LA was also acceptable. When the LA was found to be too low an iterative approach of adding more receivers and running the LWPC and LA models was taken.

The modelling results show that over most of the MTG LI domain it is feasible to provide coverage approximately equivalent to ATDnet over Europe. This would require 63 additional receivers.

It would not be feasible to add 63 new receivers into ATDnet. The Met Office is currently running a project to replace ATDnet with LEELA. Some of the advantages of LEELA includes significantly reduced installation and hardware costs, and a more flexible central processing system providing the flexibility to add an arbitrary number of new receivers. This would still be a significant undertaking, with hardware manufacture, site identification (including surveys) and installation each being a notable piece of work.

Introduction

There has recently been significant interest in space-based lightning location instruments. TRMM LIS, ISS LIS and the NOAA OTD (1995-2000), GOES-16 and GOES-17 instruments have all demonstrated the possibility of detecting lightning from space. In Europe EUMETSAT has a planned an instrument on the Meteosat Third Generation (MTG), the Lighting Imager (LI). The first launch of MTG LI is currently planned for the end of 2021. The LI will have four sensors covering four sectors centred over 0° lat, 0° lon with an overlap between each sensor sector. The planned coverage area of MTG LI is shown by the blue shapes in figure 0.

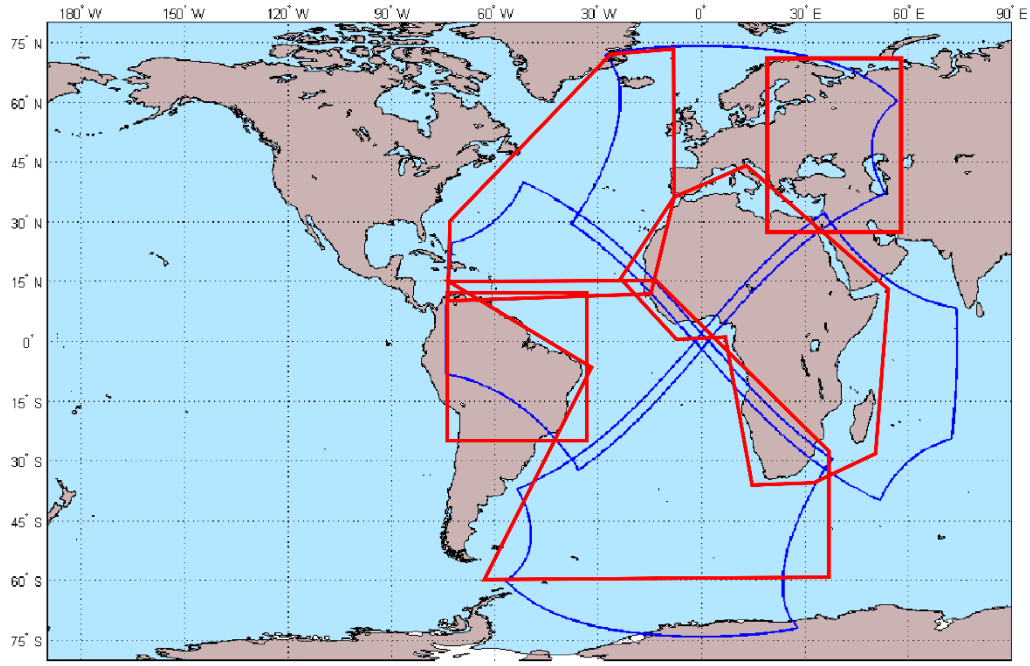


Figure 0. The Meteosat Third Generation Lightning Imager domain shown in blue with the regions to model being shown in red.

The EUMETSAT community are interested in the options available for ground-based measurements of lightning. From previous work (Enno et al., (2016b)), it is known that the Met Office operational lightning location network, ATDnet, does not have sufficient detection efficiency (DE) or location accuracy (LA) over a significant part of the MTG LI domain. This project contains two tasks; the first to conduct a literature review into what is known of the ATDnet DE and LA; the second to conduct a modelling exercise of both VLF propagation and location accuracy to develop the design of an ATDnet like network with coverage over a significant proportion of the MTG LI domain.

ATDnet is being retired. The currently being developed operational replacement for ATDnet will be LEELA. Whilst different in the technologies used LEELA is fundamentally similar to ATDnet in the physics that applies. Therefore, the conclusions drawn here can be directly related to LEELA.

ATDnet

ATDnet is a Very Low Frequency (VLF) long-range lightning location system (LLS) operated by the Met Office. The network locates lightning discharges using the Arrival Time Difference (ATD) method (Lee, 1986). The current ATDnet consists of approximately 10 sensors in and around Europe operating at the central frequency of 13.733 kHz.

ATDnet sensors detect ‘‘atmospherics’’, also referred to as “sferics”. Sferics are electromagnetic waves in the VLF range that propagate in the earth–ionosphere waveguide and are generated by cloud-to-ground (CG) return strokes and powerful cloud lightning (IC) pulses (Rakov and Uman 2003). The system takes the advantage of the long propagation paths of sferics to cover large areas with only a limited number of sensors.

Arrival time differences (ATDs) between peak amplitudes of sferics at a minimum of four contributing sensors are needed for an unambiguous lighting location solution. All detected locations (also referred to as ‘fixes’) are classified as ‘good’ or ‘poor’ using predefined signal quality and theoretical location error thresholds. Only ‘good’ fixes are used in ATDnet data products and disseminated to customers.

The effective range of ATDnet encompasses Europe, northern Africa, and northern parts of the Atlantic. The system also detects some lightning in central Africa, South America, the South Atlantic, the eastern coast of North America and in Asia. ATDnet was originally designed to detect CG lightning return strokes but it can also detect powerful IC pulses within its effective range.

ATDnet provides continuous lightning data over a large spatial domain in the field of view of MTG Lightning Imager (MTG-LI). Thus, there is a potential for using ATDnet for evaluating MTG-LI performance. Before using ATDnet as a reference system it is useful to know its main performance characteristics.

Methods

This section provides some background and methods used for the study. Split into two sections; Review of ATDnet Coverage, which contains the methods and descriptions used for the review of ATDnet coverage and Modelling which contains the methods and descriptions used for modelling an expanded ATDnet like network.

Methods for the Review of ATDnet Coverage

There are two widely used parameters for describing the performance of lightning location systems, detection efficiency (DE) and location accuracy (LA). Detection efficiency is used to quantify the fraction of detected strokes or flashes compared to the real number of occurred strokes or flashes. A flash DE is likely to be higher than a stroke DE, as a flash is considered to be detected even if only one stroke of the flash was detected (e.g., Rakov 2013). Depending on the nature of the reference data, absolute or relative DE could be measured.

The absolute detection efficiency is very difficult to measure, as it requires a method of observation that detects every flash or stroke (e.g. rocket-triggered lightning, strikes to tall structures and video observations), in order to be compared with the LLS being assessed. As a result, the number of available ATDnet absolute DE estimations is very small. Relative DE is much easier to measure. One lightning dataset is taken as “truth” and the detection efficiency of the other network is calculated by dividing the number of coincident strokes or flashes by the total number detected by the reference network. ATDnet relative DE has been measured against many lightning location systems in Europe and further away.

Location accuracy indicates how precisely the location of lightning can be determined. Location accuracy can be measured using three different methods: (1) comparison between two or more different LLSs, (2) comparison of video and LLS observations, and (3) comparison of LLS locations to known strike points (Mäkelä et al., 2016). Method 1 is most widely used but it gives only the relative LA of the test network against the reference network and location errors of the reference network are ignored. Method 3 is the most objective method, but its usage is limited by the small number of known ground strike points. ATDnet LA studies normally measure relative LA using method 1.

Lightning location systems can be divided into four main types: long-range LLSs, short-range LLSs (sometimes divided into medium-range and short-range systems), lightning mapping arrays and satellite-based optical detectors (can be divided into low-earth orbiting and geostationary). Each type is characterized by different detection efficiency and location accuracy ranges that are summarized in Table 1, for more details see e.g. Nag et al. (2015).

Table 1. Main performance characteristics of different types of lightning location systems.

LLS type	Sensor baseline	Detected lightning processes	Flash DE		Median LA
			CG	**IC**	
Long-range	Thousands of km-s	CG return strokes and IC pulses	10 to 90%	<25 to 30%	1 to >10 km
Short-range	50-400 km	CG return strokes and IC pulses	85% to >95%	50 to 75%	100 to a few hundred metres.
Lightning Mapping Array	10-40 km	Leader steps	>95%	>95%	Tens of metres.
Optical imager	A satellite-based sensor	Optical emission	70-90%		~10 km

Methods for the Modelling an Extended ATDnet Like Network

As discussed in the methods for the Review of ATDnet coverage, the key parameters of any Lightning Location Network are the Detection Efficiency and Location Accuracy. It is currently not possible to model these values holistically for a long range VLF network like ATDnet or LEELA. The Met Office has used a theoretical LA mapping method as applied in Enno et al (2016b). This location accuracy model makes some simple assumptions i.e. all receiver locations will be used for all lightning fixes, whilst this is true over a small region it is obviously incorrect for larger areas. For DE a method has been devised at the Met Office to use the Long Wave Propagation Code (LWPC) to model any given network geometry and region of the world. A lightning source is synthesised in a regular longitude-latitude grid over the region of interest. The propagation of the VLF signal to the receivers is then modelled using the normal LWPC codes. A day time ionosphere was used for this project which should result in the most pessimistic view of VLF propagation, although it should be noted that the location of the terminator can cause some irregularities in the propagation and therefore the network response to a given lightning event is somewhat unpredictable. The LWPC also contains a model for the conductivity of the earth surface, this along with the ionosphere characteristics determine the waveguide in which the VLF signal will travel.

For simplicity and efficient modelling, the MTG LI domain was split into 5 approximate domains (excluding the area already covered by ATDnet), as shown in Figure 0. These are roughly described as,

- Africa, extending from the Mediterranean southwards over the land area of Africa, including Madagascar.
- South Atlantic, extending from the west coast of Africa to the east coast of South America, below 15 degrees N and above 60 degrees S.
- South America, covering a region from the east coast of South America to 74 degrees W, between 30 degrees S and 15 degrees N, including the countries,

Brazil, Paraguay, Bolivia, Colombia, Venezuela, Guyana, Suriname and French Guiana
- North Atlantic, extending from the west coast of Europe to the east coast of North America, below 75 degrees N and above 5 degrees N.
- Eastern Europe, covering a region East of 15 degrees E and west of 54 degrees E and between 25 and 75 degrees N.

The signal strength required for each receiver to be considered a hit for a given lightning event can be tuned to a known network configuration. It is also known how many receivers are required to create a lightning fix, therefore for any given lightning event location and any given configuration of receivers it can be shown whether the sferic from the lightning would be detected. To tie this to a known lightning location network DE the information found in the review of ATDnet coverage above was used.

The approach taken was to begin with the nearby receivers either from ATDnet or previously modelled regions and add additional receivers in a course area around the outside of the region. Very few other factors were considered, mainly restricting the locations to population centres. Where it was possible capital cities were chosen as they're likely to have the infrastructure required for a receiver site (communications links). Where no suitable capitol city was near the required location other population centres were considered. In some circumstances no available location could be found and these are noted in the analysis below.

When a network geometry has been found where the effective DE is deemed to be high enough, the large region is split into small areas in which only a subset of the receivers would receive any sferic. These sub-regions and subset of receivers are then each run through the LA model. The results for each LA model are amalgamated together to create a single consistent output for each region (and the global output below). This amalgamation takes each grid point from the model and assigns the final value to the lowest (the best case) from any of the models that has output in that grid point.

Results of Review of ATDnet Coverage

ATDnet performance has been evaluated mostly against short-range lightning location systems. This is technically very easy as both detect CG return strokes and IC pulses and record them as points in space and time. It is also scientifically justified as short-range systems normally have higher DE and better LA. Comparisons against lightning mapping arrays are probably the best way to assess absolute DE as LMAs rarely miss flashes. However, only one such study is available due to the complexity of matching ATDnet and LMA observations, as the systems observe different lightning processes.

ATDnet has also been compared against other long-range systems and satellite-based optical lightning detectors. Such studies are useful for learning more about similarities and differences of LLSs that cover large areas, including the oceans. There are certain limitations, e.g. satellite-based sensors are not suitable for evaluating ATDnet LA as they are characterized by larger location errors than ATDnet (the opposite can be done). At the same time, they offer a good reference dataset for evaluating ATDnet DE over large areas.

The rest of the chapter presents the results of the main ATDnet evaluation studies during the last ten years in chronological order. It must be considered that some earlier analysis, although published in 2010, use ATDnet data prior the latest major upgrade in 2008. It is assumed that the system was characterized by somewhat lower DE and larger location errors before the upgrade. It is also important to consider that only 'good' fixes that are used in ATDnet data products and disseminated to the customers are used in DE and LA studies.

It should be noted that only studies that were available to the authors were used. This results in some notable omissions, there is no detailed in-depth study of ATDnet vs GLD360 or LINET. Although some results against GLD360 are discussed below. It would be a valuable addition to the community to have further study of these networks.

ATDnet vs Meteo France

Seven days of detected strokes by ATDnet over France were compared with the French lightning detection system in summer 2007 (Gaffard et al., 2008). The French system was a short-range system that used broadband VLF/LF (~1-350 kHz) lightning emission. It consisted of IMPACT sensors developed by Vaisala and software developed by Météorage.

The two systems detected about the same number of events on a daily basis and the general patterns of observed storm locations were similar. On average over the week, ATDnet detected 6% more strokes than Meteo-France. ATDnet DE relative to Meteo-France was clearly lower at night (Fig. 1). 85,197 strokes were matched between ATDnet and Meteo-France, with a mean measured distance between each pair of 4.9 km and standard deviation of 5.1 km. The measured location error was larger at night (Fig. 2).

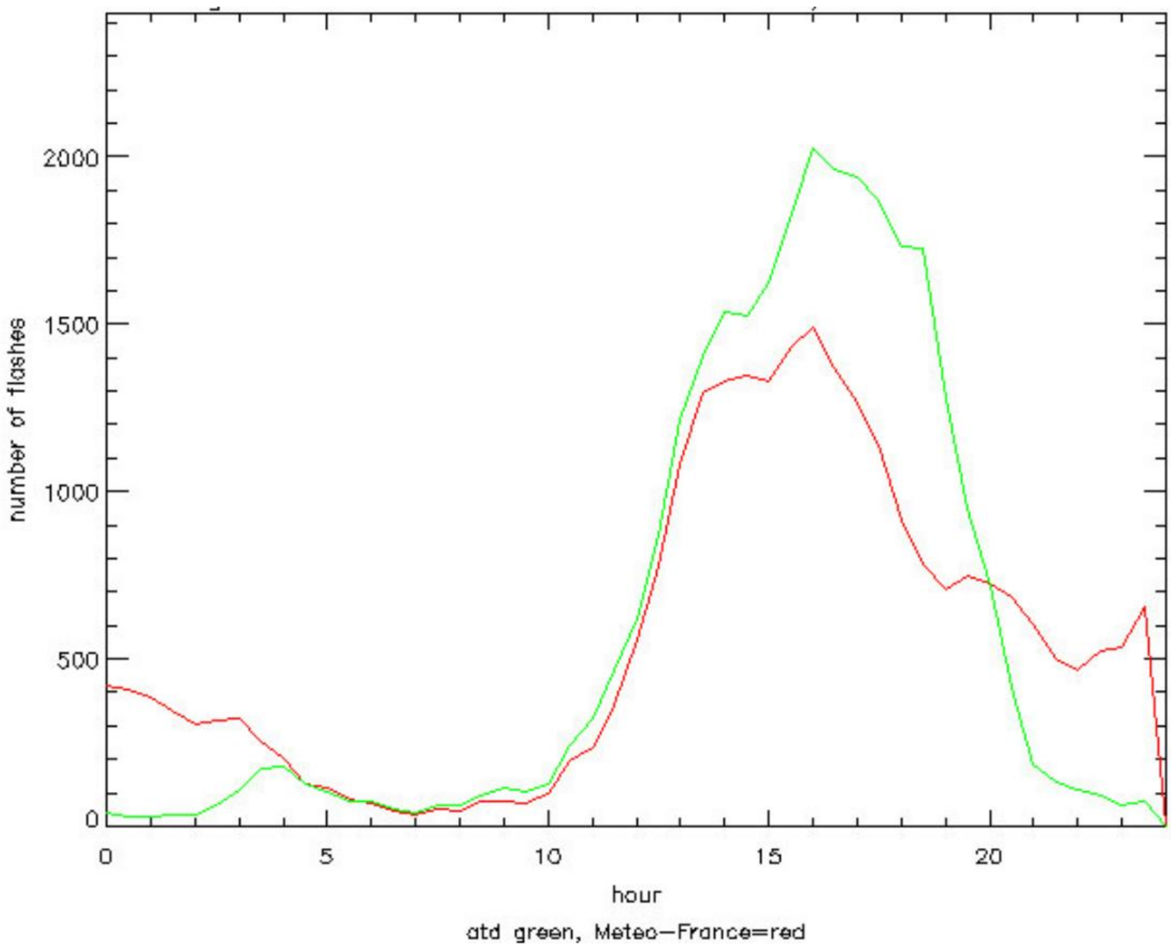


Figure 1. Diurnal variation of number of strokes detected in 30-minute intervals by ATDnet (green) and Meteo-France (red), averaged over a week in summer 2007. Time in UTC (Gaffard et al., 2008).

Measured location errors were compared with theoretical location errors provided by ATDnet central processing for every detected lightning location. Theoretical location errors are computed as the root- mean-square of the major axis and the minor axis of the error ellipse in which a detected lightning event is located with a 95% probability. Theoretical and measured location errors agreed well during the day whereas underestimation of theoretical location errors was obvious at night (Fig. 2).

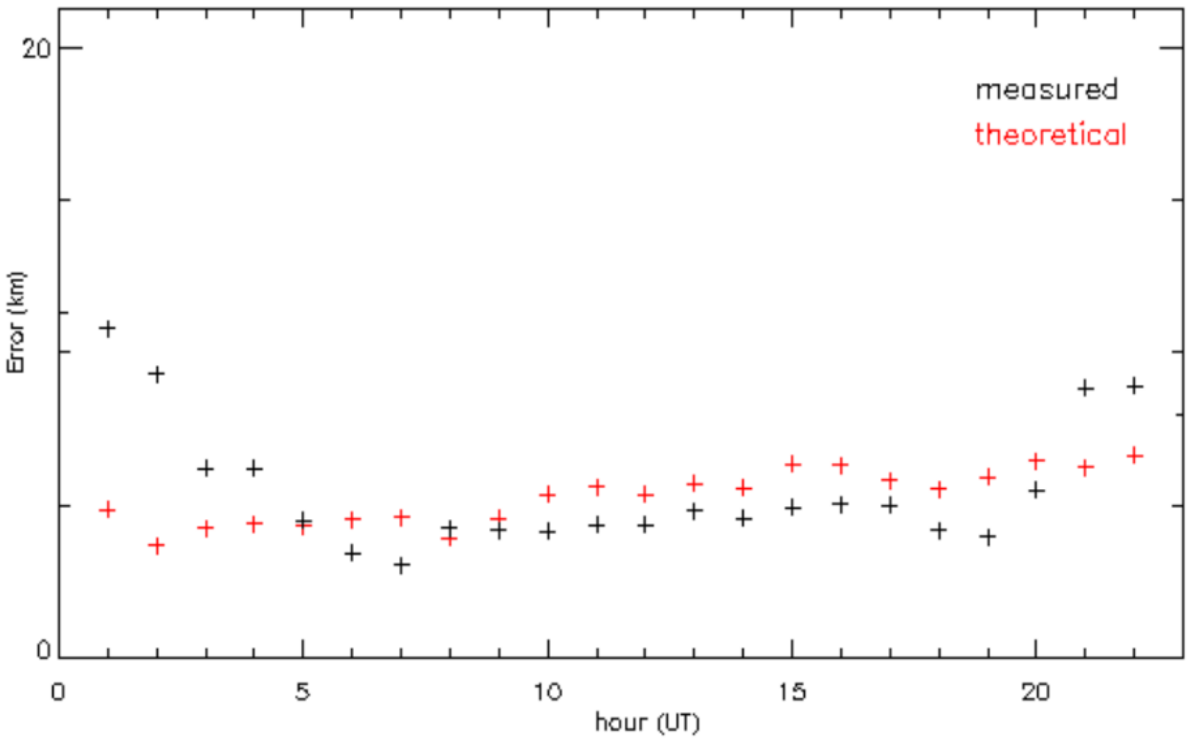


Figure 2. Diurnal variation of measured (black) and theoretical (red) ATDnet location error for co-located strokes over France over a week in summer 2007 (Gaffard et al., 2008).

ATDnet vs ALDIS

Seven days of detected strokes by ATDnet over Austria were compared with the Austrian Lightning Detection and Information System (ALDIS) in summer 2007 (Gaffard et al., 2008). ALDIS is a short-range system that uses broadband VLF/LF (~1-350 kHz) lightning emission.

ALDIS recorded approximately twice as many lightning strokes as ATDnet with ~50% of the ATDnet fixes co-located with those of ALDIS. The fraction of ALDIS strokes detected by ATDnet was clearly higher towards higher peak amplitudes (Fig. 3). This trend was absent in the comparison against Meteo-France, the reason is unknown.

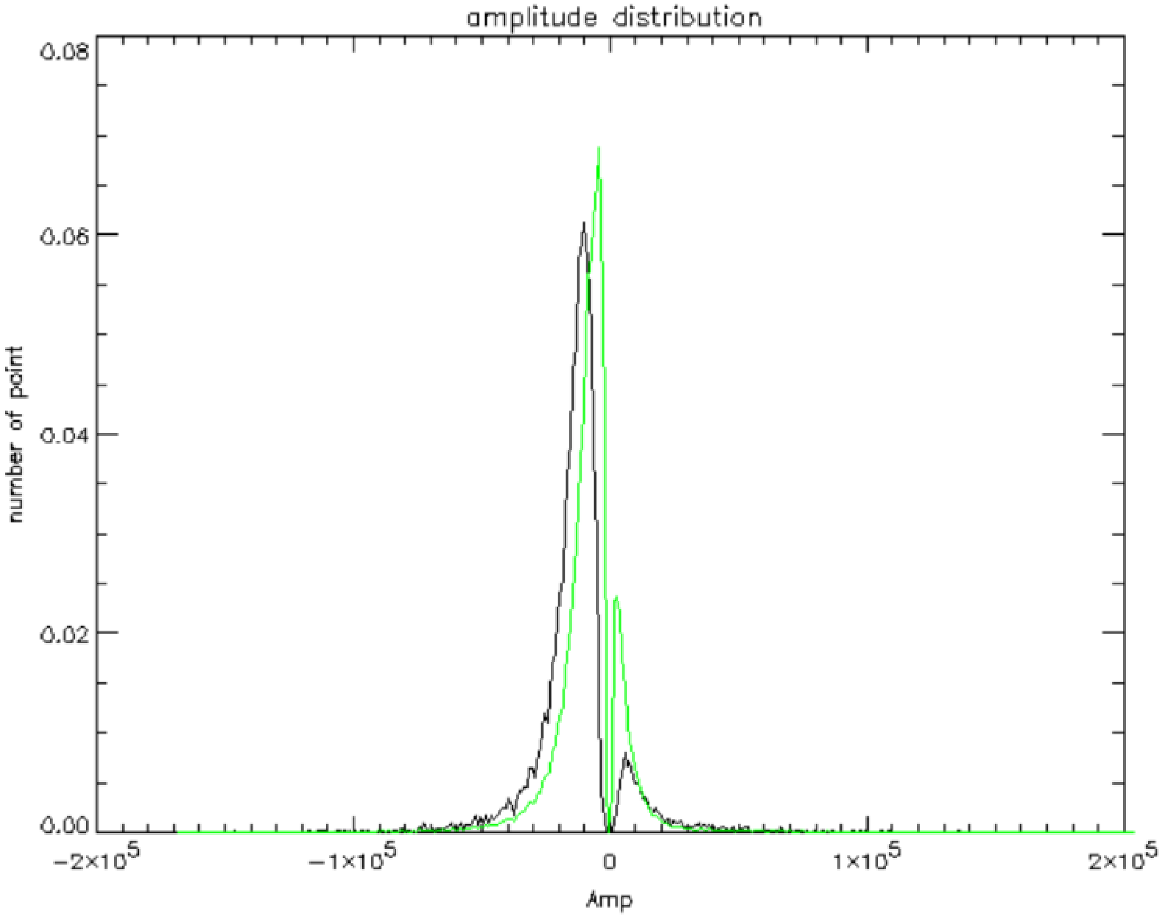


Figure 3. Stroke amplitude distribution (relative to total strokes for each dataset) with green denoting all strokes measured by ALDIS and black being strokes which were also detected by ATDnet.

ATDnet vs NORDLIS August 2007

NORLIS is a combination of Finnish, Swedish, Norwegian and Estonian lightning location networks operating Low Frequency (LF) Vaisala sensors.

Data from ATDnet and NORDLIS were compared between 9-18 August 2007 in a geographical area bounded by 57-66°N, 17-29°E (Bennett, 2010). The two datasets were compared directly by identifying coincident cloud-to-ground lightning strokes detected by both networks. Coincident was defined as a stroke time difference of less than one millisecond. This selection produced a reasonably large sample size (28,761 coincident CG lightning strokes) over the ten days (Fig. 4).

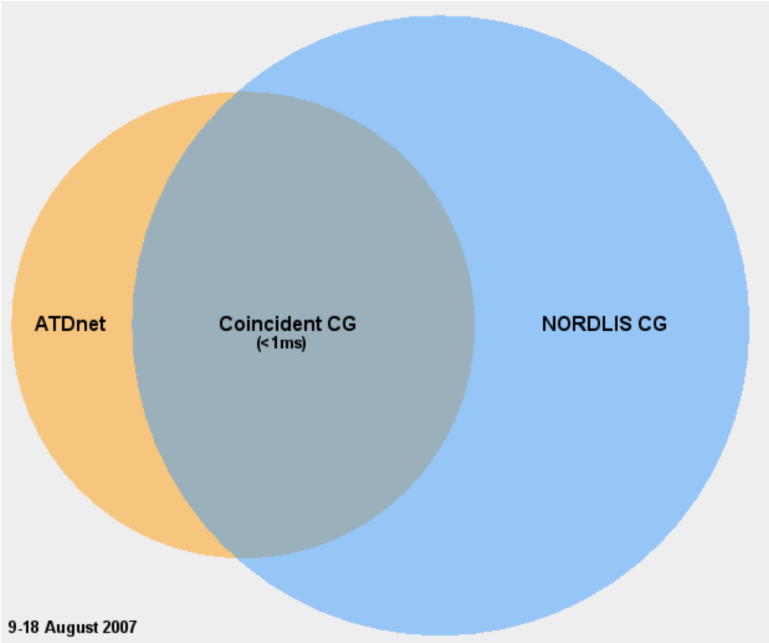


Figure 4. Venn diagram representing the total CG strokes located by both networks and the proportion of those which were coincident, defined as having a source time difference of less than 1ms and within the comparison region (Bennett, 2010).

The total number of ATDnet strokes in the study area during the 10-day period constituted 57% of that for NORDLIS. ATDnet was clearly more sensitive to NORDLIS strokes with higher peak current with only ~25% of 10kA strokes detected by ATDnet, compared to ~70% of 50kA strokes. ATDnet also appeared to have lower detection efficiency for weak to moderate positive CG strokes compared to negative (Fig. 5). The reason for this slight polarity relation to detection efficiency is not clear.

Obvious diurnal variations in ATDnet detection efficiency (DE) relative to NORDLIS were observed. During the night, ATDnet relative DE dropped to less than 40% whereas during the day it was mostly 60-90% (Fig. 6). The diurnal variations were attributed to the modal interference where the secondary propagation mode, which travels over a greater distance at night, interferes with the primary mode and causes waveform distortion leading to poor correlation and associated reduction in the number of strokes passing quality control.

The modal location difference between ATDnet-NORDLIS matches was 1-1.5 km, with a median value of 4.5 km. Large location differences were preferably orientated in the east-west direction, which is in line with the network geometry (Fig. 7).

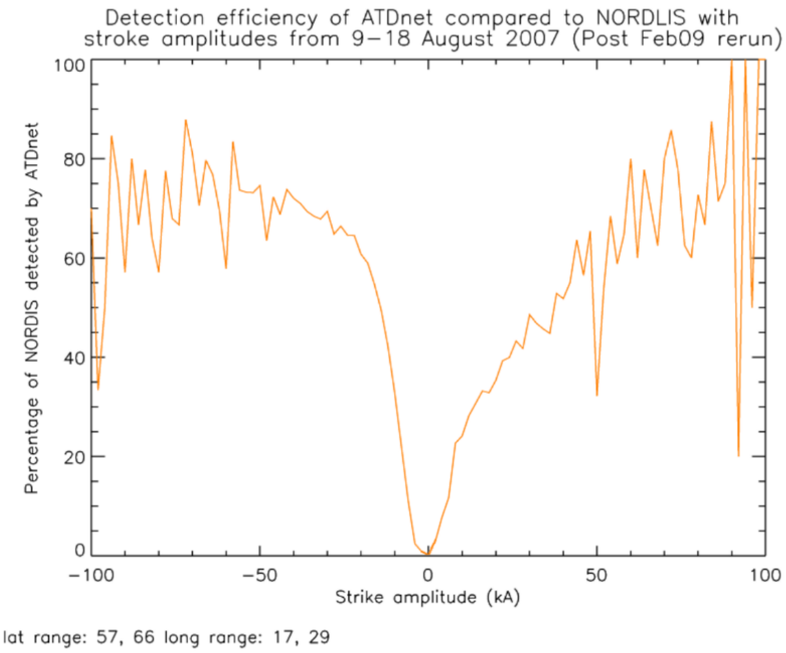


Figure 5. Detection efficiency of ATDnet compared to NORDLIS as a function of lightning peak current (Bennett, 2010).

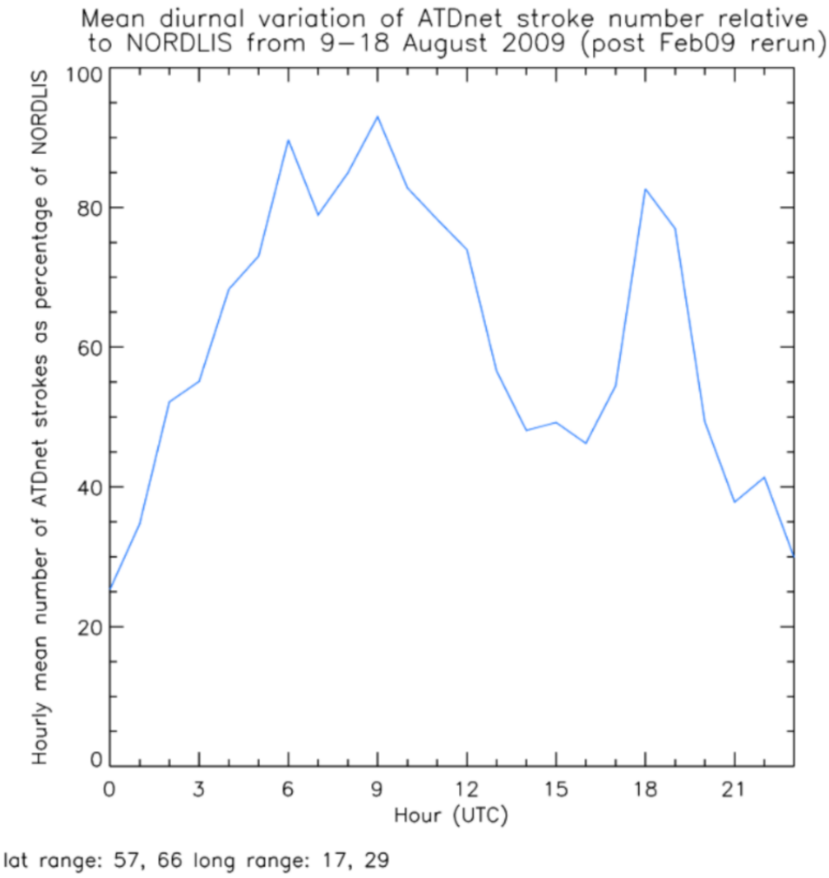


Figure 6. Diurnal variation of ATDnet detection efficiency relative to NORDLIS, averaged over the ten-day case study (Bennett, 2010).

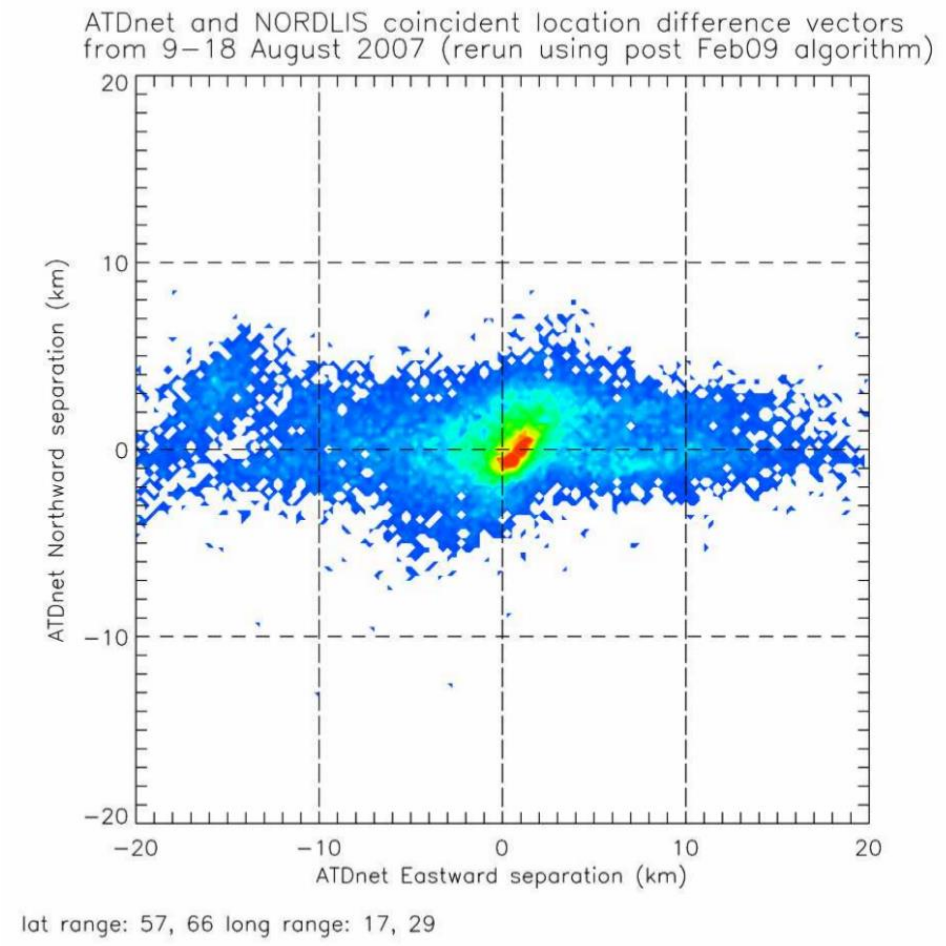


Figure 7. Coincident ATDnet and NORDLIS stroke location difference contour plot for all coincident strokes. Red denotes maximum number concentration (Bennett, 2010).

ATDnet vs BrasilDAT

ATDnet theoretical location accuracy model was assessed by comparing ATDnet lightning stroke locations to cloud-to-ground strokes detected by a local network covering southern Brazil (Bennett et al., 2010). The network (BrasilDAT) is a highly accurate short-range LLS (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. Note that ATDnet detection efficiency was not assessed in that study.

The distribution of observed location errors was in close agreement with the theoretical ellipse, which would represent the area enclosing ~70% of data (Fig. 8). Minor deviations in the orientation of observed location error along axis are due to the use of different sensor sites by the ATDnet algorithms. Larger location errors were observed during the day (peak around sunrise) and smaller at night as ATDnet phase and group velocity were tuned for the night time ionosphere back then.

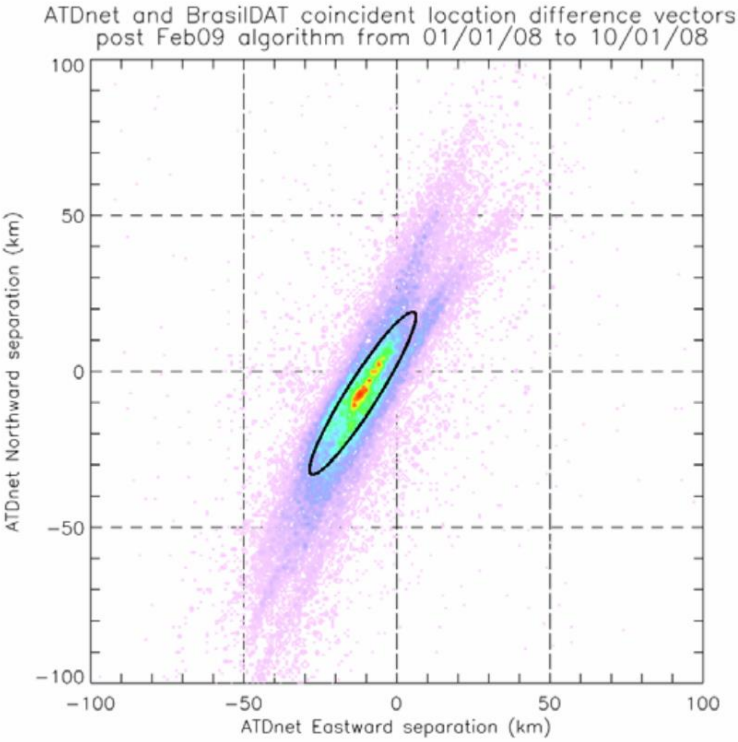


Figure 8. Colour density of observed ATDnet location errors (derived using coincident strokes with the BrasilDAT network), with the theoretical ATDnet location accuracy model error ellipse for Southern Brazil superimposed (black line). The ellipse is centred on the modal observed location error. Data collected during 1-10 January 2008. The scatter plot is coloured according to event density with red being most dense (Bennett et al., 2010).

ATDnet vs WWLLN

The World Wide Lightning Location Network (WWLLN) is a long range network mainly supported by academia. Whilst they have a relatively large number of receivers (~60) giving global coverage to some degree it is unclear how consistent the coverage in terms of DE and the low density of receivers will result in a lower LA than ATDnet (over Europe).

Bennett (2011) compared ATDnet WWLLN in the tropical North Atlantic Ocean during January and June 2010. The study area was defined as 5°S-20°N and 10°W-60°W. All ATDnet and WWLLN strokes less than one millisecond apart were considered as matches, no additional spatial coincidence threshold was applied. There were 83,733 matching ATDnet and WWLLN strokes in the study area during January and 197,808 in July.

The results revealed that ATDnet detected approximately three times the number of strokes compared to WWLLN (Fig. 9). Of the WWLLN totals, approximately 80% were coincident with ATDnet. The modal location differences of matching fixes were 10.0 km and 11.5 km for January and June respectively (Fig.10). ATDnet strokes were predominately located either to the southwest or northeast of their corresponding

WWLLN strokes. This is in line with the dominant spatial error ellipses of ATDnet for the comparison region, which can be calculated according to network geometry.

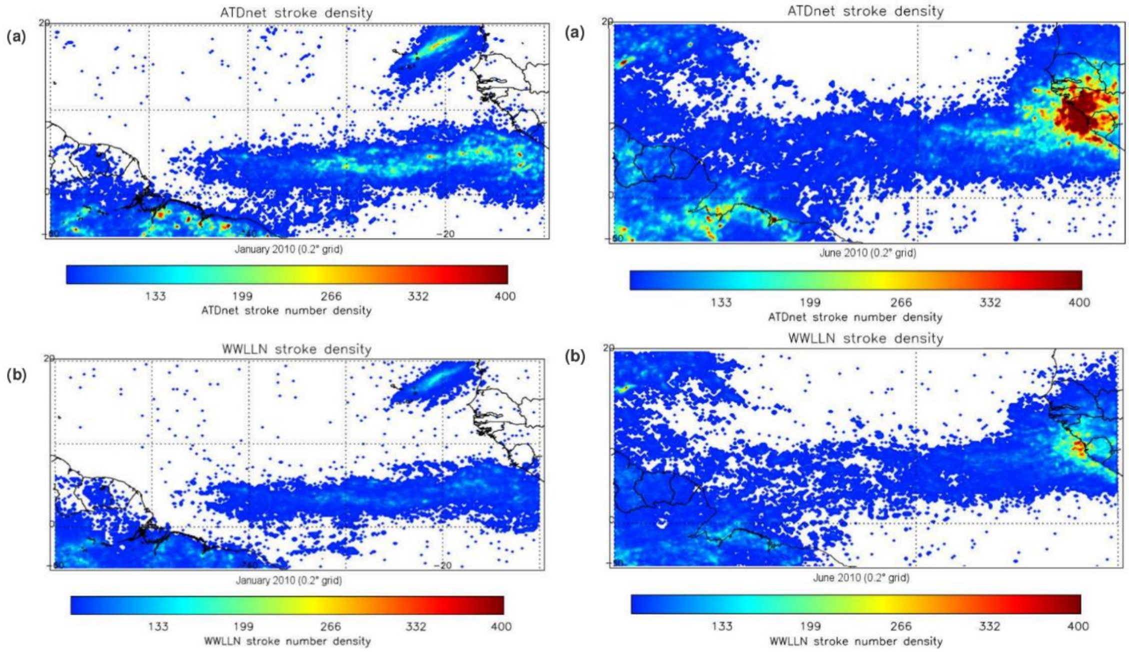


Figure 9. Lightning stroke density for January (left) and June (right) 2010 in the comparison region for ATDnet (top) and WWLLN (bottom) (Bennett, 2011).

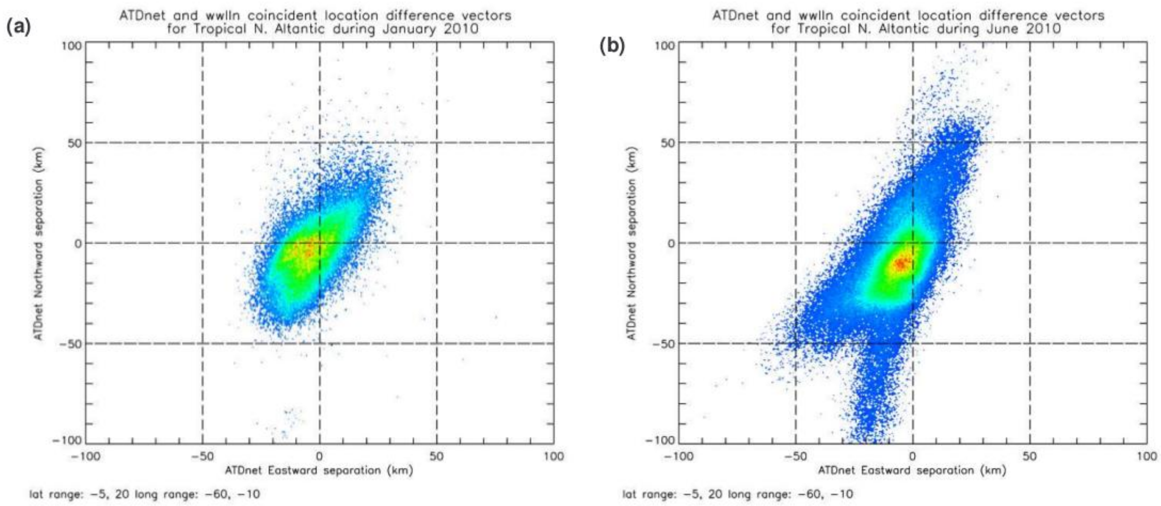


Figure 10. The distribution of coincident location difference vectors between ATDnet and WWLLN for January (left) and June (right) 2010. Maximum density (e.g. modal vectors) represented by red areas, with individual values shown in blue (Bennett, 2011).

There was no clear diurnal variation of WWLLN detection efficiency relative to ATDnet during June, with WWLLN detecting ~30% of ATDnet strokes throughout the day. A diurnal variation was more apparent during January, when the value exceeded 40% between 13-19 UTC (Fig. 11). The location difference was lowest between 20-06 UTC during January and 00-04 UTC during June. Similar variation was observed in comparisons between ATDnet and BrasilDAT in Brazil and is due to the diurnal variation of the ionospheric reflection height for VLF (Bennett et al. 2010). ATDnet assumes a fixed ionospheric height (and therefore group velocity) corresponding to that found during the night (~85 km), whereas in reality the reflection height is lower along sunlit propagation paths due to photoionisation from ultraviolet radiation (ionospheric D-layer generation). The WWLLN exploits the similarity between day and night group velocities around 12.8 kHz, so is expected to be less affected by the diurnal variation of reflection height.

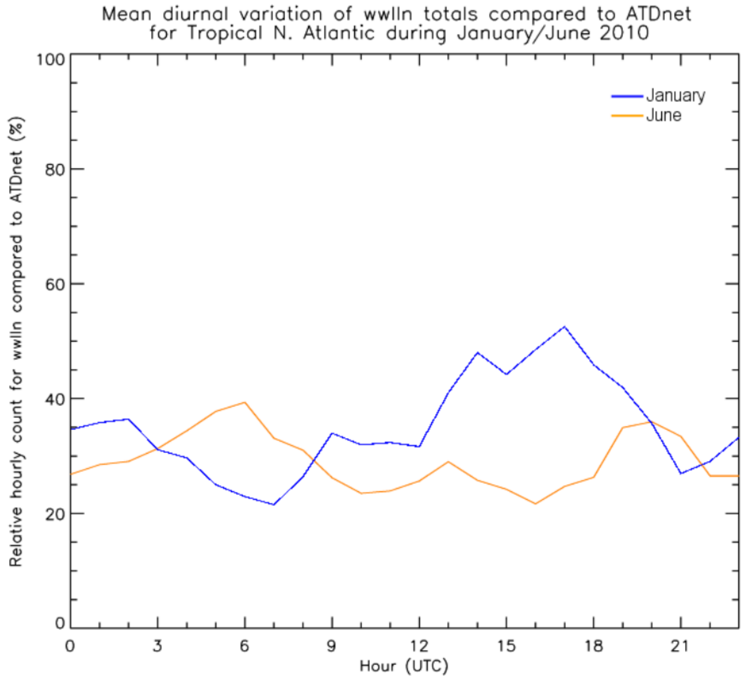


Figure 11. Mean diurnal variation of relative detection efficiency of WWLLN compared to ATDnet (Bennett, 2011).

ATDnet vs ground truth data in Belgium

Electric field measurements coupled to high-speed camera observations of cloud-to-ground lightning were carried out by Poleman et al. (2013b) in Belgium during August 2011. During the campaign 57 negative cloud-to-ground flashes, with a total of 210 strokes, were recorded. This dataset was used test the detection efficiency and location accuracy of different lightning location systems covering Belgium. Lightning detection network operated by the Royal Meteorological Institute of Belgium, the European Cooperation for Lightning Detection (EUCLID), Vaisala's Global Lightning Detection network GLD360, and the Met Office's long-range Arrival Time Difference network (ATDnet) were evaluated and compared.

ATDnet detected 88% of flashes and 58% of strokes observed during the campaign (Table 1). ATDnet flash DE was comparable to networks operated by the Royal Meteorological Institute of Belgium (OP and TP in Table 1). ATDnet stroke DE was somewhat lower than the other networks but varied significantly between the three analysed storms. It was only 23% on 22 August 2000–2300 UTC but 60% on 23 August 0700–0800 UTC and 75% on 26 August 0430–0530 UTC. Hence, the averaged stroke DE of 58% over the three days was heavily influenced by the low DE on 22 August at night. In contrast, the other long-range LLS in the study, GLD360, did not experience notable diurnal cycle in DE.

Table 1. DE and LA for the individual networks. In addition, 95% confidence intervals are reported in parentheses. N of strokes is the number of strokes used to estimate the LA (Poleman et al., 2013b).

	Stroke DE (%)	**First stroke DE (%)**	**Subsequent stroke DE (%)**	**Flash DE (%)**	**Median LA (km)**	**N of strokes***
OP	70	84	64	93	6.1 (0, 8.8)	13
TP	64	88	56	92	1.0 (0.7, 3.6)	12
EUCLID	84	98	79	100	0.6 (0.2, 1.9)	23
GLD360	70	79	66	96	0.9 (0.5, 3.3)	22
ATDnet	58	75	51	88	1.0 (0.6, 2)	13

LA was assessed using only strokes that followed the same stroke channel as determined from the used images. These strokes were assumed to strike ground at the same point. The differences between the stroke positions within a flash were then computed from the position distances in the LLS data (Fig. 12). ATDnet median LA was found to be 1.0 km, which is comparable to GLD360 and TP of the Royal Meteorological Institute of Belgium.

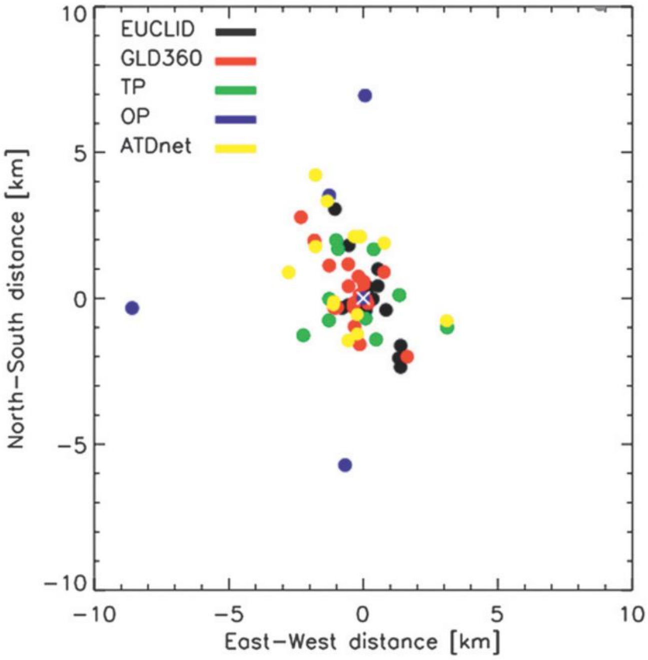


Figure 12. Location offset for the subsequent strokes following the same channel as seen in the video images. The origin corresponds to the location of the first stroke in the channel (Poleman et al., 2013b).

ATDnet vs short-range LLS in Benelux and France

The lightning datasets from a regional network employing Surveillance et Alerte Foudre par Interferometrie Radioelectrique (SAFIR) sensors operated by the Royal Meteorological Institute of Belgium (RMIB), a subcontinental network operated by Meteorage (MTRG), and ATDnet were compared in Benelux and France between May and September 2011 and 2012 (Poelman et al., 2013a). Stroke and flash data between May and September 2011 and 2012 were analysed. Here, mainly the results of ATDnet-MTRG comparison are presented as SAFIR covered only a small area and exhibited lower location accuracy.

In the smaller study area covering Benelux (49º-52ºN and 2º-7ºE), ATDnet detected more than SAFIR and MTRG (CG flashes only) and approximately as much as MTRG (CG and IC flashes). ATDnet outnumbered by far the detections of the other networks between 0300 and 2000 UTC, but not at night (Fig. 13). The comparison also suggested that at least ~25% of ATDnet flashes and 15% of ATDnet strokes were IC. ATDnet DE increased towards higher peak currents, the system detected 80-90% of MTRG negative CG flashes and 70-80% MTRG positive CG flashes with peak current >20 kA. ATDnet, MTRG and SAFIR all showed very similar spatial pattern of areas affected by lightning.

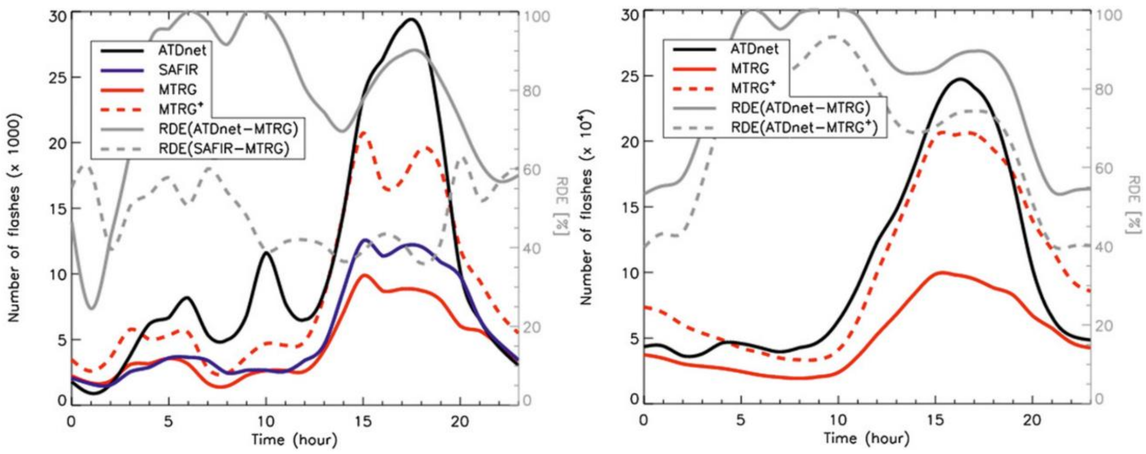


Figure 13. Temporal distribution of the number of flashes detected over the small (left) and large (right) study area during May–September 2011 and 2012 by ATDnet (black), SAFIR (blue), MTRG (CG only, red/solid), and MTRG⁺ (CG and IC, red/dashed). In addition, the variation of the flash RDE (%) of ATDnet is plotted as well. Note that SAFIR data was available only for the small study area (Poelman et al., 2013a).

In the larger study area covering Benelux, France, southern England, western Germany, and northern Spain (42º-53ºN and 5ºW-9ºE), ATDnet detected twice as many flashes as MTRG (CG only) but approximately the same amount of flashes as MTRG(CG+IC). Like in the smaller study area, ATDnet detected more during the day compared to MTRG, while a drop was noticed at night. The comparison also suggested that at least ~25% of ATDnet flashes and 18% of ATDnet strokes in the larger study area were IC.

ATDnet detected 80% of MTRG CG flashes in both study areas. Its CG stroke DE was 47% in the smaller and 49% in the larger study area. ATDnet median stroke location deviation relative to MTRG was 1.9-2.0 km and flash location deviation 2.7-3.0 km in both study areas. ATDnet stroke to flash ratio was somewhat lower compared to SAFIR and MTRG in both study areas. This is in line with the observation of Poleman et al. (2013b) that ATDnet is more likely to detect the first—and most likely strongest—stroke in a flash, but it is less likely to detect subsequent return strokes.

ATDnet vs HyMeX Lightning Mapping Array

Enno et al. (2016a) validated ATDnet against the Hydrological Cycle in the Mediterranean Experiment (HyMeX) Lightning Mapping Array (HyLMA) deployed in the south of France in autumn 2012 as a part of the HyMeX project Special Observation Period 1 (SOP1). Three daytime storms on 5, 11, and 25 September 2012 with a total of 281 CG and 1324 IC flashes were selected for the study.

ATDnet average CG flash DE was 88.6% (86.8%-89.3% in individual storms) and IC flash DE 23.7% (23.1%-34.8% in individual storms). ATDnet overall DE (including all CG and IC flashes) varied from 35-56% between the studied storms and depended on the fraction of ICs. The storm with the highest (lowest) IC fraction had the lowest (highest) overall ATDnet DE.

Vertically longer cloud flashes were detected much more efficiently than ICs with small vertical extent (Fig. 14). None of the IC flashes vertically shorter than 1 km was detected, whereas for the flashes with a vertical extent over 4.5 km, DE was around 45%. It was also demonstrated that 66.6% of the ATDnet IC detections were related to the initial breakdown which is an early and often vertical part of IC (Nag et al. 2009).

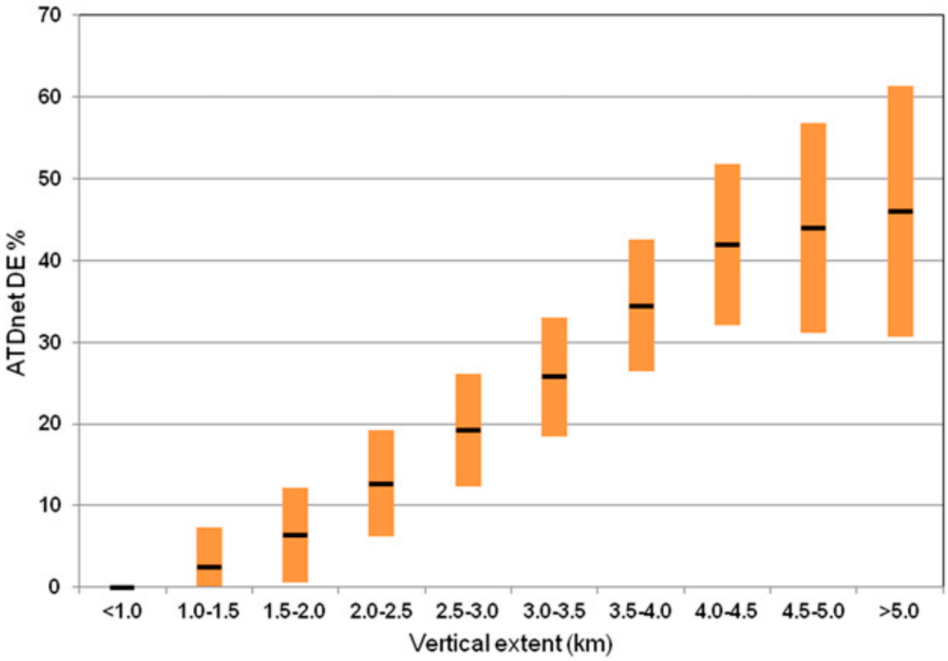


Figure 14. ATDnet IC DE as a function of the vertical extent of the flashes (black) and its 95% confidence intervals (orange) (Enno et al., 2016a).

ATDnet vs STARNET

An unpublished ATDnet-STARNET comparison was carried out in 2015. ATDnet and STARNET annual global datasets for 2014 were compared (more than 106 million ATDnet and 265 million STARNET fixes).

ATDnet detected more fixes than STARNET in Eurasia, Northern Africa, the northeast corner of North America and the North Atlantic (Fig. 15). There was also a small area in the South Pacific where ATDnet detected more lightning than STARNET. This is probably due to wrongly located European fixes as the region is antipodal to most active areas in Europe. STARNET detected more than ATDnet in most of the Americas, the Pacific, the South Atlantic and Southern Africa. An odd and unexplained rectangular region without STARNET observations was found near Indonesia to the north of the equator and to the west of 135°E.

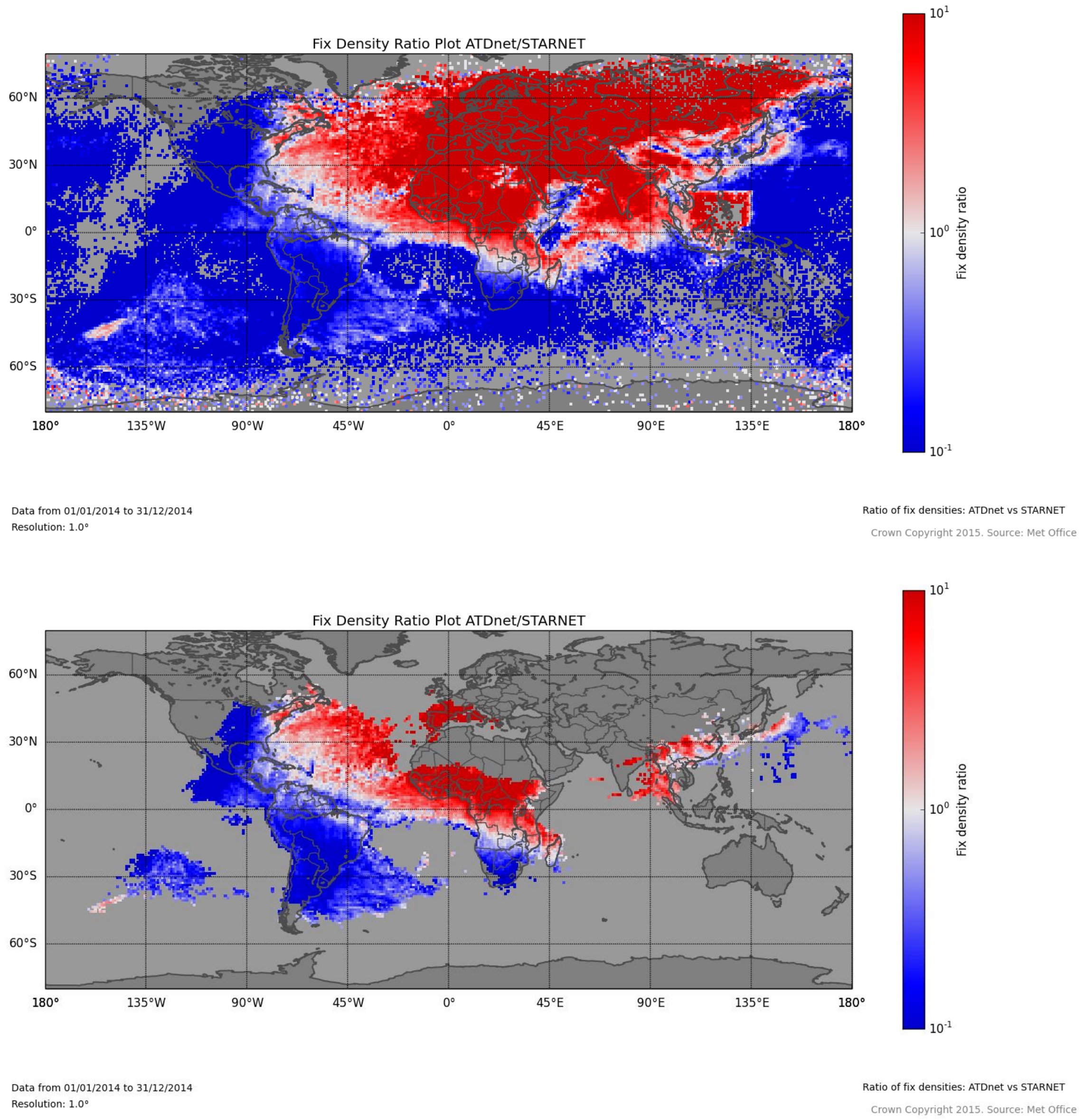
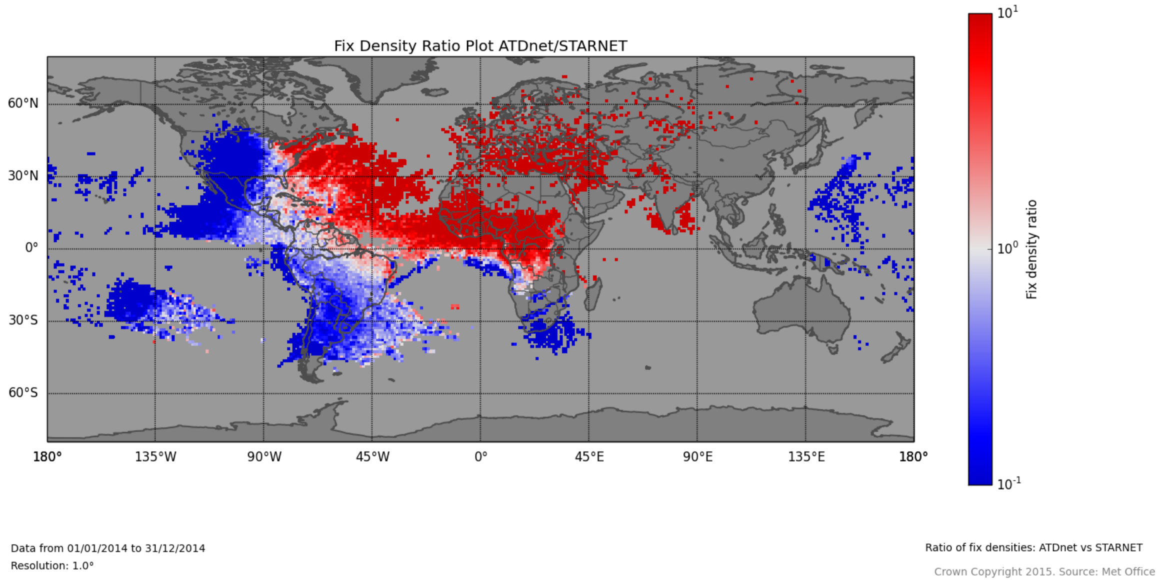


Figure 15. ATDnet/STARNET fix density ratio in 2014 in a 1x1 degrees grid for all grid cells (top) and for grid cells with at least 100 fixes detected by both systems (bottom).

Probably the most surprising finding was that ATDnet outperformed STARNET in certain areas along the east coast of North and South America at night in Europe (Fig. 16). This is remarkable as the eastern part of South America is in the perimeter of STARNET whereas ATDnet sensors are 6-10 thousand kilometres away. The effect appeared at around 21 hours UTC, peaked between 3-5 hours UTC and disappeared after 9 hours UTC. During the day in Europe, STARNET detected much more than ATDnet in South America.



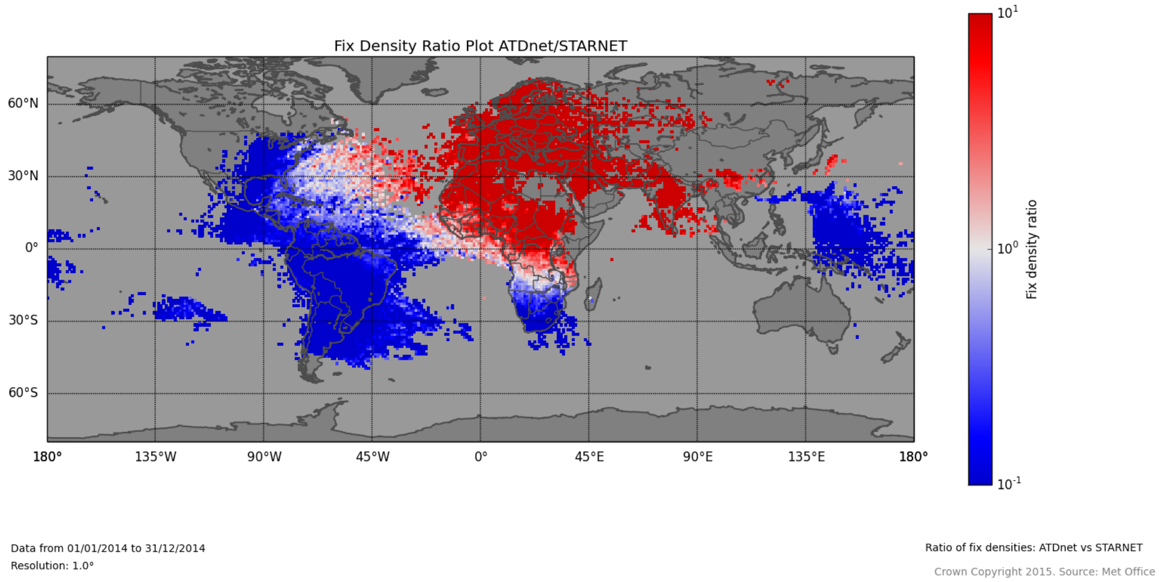
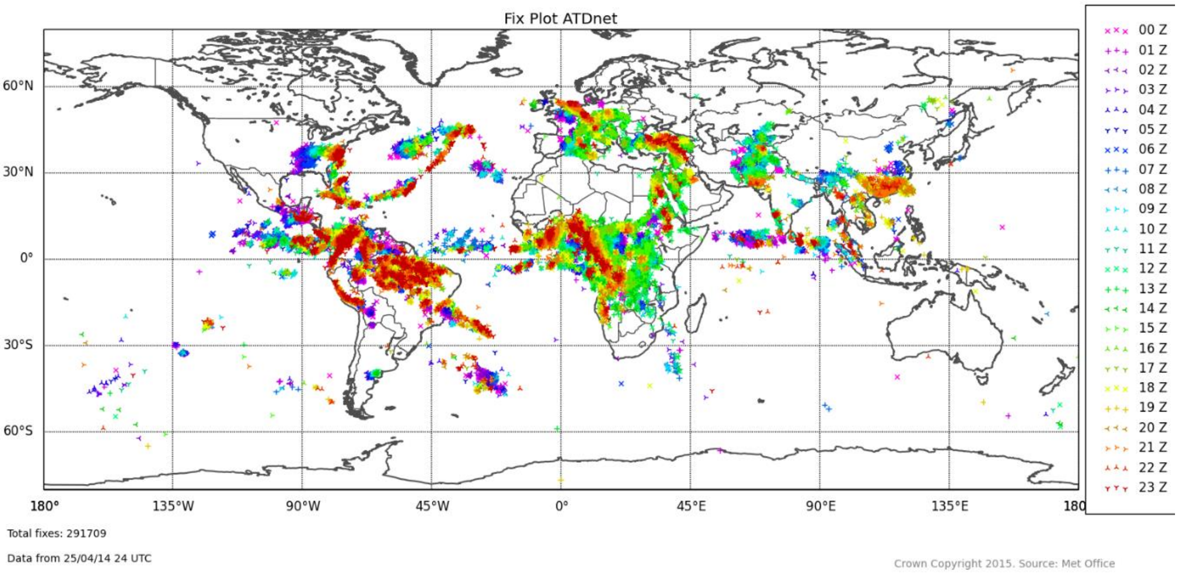


Figure 16. ATDnet/STARNET fix ration in 2014 in a 1x1 degrees grid for grid cells with at least 100 fixes detected by one of the systems during 03-05 UTC (top), and 15-17 UTC (bottom).

Another interesting finding was that ATDnet daily fix plots look much cleaner than STARNET fix plots (Fig. 17). The difference persists even if bad and questionable STARNET fixes are omitted and only good fixes are plotted. This indicates that ATDnet quality control is more efficient in removing spurious lightning locations. However, some other studies have suggested that this might come at the cost of rejecting a lot of usable fixes.



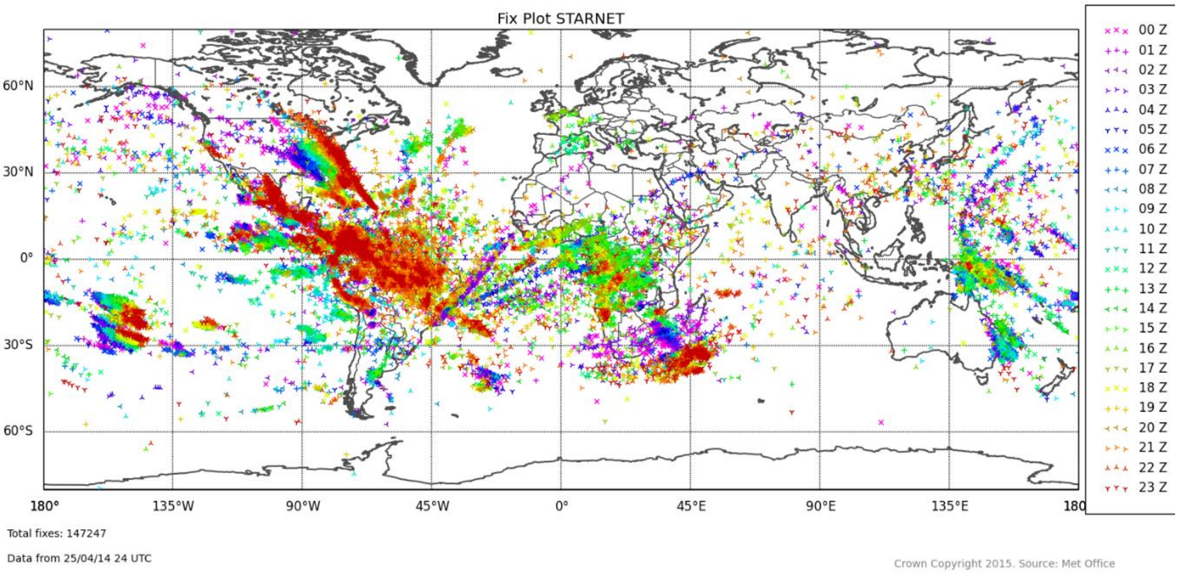


Figure 17. ATDnet (top) and STARNET (bottom) good fixes on 25/04/2014, coloured by hour.

ATDnet vs Blitzortung

An attempt to validate ATDnet against Blitzortung was made in 2017. Blitzortung is an enthusiast built and run short range network. The DE and LA of the network depends on the number of volunteers who are currently providing a receiver in the area of interest. It can be assumed that the density of volunteers is high enough for acceptable coverage over most of western Europe, with especially good coverage over France and Germany. Due to the frequency band used the DE over water away from coastlines is very poor.

Data from summer 2016 was used. The focus was to assess ATDnet quality control and rescue procedures. Besides the main task, some detection efficiency maps were also plotted. An example for August 2016 is shown in Fig. 18.

It is obvious that ATDnet DE was remarkably higher during the day with 20-40% Blitzortung fixes in western and central Europe and 40-80% of Blitzortung fixes elsewhere in Europe detected by ATDnet. At night, in contrast, the figures were only 10-30% in western Europe and mostly between 30-50% elsewhere. It is also obvious that ATDnet DE relative to Blitzortung increases with distance from western and central Europe. This trend can be attributed to decreasing Blitzortung sensor density that makes Blitzortung less sensitive to weaker cloud lightning discharges often missed by ATDnet. During the day, almost all Blitzortung fixes near the southern, eastern and northern edge of the study area were also detected by ATDnet. This indicates that Blitzortung, which is a short-range system, detects only strong lightning that is rarely missed by ATDnet in these areas. In fact, the number of ATDnet detections often exceeds the number of Blitzortung observations in these areas. The comparison code is still available and well documented. Thus, it should be relatively easy to run it again with a larger dataset, should a more comprehensive ATDnet validation be needed.

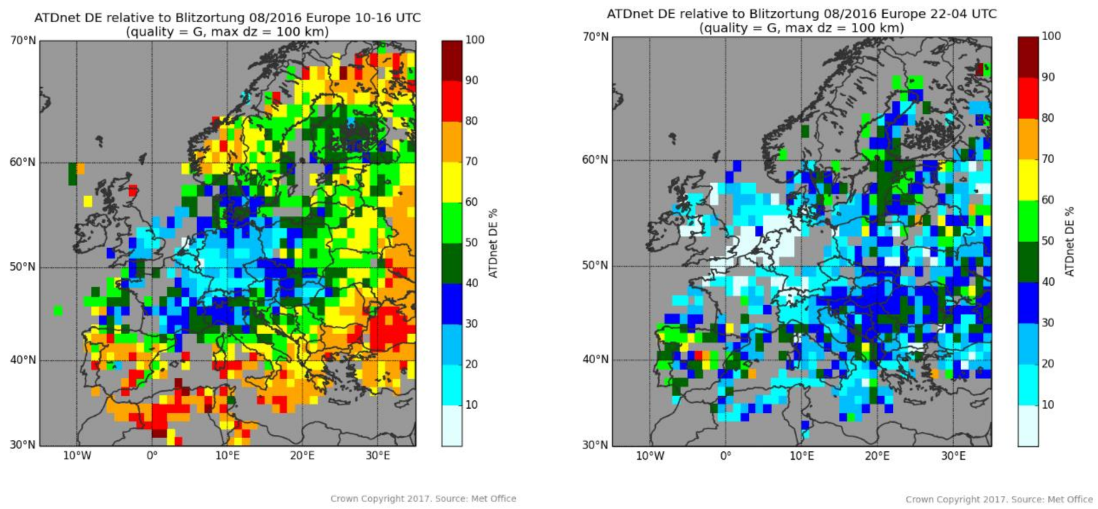


Figure 18. ATDnet DE relative to Blitzortung in August 2016 during 10-16 UTC (left) and 22-04 UTC (right). A threshold of 100 km was used in matching ATDnet and Blitzortung fixes and only ATDnet good fixes were used.

ATDnet vs TRMM-LIS

The first attempt to compare ATDnet and the Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS) by Collins et al. (2012) showed a very small number of ATDnet strokes and flashes matching with LIS groups and flashes. The main reason was probably a short study period (only seven days) with most of the lightning activity near the equator, i.e. far from ATDnet sensors. The NOAA OTD (1995-2000) dataset was also included in some of the analysis.

As the number of matches between ATDnet and TRMM-LIS was very small, a more general ‘transfer function’ between gridded OTD/LIS and ATDnet datasets was created. ATDnet flash density during January 2010 to May 2012 was compared against TRMM-

LIS (1998-2010, 38°N-38°S) and OTD (May 1995-March 2000, 75°N-75°S) combined flash density. The output transfer function (i.e. the ratio of LIS/OTD climatology flash density to ATDnet climatology flash density) is shown in Fig. 19.

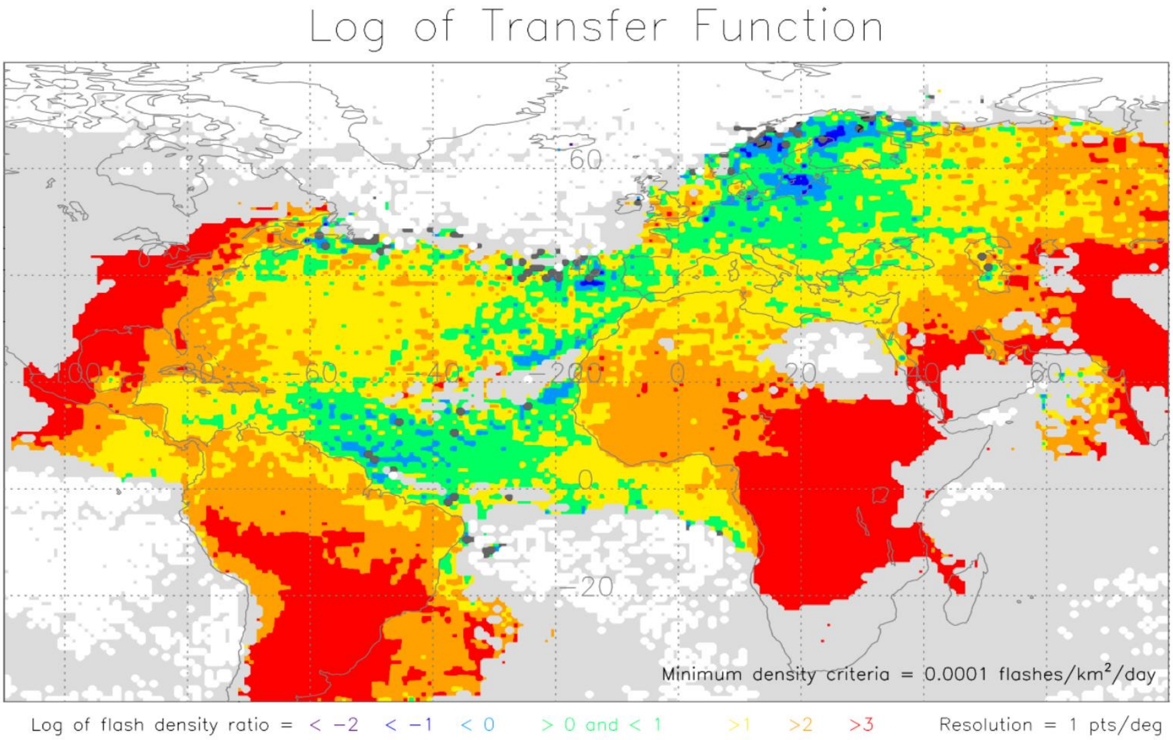


Figure 19. Plot of Log_{10} of the 'transfer function' – ratio of LIS/OTD to ATDnet flashes, using ATDnet data from 2010-2011 and LIS/OTD climate data from 1995- 2010 (Collins et al., 2012).

It must be emphasized that Fig. 19 is not a detailed map of ATDnet DE relative to OTD/LIS. Instead, it only approximately presents the main spatial features of ATDnet DE. There are multiple artefacts caused by OTD/LIS short view times and lack of temporal overlapping between the ATDnet and OTD/LIS datasets. For example, blue areas in northern Europe where ATDnet seems to have detected more than 100 times as much as OTD/LIS are probably intense storms that were missed by OTD/LIS as they are rare in these areas. The opposite seems to be the case in England where the satellite-based flash density is much higher than ATDnet flash density. This is probably related to the fact that OTD observations during 1995-2000 were compared against ATDnet observations in 2010-May 2012. It is likely that OTD data is biased towards higher than average flash densities whereas ATDnet observations represent lower than average lightning activity in England in summers 2010 and 2011.

Another important limitation arises from latitudinal variations in the average CG and IC lightning ratio. The ratio is estimated to vary with latitude from around unity at high latitudes to nearer ten between the tropics (Pierce, 1970). These variations are expected to significantly affect the values of the transfer function as ATDnet is designed to detect CG return strokes whereas satellite-based sensors tend to be more sensitive to cloud lightning.

The log values of the transfer function were interpreted as follows: regions of blue or purple (transfer function < 1) suggest regions of high ATDnet detection efficiency of CG flashes (> 90%); green regions (transfer function between 1 and 10) suggest good ATDnet CG detection efficiency (greater than 50%); yellow regions suggest CG detection efficiencies in the region of generally better than 10%; orange regions suggest CG DE < 10%; red regions suggest CG DE < 1%. Note that this interpretation looks rather pessimistic compared to some other European comparisons presented in this report. For example, Enno et al. (2016) found that ATDnet detected 89% of CG flashes in the south of France where the interpretation above suggests ATDnet DE well below 50%.

A more detailed evaluation of ATDnet flash DE relative to TRMM-LIS was carried out by Enno et al. (2016b). LIS and ATDnet observations during 2008-2014 within the LIS data domain (38°N-38°S; 180°W-180°E) were compared. A LIS flash was considered to be detected by ATDnet if at least one ATDnet detection had occurred within 25 km of any group in the LIS flash within 330 ms before, during or after the LIS flash.

ATDnet performed best over the Mediterranean and the East Atlantic where 20-30% of LIS flashes were detected (Fig. 20). ATDnet detected 10-15% of LIS flashes over the West Atlantic and 5-10% in northern and western Africa. More distant regions like South America and the South Atlantic had ATDnet DE values of approximately 5%. ATDnet also detected some lightning in the eastern seaboard of the US and in central and southern Africa. Diurnal cycle in ATDnet DE with a minimum at night was observed in areas closer to Europe such as the Mediterranean and the North Atlantic (Fig. 21).

The average number of ATDnet fixes per detected LIS flash was 1.23 and 15% of the detected LIS flashes had more than one matched ATDnet fix. Sharp contrast in ATDnet DE and the average number of ATDnet fixes per LIS flash appeared between land and water with higher values over the Atlantic and the Mediterranean. This is probably related to the fact that flashes over the oceans are generally stronger than over land (e.g. Said et al. 2013; Hutchins et al. 2013). Uniform propagation paths over salty ocean also result in weaker waveform attenuation.

LIS flashes with larger area, longer duration and greater number of groups and events were generally detected more efficiently by ATDnet (Fig. 22). This can be explained by the observation that large LIS group area and high number of events per group are characteristic to CG return strokes (Koshak 2010) that ATDnet is designed to detect. Differences in flash properties and diurnal changes in ATDnet performance resulted in large differences in ATDnet DE between individual storms. For example, in some storms in the Mediterranean basin ATDnet detected no more than 3-4% of LIS flashes whereas in other storms in the same area up to 55% of LIS flashes were detected.

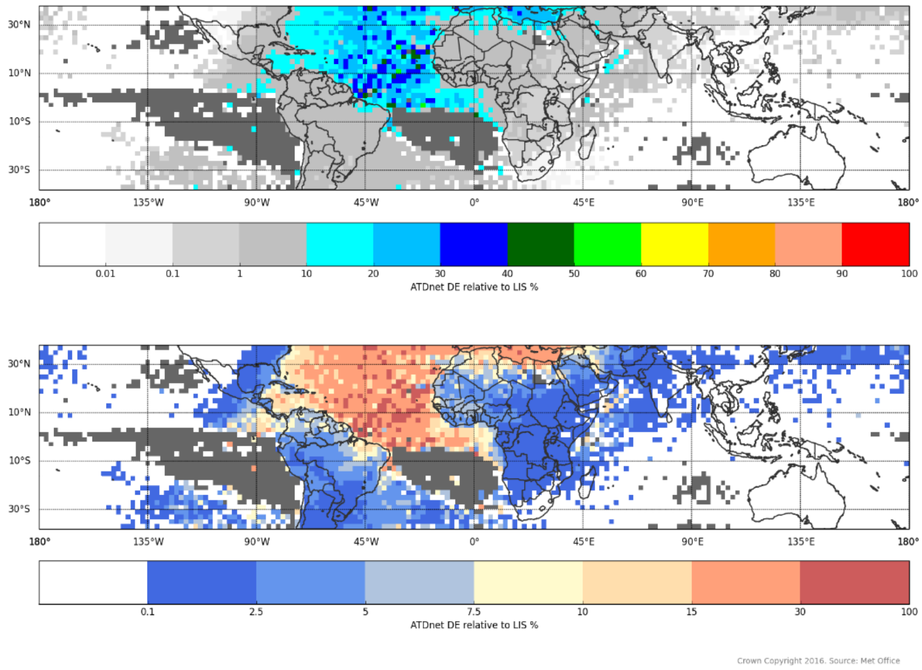


Figure 20. ATDnet flash DE relative to LIS in an equal interval (top) and logarithmic colour scale (bottom). Dark grey areas represent grid cells where ATDnet DE was not computed as there were less than 10 LIS flashes during the study period (Enno et al., 2016b).

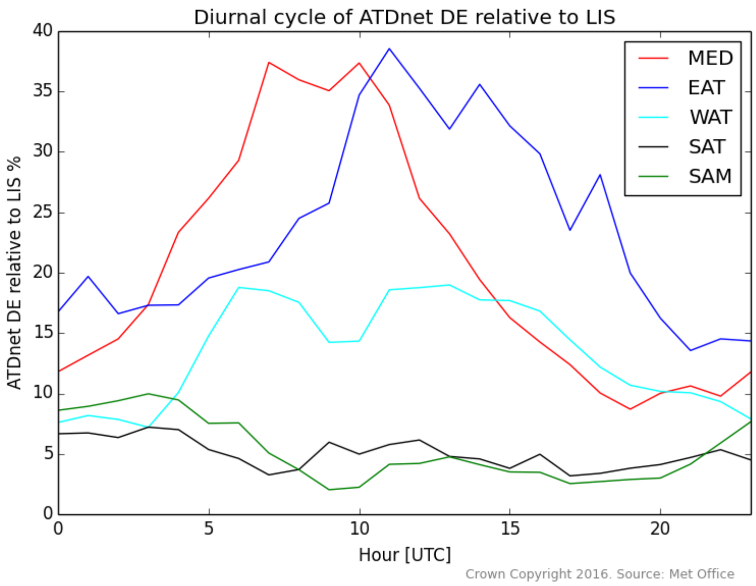


Figure 21. Diurnal cycle of ATDnet flash DE relative to LIS in different regions including the Mediterranean Basin (MED), the East Atlantic Ocean (EAT), the West Atlantic Ocean (WAT), the South Atlantic Ocean (SAT) and South American (SAM) (Enno et al., 2016b).

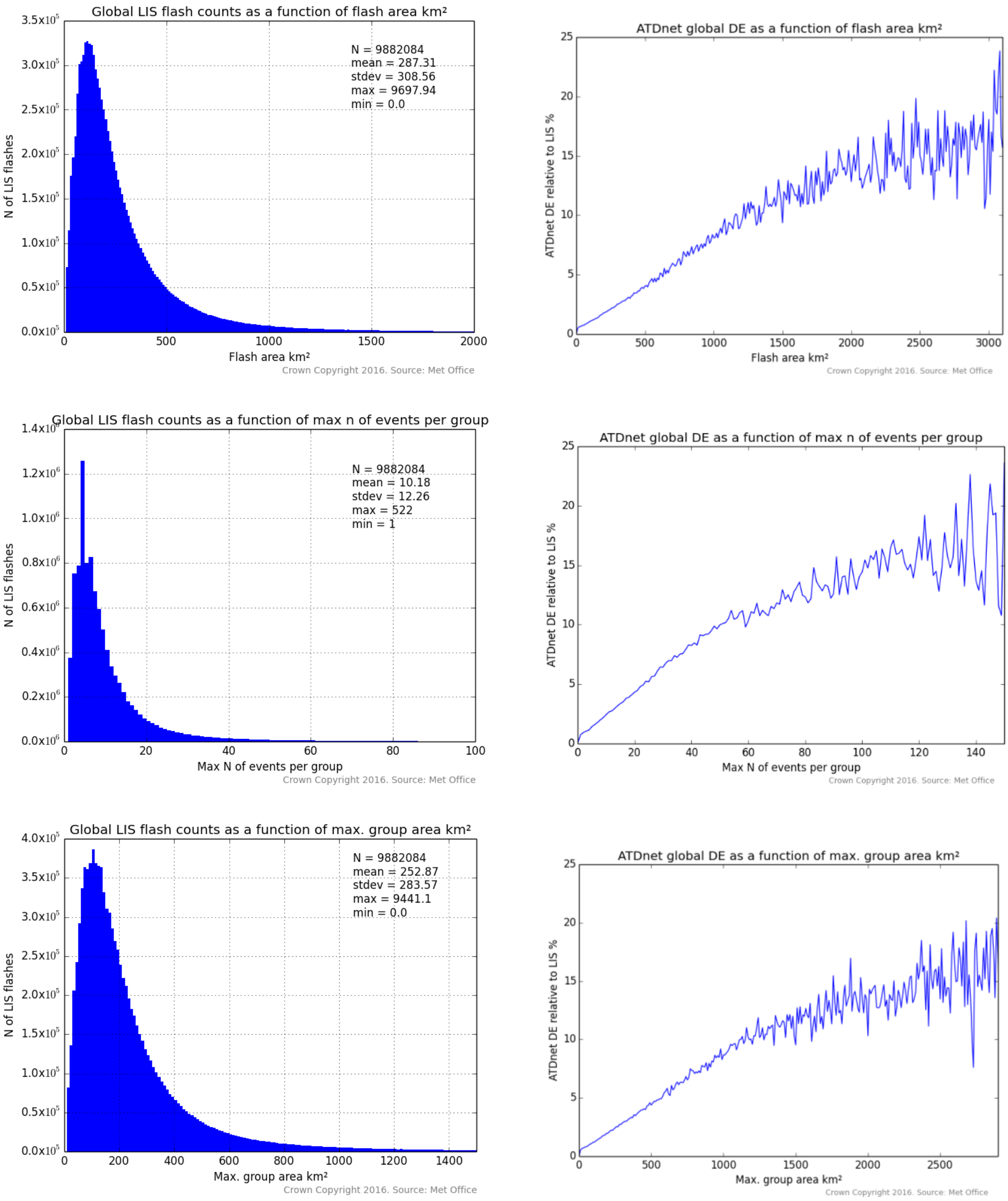


Figure 22. (top) LIS flash histogram (left) and ATDnet DE (right) as a function of LIS flash area (using a bin size of 10); (middle) LIS flash histogram (left) and ATDnet DE (right) as a function of the maximum number of events per group (using a bin size of 1); (bottom) LIS flash histogram (left) and ATDnet DE (right) as a function of maximum group area (using a bin size of 10) (Enno et al., 2016b).

ATDnet vs. GLM

ATDnet fix data was compared with the GLM (Geostationary Lightning Mapper on the GOES-16 satellite) flash data during a 9-month period of May 2018 to January 2019. The analysed 9-month datasets contained over 295 million GLM flashes and approximately 21.4 million ATDnet fixes. ATDnet and GLM detected broadly similar patterns in lightning density (Fig. 23). The only remarkable exception was over the northwest of the North American continent. Inland from the Atlantic coast of the US and Canada, ATDnet fix densities dropped off rapidly to almost zero by the middle of the continent, in a way which was not observed in the GLM data. The probable explanation is very high attenuation of VLF radio waves over Greenland ice, which lies on the direct path from the west of North America to Europe.

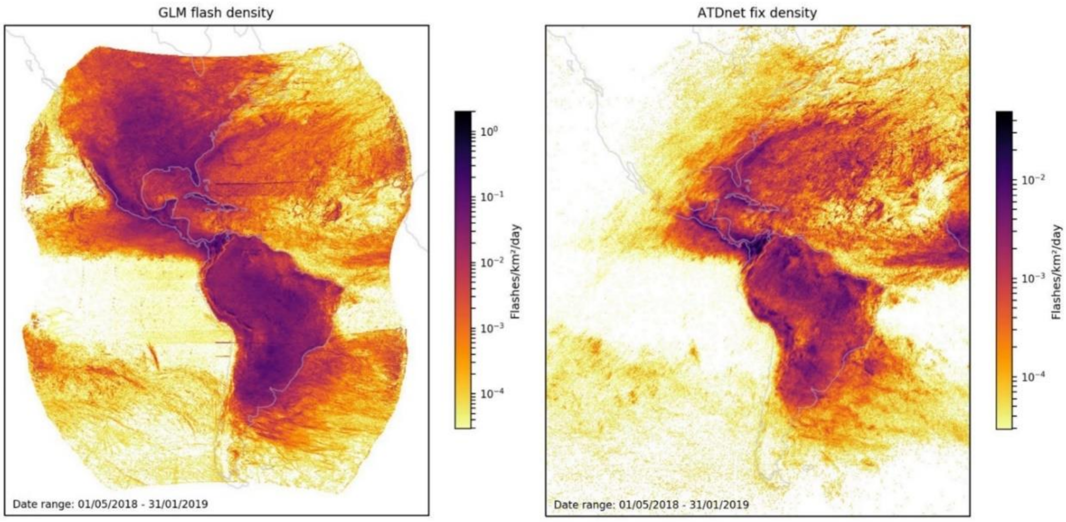


Figure 23. GLM full field of view flash density (left) and ATDnet fix density in 142°W – 8°W, 67°S – 67°N (right) from May 2018 to January 2019, inclusive (Anderson, 2019).

Over almost the entire GLM field of view (FOV) GLM detected higher densities of flashes than ATDnet detected densities of fixes (Fig. 24). GLM flash and ATDnet fix density ratio was highest over North America where GLM generally observed densities at least two orders of magnitudes greater than ATDnet. GLM flash densities were also greater over the South and West Atlantic and South America, but not to the same extent. The Northeast Atlantic was the only region where GLM flash densities and ATDnet fix densities were broadly comparable. This is probably the combined effect of lower GLM DE towards the edge of the GLM FOV and higher ATDnet DE as this corner of the domain is closest to ATDnet sensors in Europe. A region of anomalously high density ratio of ATDnet fixes to GLM flashes off the coast of Peru is probably caused by large ATDnet location errors. As a result, some lightning discharges over land are mis-located to the sea where actual lightning frequency is very low.

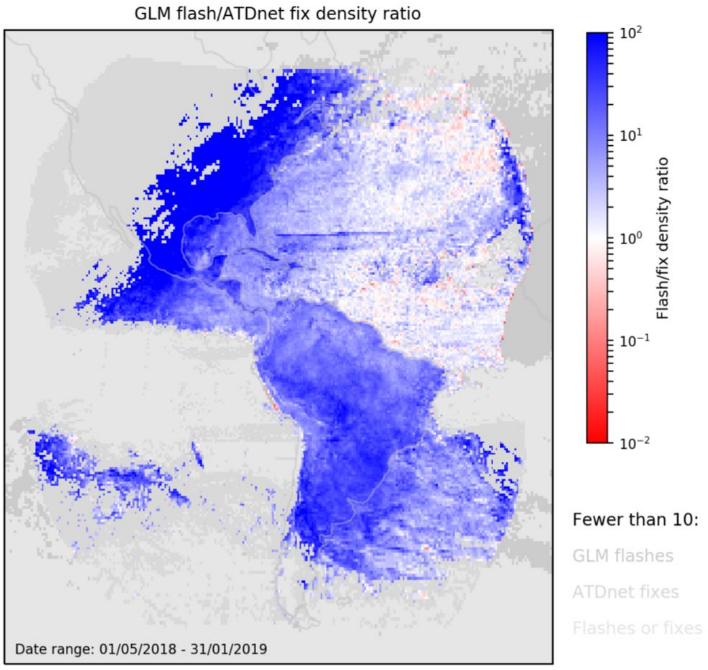


Figure 24. Ratio of GLM flash density to ATDnet fix density (Anderson, 2019).

ATDnet matches were defined as ATDnet fixes within 25 km of a GLM flash which occurred within a window starting 1 ms before the first recorded event in the flash and ending 1 ms after the last event in the flash. The density of GLM flash locations relative to matched ATDnet fixes was spread along a northeast-southwest axis (Fig. 25). This can be largely attributed to the location uncertainty of ATDnet in South America. The location uncertainty of fixes was reduced if the study area was limited to the North Atlantic Ocean where ATDnet is known to perform reasonably well. Location differences were still spread along a northeast-southwest axis, but in this region the reason is probably not only the location uncertainty of ATDnet, but also parallax errors of GLM near the edge of its FOV.

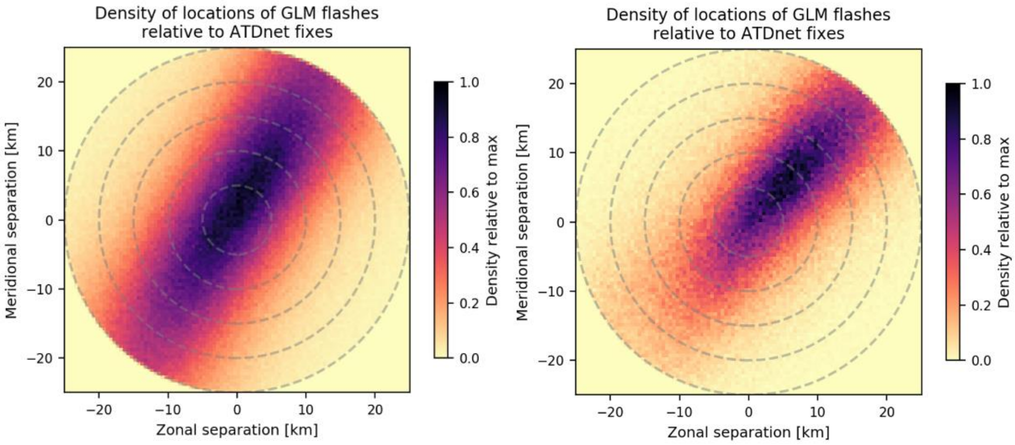


Figure 25. Density of relative positions of GLM flashes to matched ATDnet fixes for the full GLM field of view and (left) for the domain 75°W – 22.5°W, 12.5°N – 47.5°N (right) from May 2018 to January 2019 (Anderson, 2019).

It was also demonstrated that increasing flash area, energy or duration leads to higher ATDnet relative DE. This is expected as a more intense lightning event would logically release more intense sferics and be easier to detect by ATDnet.

ATDnet vs NORDLIS 2008-2018

A comprehensive ATDnet-NORDLIS comparison has been recently completed. ATDnet fixes were compared against NORDLIS CG strokes in northern Europe during 2008-2018. ATDnet and NORDLIS matches were defined as strokes within 0.5 ms and no more than 10 km from each other. NORDLIS strokes normally preceded matching ATDnet strokes by 0.1-0.2 milliseconds, which is attributable to different timing procedures.

The total number of ATDnet fixes exceeded that of NORDLIS CG strokes over most of the study area, except for Finland and its nearest surroundings (Fig. 26). This is partly attributable to some cloud lightning in ATDnet data. ATDnet stroke DE relative to NORDLIS was in the order of 20-40% in and around Finland. The figure increased to 50-70% in Sweden, western Russia, and parts of the Baltic countries and Norway. It was even higher in parts of Poland and Germany. A decrease in ATDnet relative DE near the edges of the study area, including the Nordic Sea, is probably related to lower NORDLIS location accuracy which hampers matching NORDLIS strokes and ATDnet fixes.

The diurnal cycle of ATDnet stroke DE relative to NORDLIS exhibited a deep minimum around midnight and a secondary weaker minimum during the afternoon (Fig. 27). The deep minimum around midnight is expected as ATDnet performance is known to deteriorate under the night-time ionosphere. The secondary minimum in the afternoon is somewhat unexpected. It can reflect either a larger fraction of weak CG return strokes that are harder to detect for ATDnet or suggest that ATDnet gets saturated during intense and widespread afternoon storms in Europe and misses weaker strokes more easily.

The mean and median location difference between matching ATDnet and NORDLIS strokes are generally smaller in the west and southwest of the study area (Fig. 28). This is probably because ATDnet location errors are somewhat smaller there. It can also be seen (Fig. 29) that location difference was significantly higher at night. This can be attributed to worse ATDnet performance at night. Most of the matching ATDnet fixes were smeared along west-southwest to east-northeast oriented line relative to their corresponding NORDLIS strokes. This is in line with the predictions of the ATDnet location accuracy model.

Finally, it was once again demonstrated that ATDnet is much more sensitive to moderate and strong strokes (Fig. 30). Approximately 70% of positive and 80% of negative NORDLIS strokes with peak currents exceeding 40 kA were detected.

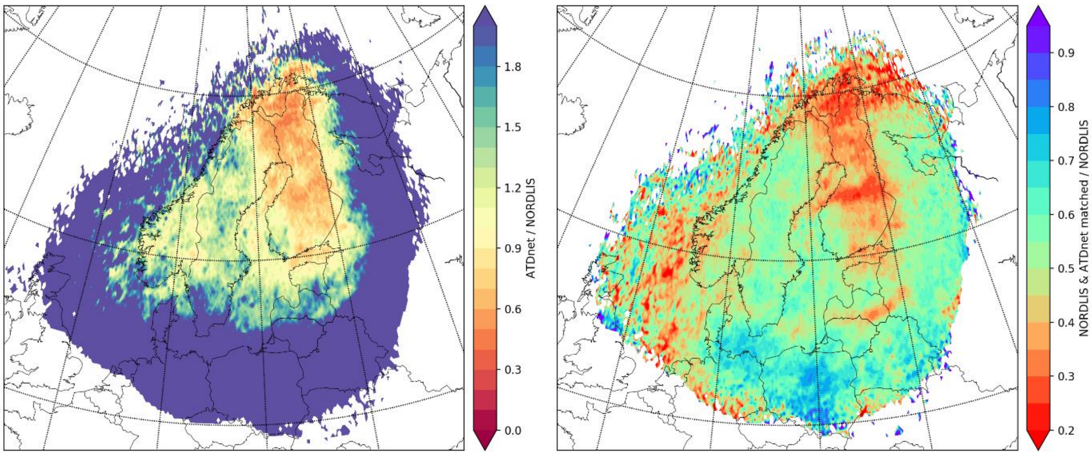


Figure 26. The total number of ATDnet fixes divided by the total number of NORDLIS CG strokes (left) and ATDnet CG stroke DE relative to NORDLIS (right) during 2008-2018.

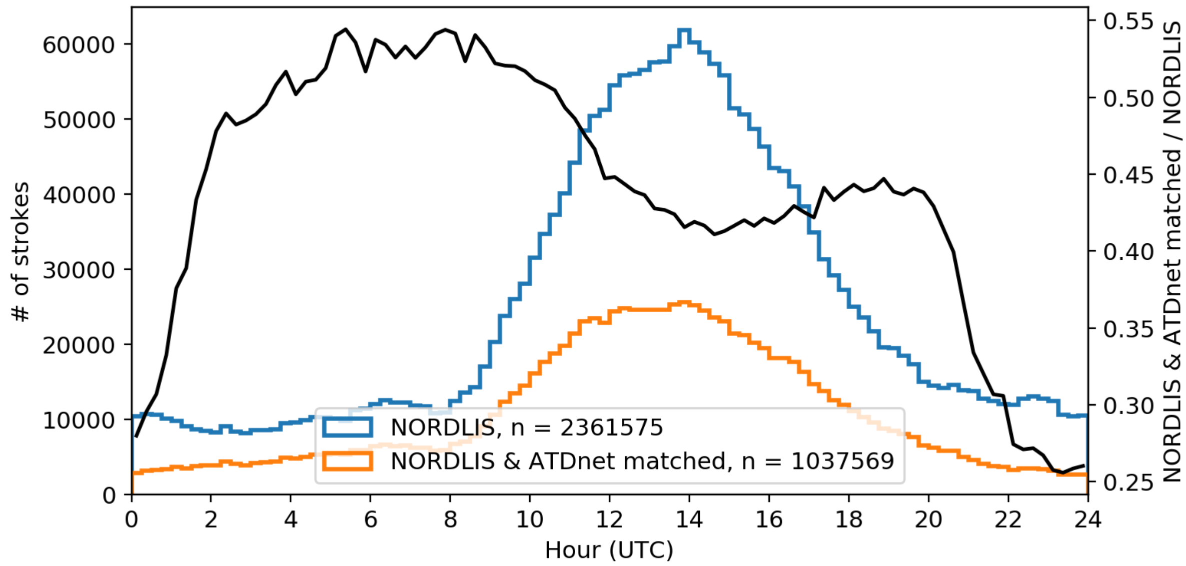


Figure 27. Diurnal cycle of ATDnet CG stroke DE relative to NORDLIS.

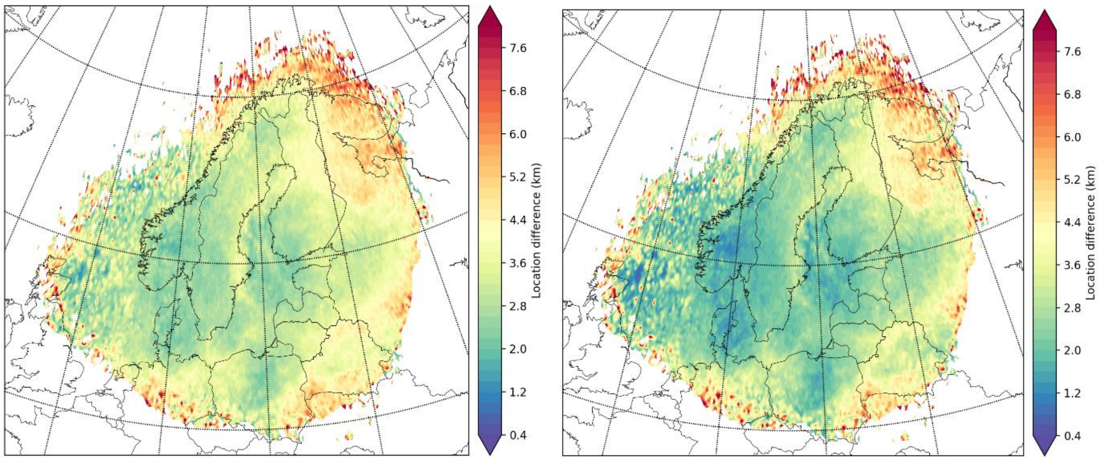


Figure 28. Mean (left) and median (right) location difference of matching ATDnet fixes and NORDLIS CG strokes.

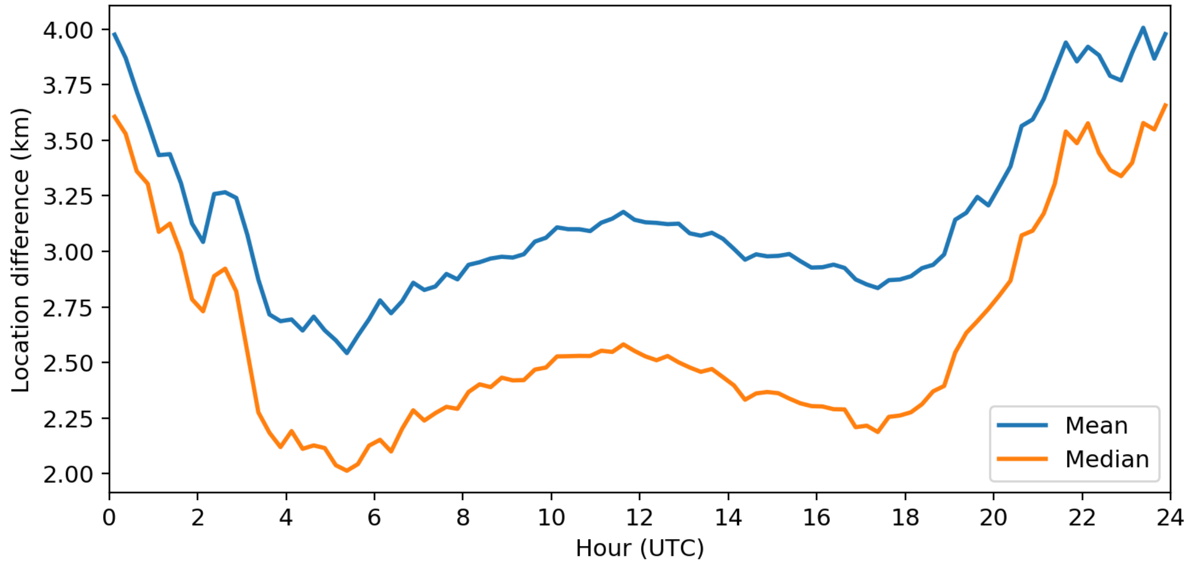


Figure 29. Diurnal cycle of mean and median location difference of matching ATDnet fixes and NORDLIS CG strokes.

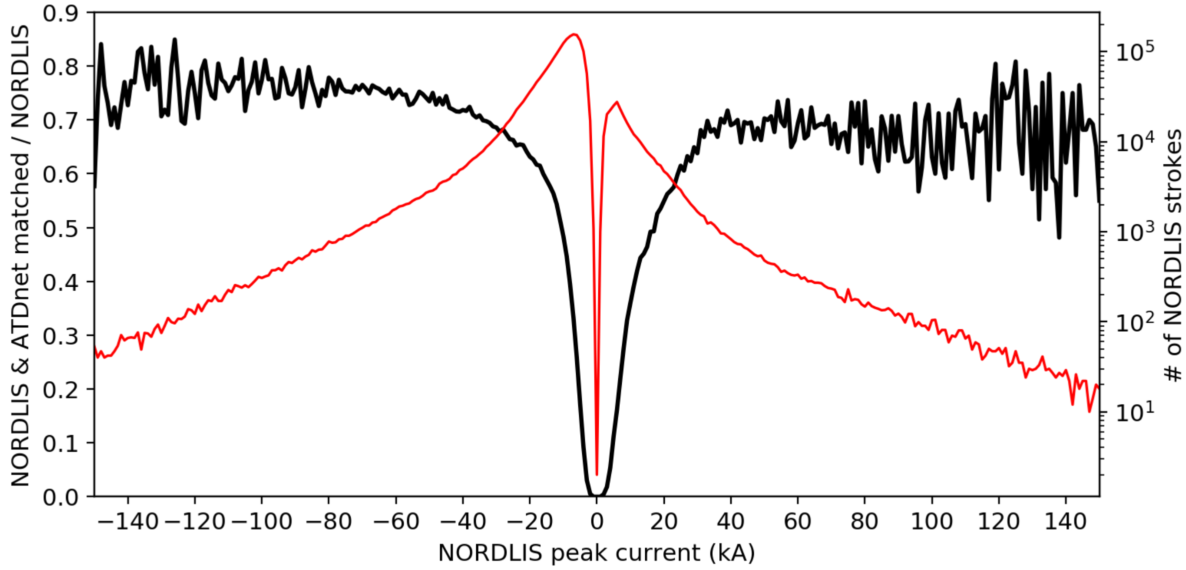


Figure 30. ATDnet CG stroke DE relative to NORDLIS as a function of peak current.

Results of Modelling an Expanded ATDnet Like Network

This section discusses the modelling results using the methods discussed in “Methods for the Modelling of an Extended ATDnet Like Network”, above. First, a comparison to the literature review above is made by modelling ATDnet. Next each region is discussed, and then combined for a complete global modelling discussion. Finally, some discussion of outage scenarios is included.

ATDnet Reference

The review of ATDnet coverage above identified the geographical region over which ATDnet can be expected to have sufficient coverage. Due to the way ATDnet operates it is known that at least four receivers must receive any given sferic; With these two pieces of information it is possible to modify the received signal intensity to create a DE map similar to that seen when ATDnet is compared to other networks.

Broadly the comparisons to Starnet (figures 15,16, 17) TRMM LIS (figure 20), GLM (figures 23 and 24) and ATDnet fix density plots (figure 31) show that ATDnet coverage is good over central and western Europe. LWPC output is shown in figure 32, where the colours identify the number of receivers in range for a lightning strike at that location (regular latitude and longitude grid). The three panes show three different signal strength thresholds of 45, 65 and 85; as the input signal is static but arbitrary these values are also arbitrary. The higher the number the less sensitive the network is perceived to be. The white and green regions show that at least 4 receivers would have seen the signal (colour scale shown in figure 33), therefore, a fix could be found. From this the signal value of 65 was chosen, this is somewhat conservative; For the purpose of network design a more conservative value is better as it’s reasonable to expect some local interference to cause some receivers to not always be operating to their full capability. This value was also chosen to more closely match the land/sea differential seen over the north coast of Africa. This is in part to ensure the more complicated over ground modelling is more accurately representative of network performance.

Due to how ATDnet works, requiring 4 stations to create a fix (with more stations helping to reduce the LA) it is useful to consider receiver spacing. This is tertiary to the modelling results, although useful. For any given receiver the distance between it and the nearest 4 other sites was calculated. Averaging these four nearest neighbour values for ATDnet gives a baseline value of 1212 km.

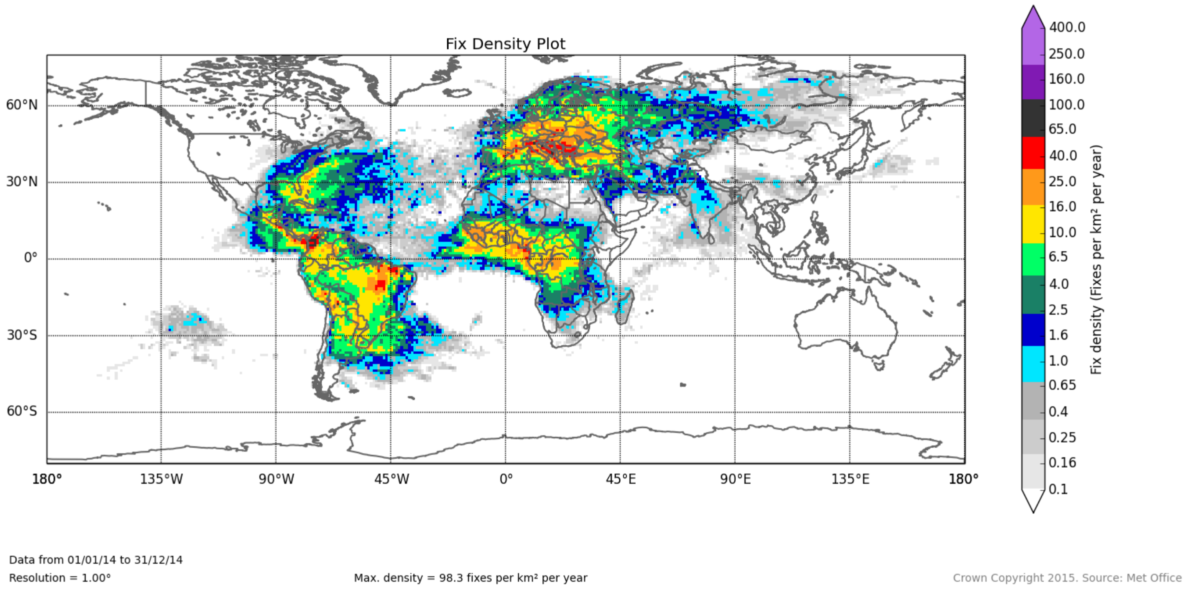


Figure32 . An example ATDnet fix density plot.

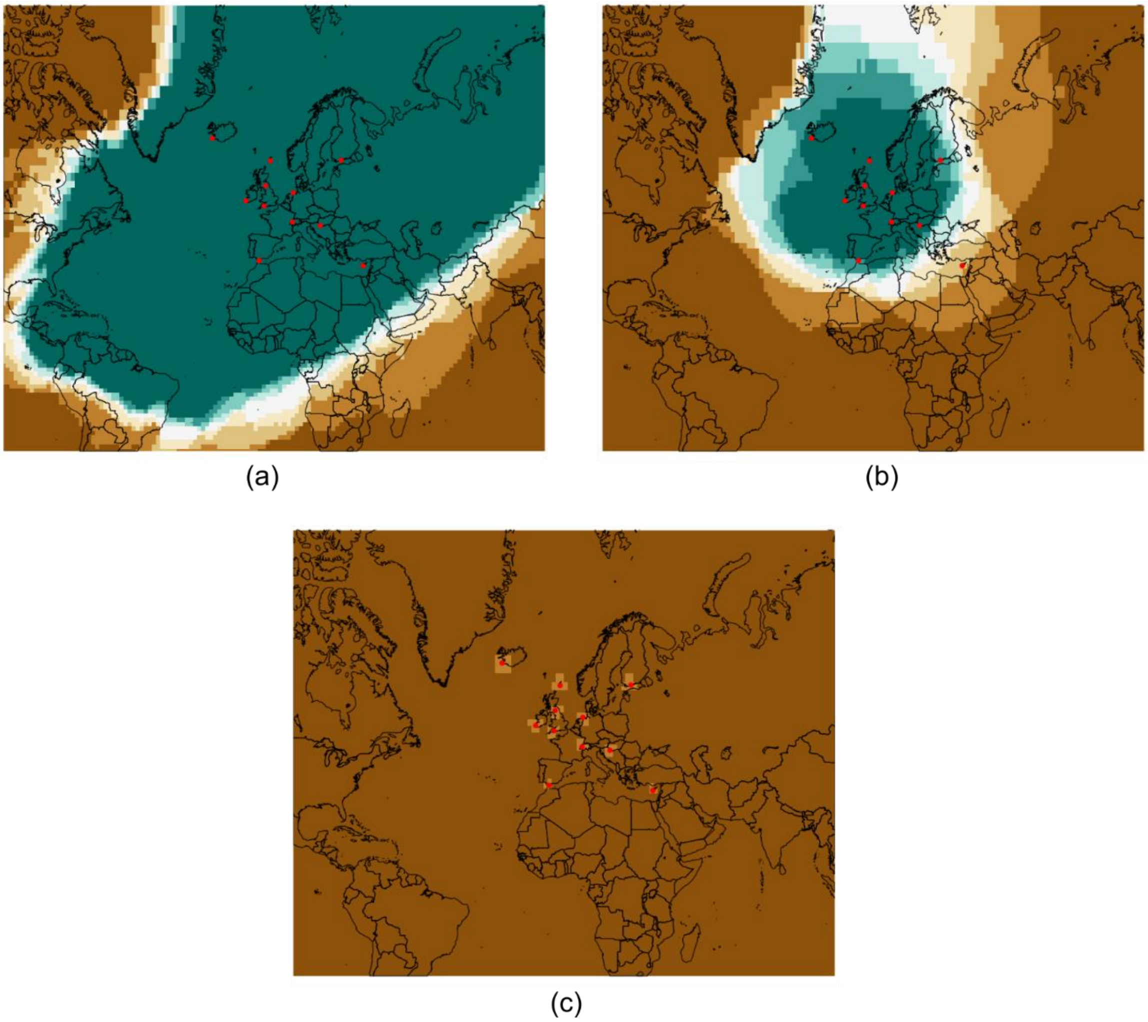


Figure33 . The colour map shows the modelled number of receivers that would see any given lightning strike (legend in Figure 33) for ATDnet, white and green indicates that the network has enough receivers to see most cloud to ground lightning strikes in that area. The resolution is 1.5 degrees latitude and 1.5 degrees longitude. Three different sensitivities are shown, (a) 45, (b) 65 and (85).

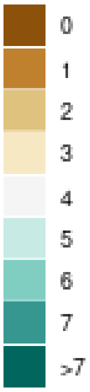


Figure 33. The colour scale used for all figures where the modelled number of receivers is shown. 4 is the minimum number of receivers required to locate a lightning event.

Regions.

For each model the results will be presented with some discussion.

Africa

Figure 34 shows the model output for the Africa region. The colour scale shows the number of receivers that would receive a lightning strike in that area with a signal threshold of 65, as discussed above. The contours show the output of the Location Accuracy model, which should be considered valid within the solid thick black shape. The red dots show the locations of the receivers that would be required.

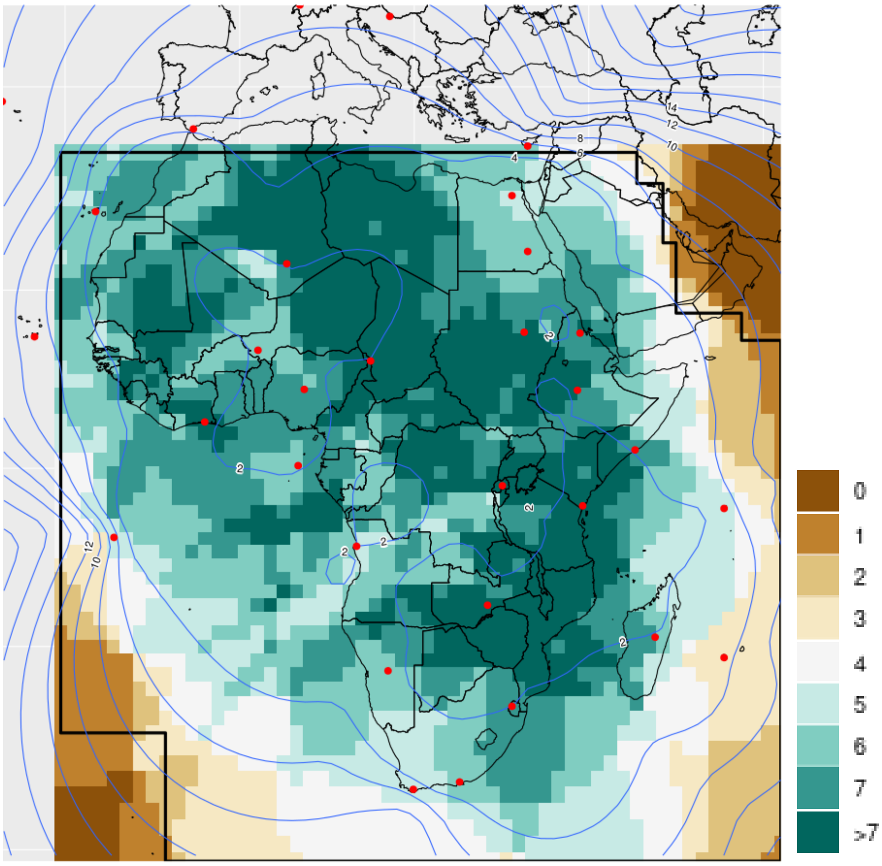


Figure 34. The African region network modelled response. Here the red dots show the locations of the receivers modelled. The blue contours are the amalgamated location accuracy model output. The colour map shows the modelled number of receivers that would see any given lightning strike (legend in Figure 33), white and green indicates that the network has enough receivers to see most cloud to ground lightning strikes in that area. The resolution is 1.5 degrees latitude and 1.5 degrees longitude.

The modelling results show that coverage in Africa can be provided to a similar level to ATDnet in Europe. Large parts of the region have a LA of below 2 km, with almost all the landmass having a LA of below 4 km. The location accuracy is notably lower around the Sudan, South Sudan, Chad and Central African Republic area (between 4 and 2 km). This is due to there being no suitable population centres which could be used to improve the LA. The density of stations may seem quite high around the north west of Sub Saharan Africa, more receivers were required as there is poor propagation of VLF over the very dry ground conditions (and therefore low conductivity) in the Sahara. Six stations are located on relatively small island groups, these increase the baseline of the network and the area inside the geometry of the network, therefore, improving the LA. It should be noted that it may not be feasible to install on these islands as data bandwidth may not be high enough; bandwidth will depend greatly on the exact island group though. The island stations to the East and North of Madagascar are especially important for coverage over Madagascar.

The average four nearest neighbour spacing value is 1496 km.

South Atlantic

Figure 35 shows the model output for the South Atlantic region. The colour scale shows the number of receivers that would receive a lightning strike in that area with a signal threshold of 65, as discussed above. The contours show the output of the Location Accuracy model, which should be considered valid within the solid thick black shape. The red dots show the locations of the receivers that were used in the models.

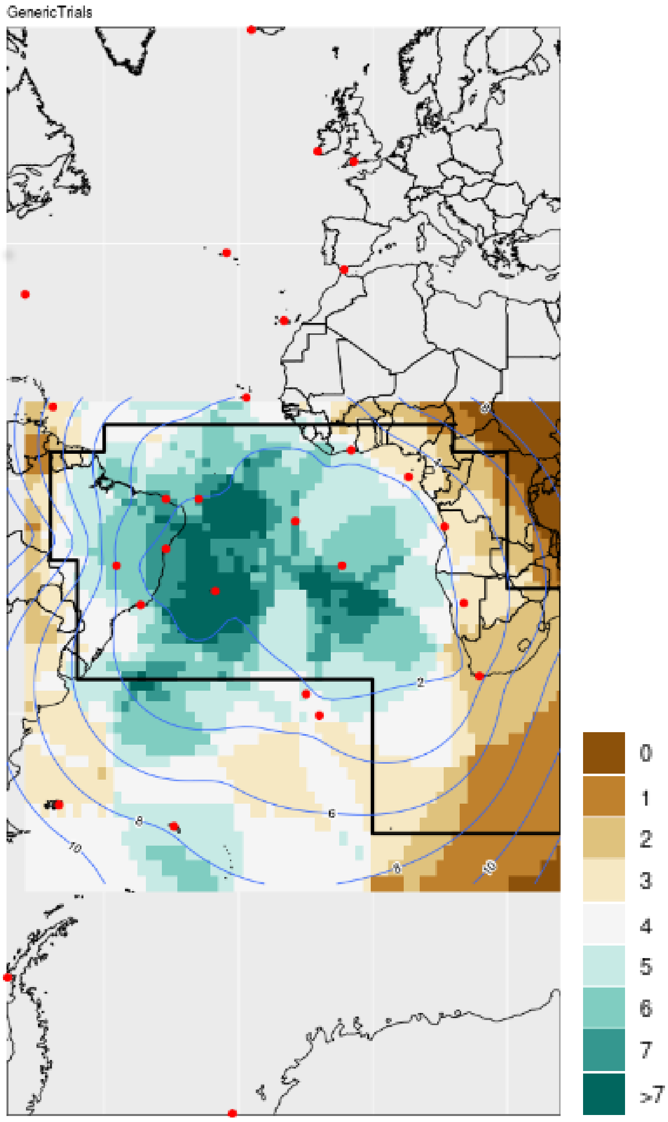


Figure 35. The southern Atlantic region network modelled response with the normal sensitivity threshold of 65. Here the red dots show the locations of the receivers modelled. The blue contours are the amalgamated location accuracy model output. The colour map shows the modelled number of receivers that would see any given lightning strike (legend in Figure 33), white and green indicates that the network has enough receivers to see most cloud to ground lightning strikes in that area. The resolution is 1.5 degrees latitude and 1.5 degrees longitude.

The South Atlantic region presented some different challenges compared to the Africa region. Whilst the propagation of VLF signals over oceans is excellent compared to the propagation over deserts the significant distances between land, let alone significantly populated land leads to difficulties in both DE and LA. This has been somewhat mitigated by stations on small islands and Antarctic research stations, both have significant risks associated with them both in terms of local engineering support if a fault occurs and appropriate infrastructure (communications mostly) being in place. For example, Tristan da Cunha has a satellite link internet connection for the whole island of 3Mbps, LEELA in its current form requires 2Mbps upload. Whilst these challenges exist, it should be possible to provide coverage with acceptable DE and LA for a significant proportion of the region, even if some of the proposed sites were not feasible. Interestingly, the area south of Côte d'Ivoire and west of Gabon is better captured in terms of DE for the Africa defined network, this suggests that when defining regional subnetworks for central processing then smaller regions than those used here should be considered.

In section 'ATDnet reference' above the reference value for the signal strength cut off was chosen to be 65. This was chosen, in part, to ensure the VLF propagation over land areas was suitably pessimistic and close in shape to ATDnet. Over water it could be expected that this value may be too high .Figure 36 shows the LWPC number of receiver colour scale plot when the reference value is dropped to 62. The DE proxy improves significantly over most of the region.

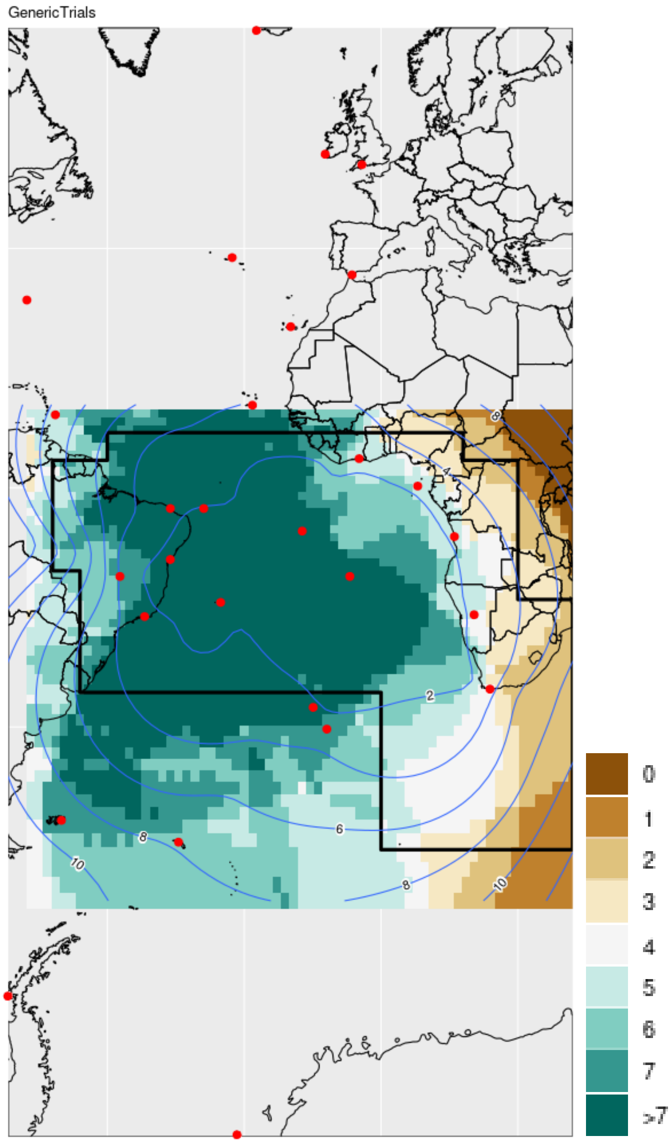


Figure 36. The southern Atlantic region network modelled response with a reduced sensitivity threshold of 62. Here the red dots show the locations of the receivers modelled. The blue contours are the amalgamated location accuracy model output. The colour map shows the modelled number of receivers that would see any given lightning strike (legend in Figure 33), white and green indicates that the network has enough receivers to see most cloud to ground lightning strikes in that area. The resolution is 1.5 degrees latitude and 1.5 degrees longitude.

The average four nearest neighbour spacing value is 2016 km. This is high due to the large areas of water with no suitable locations.

South America

Figure 37 shows the model output for the South America region. The colour scale shows the number of receivers that would receive a lightning strike in that area with a signal threshold of 65, as discussed above. The contours show the output of the Location Accuracy model, which should be considered valid within the solid thick black shape. The red dots show the locations of the receivers that would be required.

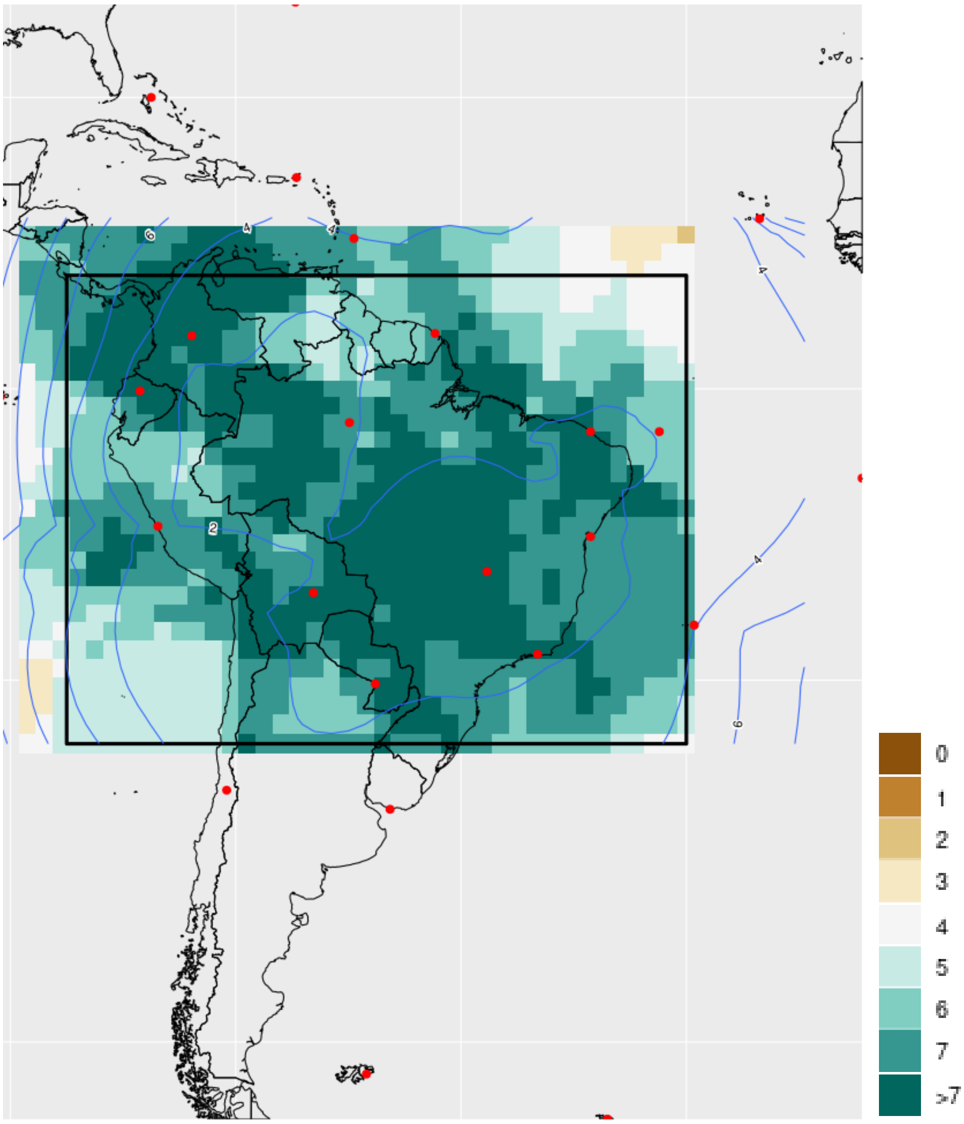


Figure 37. The South America region network modelled response. Here the red dots show the locations of the receivers modelled. The blue contours are the amalgamated location accuracy model output. The colour map shows the modelled number of receivers that would see any given lightning strike (legend in Figure 33), white and green indicates that the network has enough receivers to see most cloud to ground lightning strikes in that area. The resolution is 1.5 degrees latitude and 1.5 degrees longitude.

The South America region presented few challenges. The region covered only part of the land area of the Continent; Receivers could be placed in reasonable places around the edge of the region of interest including some suitably placed islands. There are also reasonable population centres throughout the region allowing for some useful receiver locations. The modelled LA is below 4 km for the whole region and below 2 km for a significant proportion of the area modelled.

The average four nearest neighbour spacing value is 1710 km.

North Atlantic

Figure 38 shows the model output for the North Atlantic region. The colour scale shows the number of receivers that would receive a lightning strike in that area with a signal threshold of 65, as discussed above. The contours show the output of the Location Accuracy model, which should be considered valid within the solid thick black shape. The red dots show the locations of the receivers that would be required.

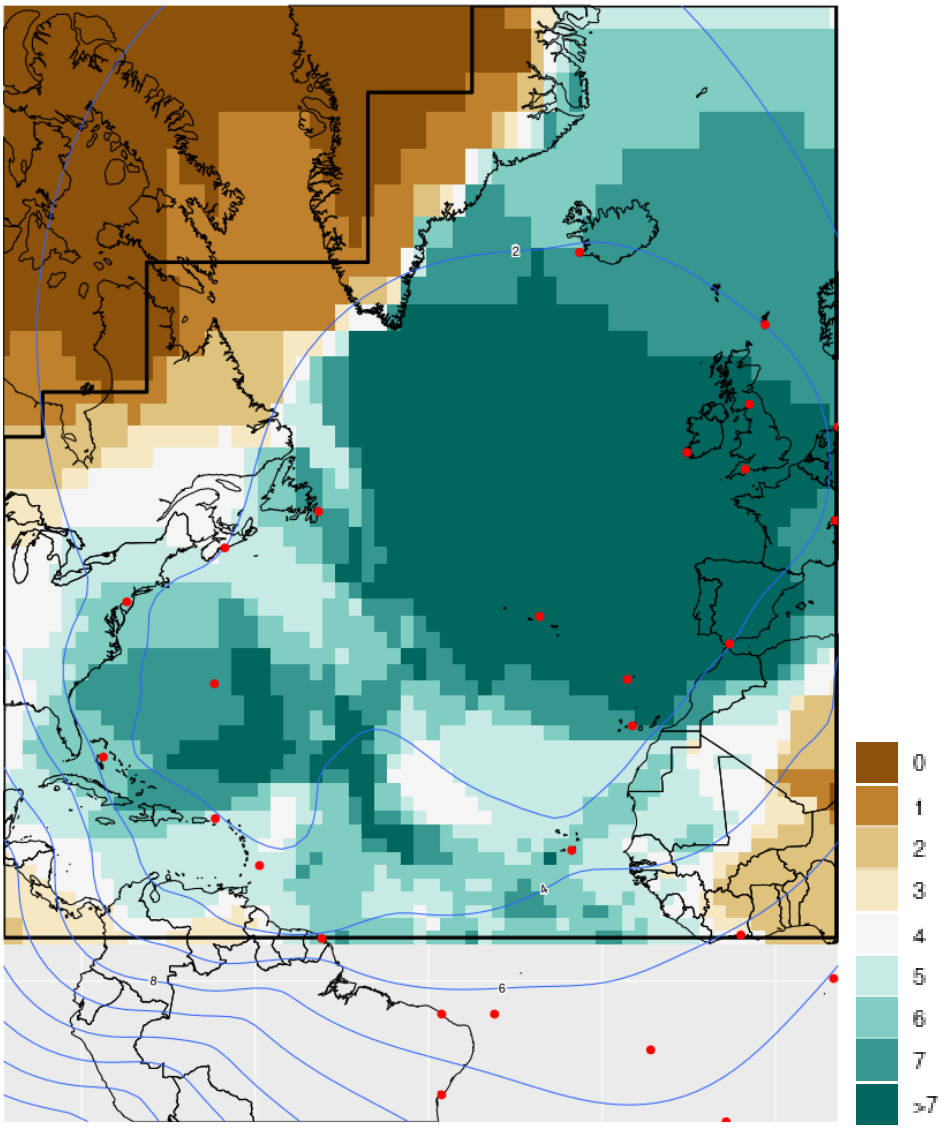


Figure 38. The North Atlantic region network modelled response. Here the red dots show the locations of the receivers modelled. The blue contours are the amalgamated location accuracy model output. The colour map shows the modelled number of receivers that would see any given lightning strike (legend in Figure 33), white and green indicates that the network has enough receivers to see most cloud to ground lightning strikes in that area. The resolution is 1.5 degrees latitude and 1.5 degrees longitude.

The North Atlantic is similar to the South Atlantic region with large areas without any suitable locations. Although there is significantly more land on the outskirts of the region providing good locations for sites. Even with this it is difficult to provide enough coverage throughout. Increasing the modelled sensitivity of receivers has a similar effect to that shown above for the South Atlantic region, i.e. the coverage over water improves significantly.

The average four nearest neighbour spacing value is 1498 km.

Eastern Europe

Figure 39 shows the model output for the Eastern Europe region. The colour scales shows the number of receivers that would receive a lightning strike in that area with a signal threshold of 65, as discussed above. The contours show the output of the Location Accuracy model, which should be considered valid within the solid thick black shape. The red dots show the locations of the receivers that would be required.

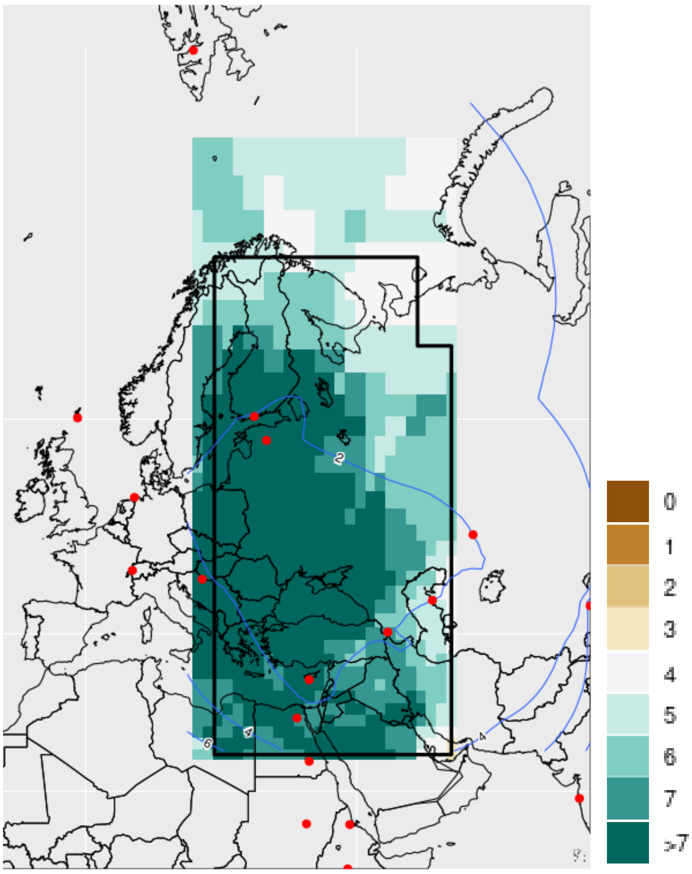


Figure 39. The eastern European region network modelled response. Here the red dots show the locations of the receivers modelled. The blue contours are the amalgamated location accuracy model output. The colour map shows the modelled number of receivers that would see any given lightning strike (legend in Figure 33), white and green indicates that the network has enough receivers to see most cloud to ground lightning strikes in that area. The resolution is 1.5 degrees latitude and 1.5 degrees longitude.

This region was relatively easy to cover, with significant coverage already being provided by the ATDnet and Africa region receivers. The north western portion offered some challenge, although this was mitigated by a station in Svalbard. It’s unclear how well this station is likely to perform, especially during northern hemisphere winter as the propagation of VLF over ice is significantly worse than over other surfaces. The LA is better than 4 km over the whole region, with a significant proportion at better than 2 km.

The average four nearest neighbour spacing value is 1501 km.

Global

Figure 40 shows the merged output from all the LA models. The output of the LWPC was rerun combining the receivers from each of the regions to create a consistent combined network. The output shows that the modelled network would be effective over the MTG LI domain. The LA is consistently below 4 km and below 2 km for most of the area. The DE should be comparable with ATDnet over the whole range. Whilst the number of receivers modelled to detect a strike in any given grid point is lower than for ATDnet this is likely due to the higher density of ATDnet receivers around the UK. The UK has a higher density of receivers as a design decision to ensure the highest possible DE for ATDnet.

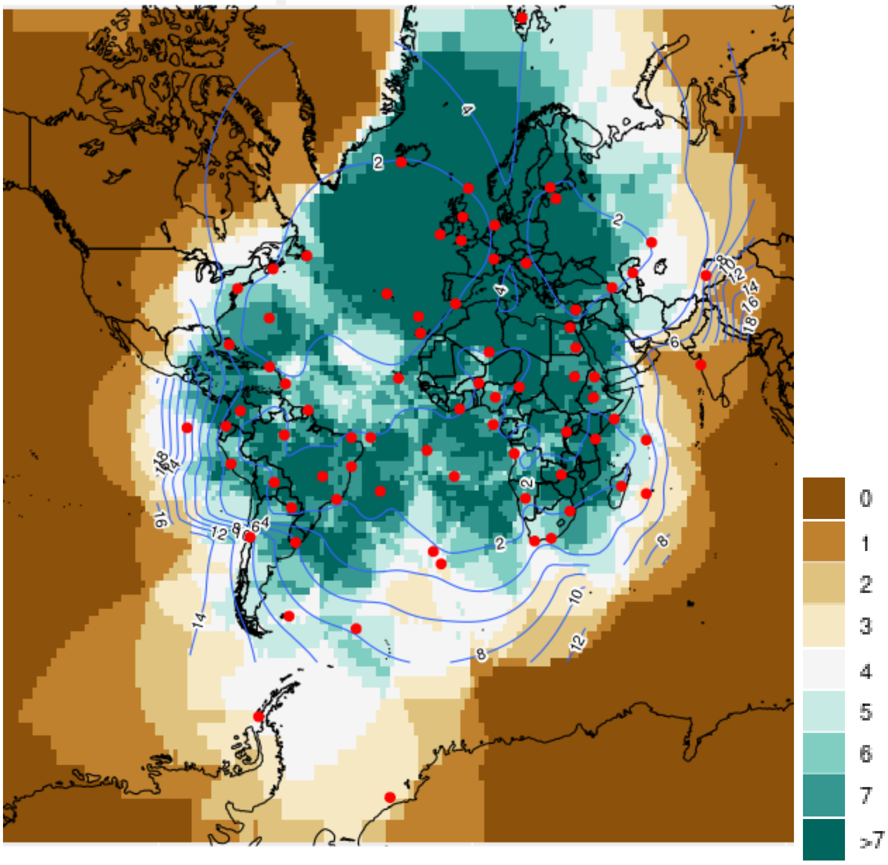


Figure 40. The complete global network modelled response. Here the red dots show the locations of the receivers modelled. The blue contours are the amalgamated location accuracy model output. The colour map shows the modelled number of receivers that would see any given lightning strike (legend in Figure 33), white and green indicates that the network has enough receivers to see most cloud to ground lightning strikes in that area. The resolution is 1.5 degrees latitude and 1.5 degrees longitude.

It's interesting to note that again the area south of Côte d'Ivoire and west of Gabon is showing a better LWPC output compared to both the Africa and South Atlantic only region modelling. Whilst only part of the Caribbean is within the MTG LI domain, the global network modelling shows that coverage is better than demonstrated in either of the nearby modelled regions. This reinforces the care that needs to be taken over the subnetwork definitions and which stations to use in combination with each other.

The average four nearest neighbour spacing value is 1485 km.

Reduced capabilities.

Whilst it's not within scope to consider the feasibility of each site it is relatively easy to model how a network with a reduced number of receivers would work in terms of LWPC number of receivers. It would be expected to have a similar effect on LA. Trials have been run randomly removing a subset of the receivers from the modelled global network. Figure 41 shows the number of receiver plots for 10%, 25% and 50% of receivers randomly removed.

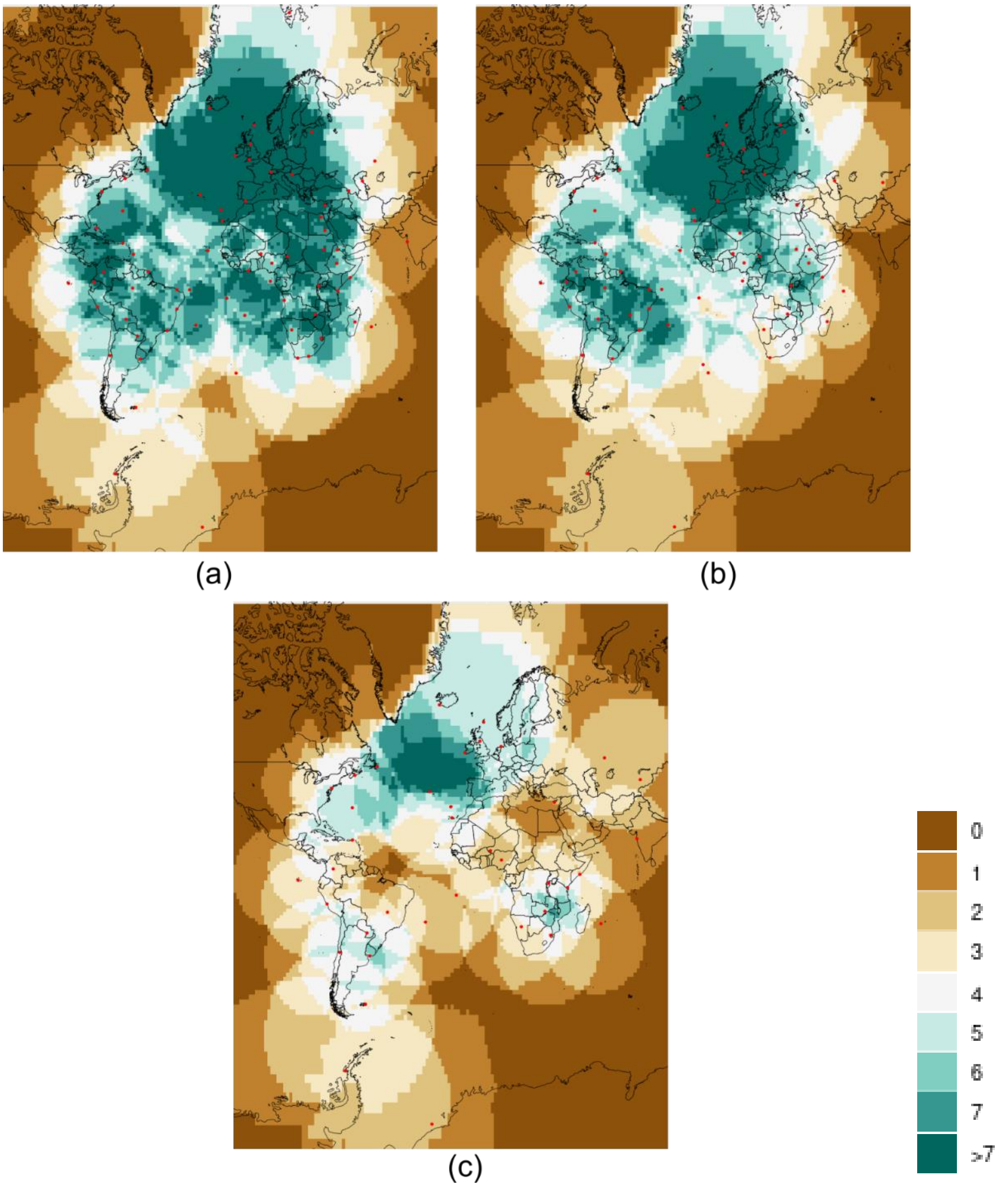


Figure 41. Showing the effect of reducing the number of receivers. Each pane shows the network response (in terms of DE proxy) for a random set of receivers removed. (a) with 10% removed, (b) with 25% removed and (c) with 50% removed. Legend in Figure 33.

Whilst the reduction of 10% of the receivers does not cause a significant reduction in the DE maps there are clear differences around the South Atlantic and Eastern Europe. At this level of reduction, the LA is more likely to be affected as the geometric baselines will have changed. When the number of receivers is reduced further (by 25%) there are clear holes shown in the LWPC results, especially over the oceans and around Africa, the effectiveness of the network would be further decreased as shown by the 50% reduction map. In this case, large areas of the MTG LI domain would have limited coverage from the network. Despite having a network with receivers that cover the entire region the density is not high enough to ensure a good DE.

Summary and Conclusions

ATDnet performance has been evaluated against different types of lightning location systems during the last ten years. Most studies used short-range reference systems and were limited to (parts of) Europe. However, some wider scale validations against other long-range LLSs and satellite based optical detectors are also available. It must be considered that the results of such comparisons are always a combination of ATDnet actual performance, characteristics of the reference system and efficiency of the used methodology, e.g. stroke/flash matching. Thus, it can be expected that different studies give somewhat different results even if the study areas and/or time periods are (partially) overlapping.

In Europe ATDnet generally detected 80-90% of CG flashes and 40-60% CG strokes. ATDnet median location accuracy relative to reference systems was in the order of 1-3 km. Larger location errors up to 4-5 km were observed in 2007, i.e. before the latest major upgrade of the system. ATDnet also detected up to ~25% of cloud lightning in Europe but the evidence is limited to two studies in Belgium and France.

Outside Europe ATDnet DE decreased and location errors increased with increasing distance from ATDnet sensors. ATDnet detected 10-15% of TRMM-LIS flashes over the West Atlantic, 5-10% in northern and western Africa and approximately 5% in more distant regions like South America and the South Atlantic. These numbers were relatively low not only due to large lighting-sensor distances but also because most lightning is cloud lightning and LIS detected all lightning whereas ATDnet mostly detects CG return strokes.

ATDnet was clearly more sensitive to lightning events with higher peak current as they emit stronger sferics that are easier to detect. In Europe, 70-90% of flashes with peak currents exceeding 20 kA and 70-80% of strokes with peak currents over 40 kA were detected. ATDnet performance was also characterized by diurnal cycle, with its DE and LA being lower at night. This can be attributed to the diurnal changes in the height of the ionosphere and the fact that the ATDnet processing is tuned for optimal performance under the daytime ionosphere.

ATDnet is an effective long range lightning location network. The network provides a good level of detection efficiency (DE) and location accuracy (LA) over Europe. In the literature the LA model has been shown to accurately model the measured relative LA between ATDnet and other lightning location networks. The long wave propagation code (LWPC) has been used to provide a method for modelling the number of receivers that would likely receive the sferic from a lightning strike in a given location for a given network geometry.

The models have been applied to the Meteosat Third Generation Lightning Imager domain (MTG LI). In this domain it has been shown that a network of 75 receivers would provide an ATDnet like level of LA and DE for the majority of the domain. This work was completed by splitting the MTG LI domain into five regions. For each region a suitable number of receivers was found in a reasonable geometry this was then combined to provide an idea of how the network would respond over the whole domain. There were some minor complexities in some regions, the density of population centres in the Sahara (where VLF propagation is particularly difficult), and the distance between land over the oceans being the most significant. Despite this the modelling results show a suitable network should be achievable.

References

Anderson G., 2019: "An Assessment of the GOES-16 GLM for Met Office Applications." Internal Report, Met Office.

Bennett A. J., 2010: "Comparison between the UK Met Office ATDnet and the NORDLIS lightning location networks during 9-18 August 2007". Internal Report, Met Office.

Bennett A. J., 2011: "Comparison between the UK Met Office ATDnet and the WWLLN lightning location networks in the Tropical North Atlantic during January and June 2010". Internal Report, Met Office.

Bennett, A., Callaghan, G., Gaffard, C., Nash, J. and Smout, R., 2010: "The Effect of Changes in Lightning Waveform Propagation Characteristics on the UK Met Office Long Range Lightning Location Network (ATDnet)". 21st International Lightning Detection Conference, 19-20 April, Orlando, USA.

Collins M., Anderson G., Callaghan G., and Bennett A., 2012: "The use of ATDnet data for MTG-LI processing: an initial concept evaluation". Final report for a EUMETSAT study, EUM/CO/11/4600000943/KJG, Met Office.

Enno S.E., Anderson G., and Sugier J., 2016a: "ATDnet Detection Efficiency and Cloud Lightning Detection Characteristics from Comparison with the HyLMA during HyMeX SOP1". Journal of Atmospheric and Oceanic Technology, 33(9), 1899-1911.

Enno S.E., Rudlosky S., Sugier J., and Labrador L., 2016b: "Comparison and characterisation of ATDnet versus LIS for the period of 2008 to 2014". Final report for a EUMETSAT study, EUM/CO/15/4600001643/KJG, Met Office.

Gaffard, C., Nash, J., Atkinson, N., Bennett, A.J., Callaghan, G., Hibbett, E., Taylor, P., Turp, M., and Schulz, W., 2008: "Observing lightning around the globe from the surface". 20th Int. Lightning and Detection Conf. (ILDC) and Second Int. Lightning Meteorology Conf. (ILMC), Tucson, AZ, Vaisala, 12 pp. [Available online at http://www.vaisala.com/Vaisala%20Documents/Scientific%20papers/Observing_lightning_around_the_globe_from_ the_surface.pdf.]

Hutchins M.L., Holzworth R.H., Virts K.S., Wallace J.M., and Heckman S., 2013: "Radiated VLF energy differences of land and oceanic lightning". Geophys. Res. Lett.,40, 2390–2394, doi:10.1002/grl.50406.

Koshak W.J., 2010: "Optical Characteristics of OTD Flashes and the Implications for Flash-Type Discrimination". J. Atmos. Oceanic Technol., 27, 1822–1838, doi: 10.1175/2010JTECHA1405.1.

Lee A.C.L., 1986: "An Operational System for the Remote Location of Lightning Flashes Using a VLF Arrival Time Difference Technique". J. Atmos. Oceanic Technol., 3(4), 630–642.

Mäkelä, A., Mäkelä, J., Haapalainen, J., and Porjo, N., 2016: "The verification of lightning location accuracy in Finland deduced from lightning strikes to trees". Atmos. Res., 172–173, 1–7, doi:10.1016/j.atmosres.2015.12.009.

Nag, A., DeCarlo, B. A., and Rakov, V. A., 2009: "Analysis of microsecond- and submicrosecond-scale electric field pulses produced by cloud and ground lightning discharges". Atmos. Res., 91, 316–325, doi:10.1016/j.atmosres.2008.01.014.

Nag, A., Murphy, M. J., Schulz, W., and Cummins, K. L., 2015: “Lightning locating systems: Insights on characteristics and validation techniques”. Earth and Space Science, 2, 65–93, doi:10.1002/ 2014EA000051.

Pierce, E.T., 1970: “Latitudinal Variation of Lightning Parameters”. Journal of Applied Meteorology, 9, 194–195.

Poelman D.R., Honoré F., Anderson G., and Pedeboy S., 2013a: “Comparing a regional, subcontinental, and long-range lightning location system over the Benelux and France”. J. Atmos. Oceanic Technol., 30, 2394–2405, doi:10.1175/JTECH-D-12-00263.1.

Poelman D.R., Schulz W., and Vergeiner C., 2013b: “Performance Characteristics of Distinct Lightning Detection Networks Covering Belgium”. J. Atmos. Oceanic Technol., 30, 942-951, doi: http://dx.doi.org/10.1175/JTECH-D-12-00162.1.

Rakov V.A., 2013: “Electromagnetic methods of lightning detection”. Surv. Geophys., 34, 731–753, doi:10.1007/s10712-013-9251-1.

Rakov V.A., and Uman M.A., 2003: “Lightning: Physics and Effects”. Cambridge University Press, 687 pp.

Said R.K., Cohen M.B., and Inan U.S., 2013: “Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations”. J. Geophys. Res. Atmos.,118, 6905-6915, doi:10.1002/jgrd.50508.

Annex 1 - Summary Table of ATDnet Comparisons

Area	ATDnet DE	ATDnet LA	Reference network used	Reference network DE	Paper reference
France	~45% (strokes)	5 km	Meteo France	90% (flashes)	Gaffard et al., (2008)
Austria	~50% (strokes)	-	ALDIS	90% (flashes)	Gaffard et al., (2008)
Finland	57% (CG strokes)	4.5 km	NORDLIS	>90% (flashes)	Bennett (2010)
Tropical North Atlantic	80% (strokes)	17 km	WWLLN	32% of ATDnet strokes	Bennett (2011)
Belgium	88% (flashes), 58% (strokes)	1.0 km	High-speed camera observations	100% (recorded flashes/strokes)	Poleman et al. (2013b)
Belgium (49^{o}–52^{o}N; 2^{o}–7^{o}E)	80% (CG flashes, 47% CG strokes), 69% (all flashes), 39% (all strokes)	2.8 km (CG flashes, 1.9 km CG strokes), 3.0 km (all flashes), 2.0 km (all strokes)	Meteorage	100% (flashes), 85% (strokes)	Poelman et al. (2013a)
W Europe (42^{o}–53^{o}N; 5^{o}W–9^{o}E)	80% (CG flashes, 49% CG strokes), 66% (all flashes), 37% (all strokes)	2.7 km (CG flashes, 1.9 km CG strokes), 2.8 km (all flashes), 1.9 km (all strokes)			
Belgium (49^{o}–52^{o}N; 2^{o}–7^{o}E)	60% (flashes), 27% (strokes)	-	SAFIR	93% (flashes), 70% (strokes)	Poelman et al., 2013a
South of France	89% (CG flashes), 24% (IC flashes)	-	HyMeX Lightning Mapping Array	100% (all flashes)	Enno et al. (2016a)
W Europe	10-30% (night) to 20-40% (day) of all strokes	-	Blitzortung	Unknown but probably >90% in Western and	-

				Central Europe	
Europe (30º–70ºN; 15ºW–35ºE)	30-50% (night) to 40-80% (day) of all strokes	-			
Mediterranean, East Atlantic	20-30% (all flashes)	-	TRMM-LIS	70% (day) to 90% (night), all lightning.	Enno et al. (2016b)
West Atlantic	10-15% (all flashes)	-			
N and W Africa	5-10% (all flashes)	-			
S America S Atlantic	~5% (all flashes)	-			
N Europe	20-40% (Finland) to >80% (Poland, Germany), CG strokes	2.0-3.5 km (CG strokes)	NORDLIS	>95% flashes in Finland, (much) less elsewhere.	Manuscript

Annex 2 – Table or receivers

Site Name	*Approximate Location*	*Regions used for modelling*	*Notes*
Exeter	50.7N, -3.5E	ATDnet, South Atlantic, North Atlantic	
Akrotiri	34.6N, 33E	ATDnet, Africa, Eastern Europe	
Gibraltar	36.2N, -5.3E	ATDnet, Africa, North Atlantic	
Payerne	46.8N, 6.9E	ATDnet, Africa, North Atlantic, Eastern Europe	
Norderney	53.7N, 7.2E	ATDnet, North Atlantic, Eastern Europe	
Keflavik	64N, -22.6E	ATDnet, South Atlantic, North Atlantic	
Valentia	51.9N, -10.2E	ATDnet, South Atlantic, North Atlantic	
Croatia	45.9N, 17.2E	ATDnet, Africa, Eastern Europe	
Helsinki	60.2N, 24.9E	ATDnet, Eastern Europe	
Lerwick	60.1N, -1.2E	ATDnet, North Atlantic, Eastern Europe	
Eskdalemuir	55.2N, -3E	ATDnet, North Atlantic	
Tartu	58.4N, 26.7E	Eastern Europe	A planned LEELA site.
Azores	38.7N, -27.2E	Africa, South Atlantic, North Atlantic	Currently an R&D site.
Mogadishu	2.1N, 45.3E	Africa	
Cape Town	-34.5N, 19.9E	Africa, South Atlantic	
Antananarivo	-19N, 47.6E	Africa	
Cape Verde	14.9N, -23.5E	Africa, South Atlantic, South	

		America, North Atlantic
N'Djamena	12.2N, 15E	Africa
São Tomé and Príncipe	0.3N, 6.7E	Africa, South Atlantic, North Atlantic
Kigali	-2N, 30.1E	Africa
Mombasa	-4.3N, 39.3E	Africa
Luanda	-8.9N, 13.4E	Africa, South Atlantic
Lusaka	-15.5N, 28.4E	Africa
Mbabane	-26.3N, 31.2E	Africa
Cairo	29.8N, 31.2E	Africa, Eastern Europe
Abidjan	5.3N, -4E	Africa, South Atlantic, North Atlantic
Abuja	9N, 7.4E	Africa
Niamey	13.4N, 2.1E	Africa
Port Elizabeth	-33.8N, 25.2E	Africa
Windhoek	-22.6N, 17E	Africa, South Atlantic
Asmara	15.3N, 39E	Africa, Eastern Europe
Addis Ababa	8.9N, 38.7E	Africa, Eastern Europe
Khartoum	15.4N, 32.6E	Africa, Eastern Europe
Aswan	24.1N, 33E	Africa, Eastern Europe
Seychelles	-4.6N, 55.5E	Africa
Mauritius	-21.2N, 55.5E	Africa
Canary Islands	28.2N, -16.5E	Africa, South Atlantic, North Atlantic
Ascension	-7.9N, -14.4E	Africa, South Atlantic, South America, North Atlantic

Tamanrasset	22.8N, 5.4E	Africa, South Atlantic	
Falkland Islands	-51.8N, -58.4E	South Atlantic, South America	
St Helena	-16N, -5.7E	South Atlantic, North Atlantic	
Rothera	-67.6N, -68.1E	South Atlantic	
Halley	-75.6N, -26.2E	South Atlantic	
Rio de Janeiro	-22.9N, -43.2E	South Atlantic, South America	
Brasilia	-16N, -47.7E	South Atlantic, South America	
Fernando de Noronha	-3.8N, -32.4E	South Atlantic, South America, North Atlantic	
South Georgia	-54.2N, -37E	South Atlantic, South America	
Salvador	-13N, -38.5E	South Atlantic, South America, North Atlantic	
Barbados	13.2N, -59.5E	South Atlantic, South America, North Atlantic	
Gough Island	-40.3N, -9.9E	South Atlantic	Limited communications links
Tristan de Cunha	-37.2N, -12.4E	South Atlantic	Limited communications links
Trindade and Martin Vaz	-20.5N, -29.3E	South Atlantic, South America	
Bermuda	32.4N, -64.7E	South Atlantic, South America, North Atlantic	
Fortaleza	-3.8N, -38.5E	South Atlantic, South America, North Atlantic	
British Virgin Islands	18.4N, -64.6E	South America, North Atlantic	
Nova Scotia	44.6N, -63.5E	North Atlantic	
St John's	47.5N, -52.7E	North Atlantic	
Philadelphia	40N, -74.8E	North Atlantic	

The Bahamas	25N, -77.5E	South America, North Atlantic
Madeira	32.8N, -17.1E	North Atlantic
French Guiana	4.9N, -52.3E	South America, North Atlantic
Montevideo	-34.9N, -56.3E	South America
Asuncion	-25.3N, -57.6E	South America
Santiago	-33.5N, -70.8E	South America
Galapagos	-0.7N, -90.9E	South America
Lima	-12.1N, -76.9E	South America
Quito	-0.2N, -78.5E	South America
Santa Cruz de la Sierra	-17.8N, -63.1E	South America
Bogota	4.7N, -73.9E	South America
Manaus	-3N, -59.9E	South America
Mumbai	19N, 72.9E	Eastern Europe
Bishkek	43.1N, 74.5E	Eastern Europe
Svalbard	78.2N, 15.9E	Eastern Europe
Armenia	40.2N, 44.6E	Eastern Europe
Aktobe	50.3N, 57.2E	Eastern Europe
Aktau	43.7N, 51.2E	Eastern Europe

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