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Comparison and characterisation of ATDnet versus LIS for the period of 2008 to 2014

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***Abstract*— In the present study the detection efficiency (DE) of the Met Office long-range Very Low Frequency lightning location system ATDnet is evaluated against the Tropical Rainfall Measuring Mission Lightning Imaging Sensor (LIS) during 2008-2014 within the LIS data domain (38°N-38°S; 180°W-180°E). If an ATDnet observation was found within 25 km and 330 ms of a LIS flash then the LIS flash was considered to be detected by ATDnet.**

ATDnet detected 20-30% of LIS flashes over the Mediterranean and the East Atlantic, 10-15% of LIS flashes over the West Atlantic and 5-10% in northern and western Africa. ATDnet DE was notably higher over salty water compared to land. The average number of ATDnet fixes per detected LIS flash was 1.23 and 15% of the detected LIS flashes had more than one ATDnet observation. ATDnet more efficiently detected stronger LIS flashes with a high number of events per group and large area.

Keywords—lightning detection; detection efficiency; ATDnet; LIS

I. INTRODUCTION

High quality real time lightning data are increasingly important for severe weather monitoring and forecasting. Nowadays there are many lightning location systems (LLS) that monitor lightning activity using different methods. Conventional ground-based LLSs detect the radio frequency electromagnetic fields produced by lightning whereas satellite-based sensors rely on the optical emission of lightning. Ground-based systems typically provide continuous data whereas early satellite-based sensors were constrained by short and sparse view times of low-earth orbiting satellites. Now that the era of geostationary lightning detection has started, the importance of satellite-based lightning observations is expected to increase significantly. Thus, it is important to know how the ground- and satellite-based detectors compare in order to develop complementary data products.

In the present study the detection efficiency (DE) of a ground-based lightning location system, ATDnet, is evaluated against a satellite-based LIS sensor. ATDnet is a Very Low Frequency (VLF) long-range 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 10 sensors in and around Europe operating at the central frequency of 13.733 kHz (Fig. 1). The effective range of ATDnet encompasses Europe, northern Africa, and northern parts of the Atlantic Ocean. The system also detects some lightning in central Africa, South America, the South Atlantic Ocean, the eastern coast of North America and in Asia.

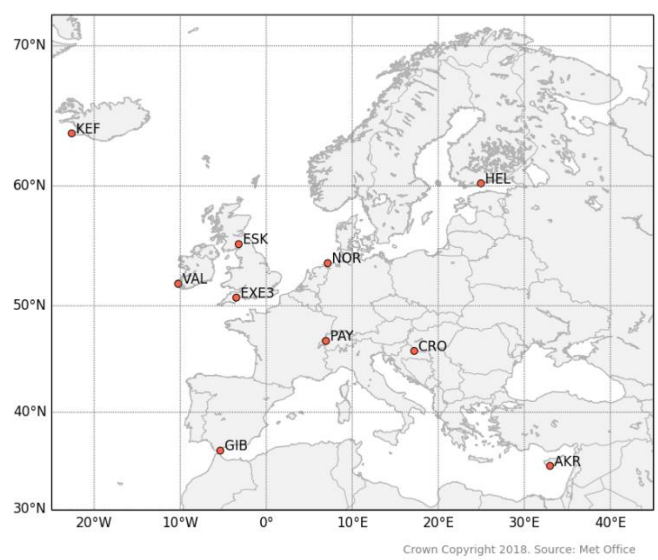

Fig. 1. Locations of ATDnet operational outstations.

ATDnet sensors detect atmospherics (also called sferics). Sferics are electromagnetic waves in the VLF range that propagate in the earth-ionosphere waveguide and are generated by cloud-to-ground lightning (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. ATDnet detections are referred to as ‘‘fixes’’ and they correspond to CG return strokes or IC pulses. Fixes are located using data from a minimum of four ATDnet outstations.

ATDnet first became operational in 1987 with its main focus being CG lightning detection. CG lightning is responsible for most of the lightning damage and it is also easier to detect for a long range LLS as CG strokes tend to emit more powerful sferics in the VLF range than cloud lightning pulses [e.g. Cummins and Murphy 2009]. On the basis of comparisons against short-range lightning location systems [Poelman et al., 2013a; Poelman et al., 2013b] and a lightning mapping array [Enno et al., 2016] ATDnet is capable of detecting around 90% of cloud-to-ground and up to 25% of cloud lightning in Europe.

The Lightning Imaging Sensor (LIS) was an instrument on the Tropical Rainfall Measuring Mission (TRMM) satellite, launched into a low-earth orbit in November 1997. LIS remained operational until the end of life of the TRMM satellite in April 2015. TRMM’s orbit had an inclination of 35° that allowed for the detection of lightning between 38°N and 38°S. LIS field of view (FOV) was 580x580 km, and its nadir resolution was 4 km decreasing to 7 km at the edges of the field of view [Christian, 1999]. LIS consisted of an optical staring imager, which detected lightning activity by identifying changes in the brightness of clouds illuminated by lightning between successive time steps of 1.8 milliseconds. It was able to detect lightning even in bright, sunlit clouds by using a narrow band filter centred at a wavelength of 777.4 nm. The instrument recorded the time and location of a lightning event as well as its radiant energy [Christian et al., 1999].

LIS was able to detect both, cloud-to-ground (CG) and cloud (IC) lightning but it was not designed to discriminate between the two. The sensor was predicted to have a detection efficiency of 93±4% during the local nighttime, dropping to nearer 73±11% around local noon due to daytime reflection of solar radiation [Boccippio et al., 2002]. Studies indicated that LIS was somewhat more sensitive to cloud lightning compared to cloud-to-ground lightning [Ushio et al., 1999; Thomas et al., 2000].

Over recent years, many ground-based lightning location systems have been validated against LIS. Examples include long range LLS such as the World Wide Lightning Location Network [Rudlosky and Shea, 2013; Thompson et al., 2014] and Vaisala’s Global Lightning Dataset 360 [Rudlosky, 2014] as well as short range systems like the Earth Networks Total Lightning Network [Rudlosky, 2015] and the US National Lightning Detection Network [Zhang et al., 2016].

The main advantage of LIS over ground based networks is its relatively long period of consistent observations with stable performance [Buechler et al. 2014] and its spatially uniform coverage over land and the oceans. Moreover, LIS used the same observing method as is used by Geostationary Operational Environmental Satellite-16 Geostationary Lightning Mapper (GOES-16 GLM) [Goodman et al., 2013] and will be used by the Meteosat Third Generation Lightning Imager (MTG-LI) [Grandell et al., 2009]. As such, LIS large dataset spanning from 1998 to 2014 provides an excellent opportunity to compare ATDnet performance against a satellite-based optical lightning sensor.

The main objectives of the present study are to evaluate ATDnet performance against LIS and to reveal the similarities and differences between the two datasets. This is achieved by measuring ATDnet DE relative to LIS and examining the impact of LIS flash characteristics on ATDnet DE.

Section 2 describes the approach used in comparing LIS and ATDnet data and Section 3 represents the main results. Section 4 provides a discussion of the results and Section 5 concludes the study.

II. Data and Methods

A. ATDnet data

ATDnet monitors lightning activity within its spatial range continuously and problems with sensors are normally rare and solved quickly. The only major issue during the study period was the loss of the Valentia sensor in Ireland which was out of service from spring 2012 to February 2015. Another notable change in the network occurred in February 2014 when the Manas outstation in Kyrgyzstan (not shown in Fig. 1) was permanently decommissioned.

The original ATDnet fix dataset was used in the present study. ATDnet fixes correspond to CG lightning return strokes or strong IC pulses but no discrimination between lightning types is provided. The dates, times (0.1-µs precision) and locations (latitude and longitude) of fixes were used.

All ATDnet fixes are checked by the ATDnet quality control system against predefined location uncertainty and signal quality criteria and classified as “good” or “poor”. Only “good” fixes that pass the criteria are used in ATDnet data products. The present study also used only “good” fixes in order to reflect ATDnet DE at the customer level.

ATDnet fixes were not filtered for LIS view times as ATDnet was validated against LIS, and not vice versa. Thus, the whole ATDnet and LIS datasets were compared directly as LIS flash times and locations automatically filtered out all ATDnet fixes that were potentially linked to LIS flashes.

B. LIS Data

LIS data availability was limited by LIS view times, i.e. the overpass times of the TRMM satellite that constituted only about 0.1% of the time. However, this provides sufficient observations to map long term lightning patterns accurately [Christian et al., 2003]. The LIS flash database used for this study (i.e. 2008 - 2014) consisted of approximately 9.9 million flashes. The study area was limited to 38°N-38°S due to the orbital inclination of the TRMM satellite.

LIS reported the time, location, and radiant energy of individual total lightning events [Christian et al., 1999]. Events were defined as single pixels that exceeded the LIS background level during a single frame (1.8 ms). Events in adjacent pixels (i.e. with a side or corner touching) of the same frame were combined to form groups. A group centroid was geo-located for each group by spatially weighting the event locations by their radiance [Zhang et al., 2016]. Groups that occurred within 330 ms and 5.5 km were further combined into flashes using a weighted Euclidean distance method [Mach et al., 2007]. A flash centroid was geo-located by all the included groups.

In the present study LIS flash level data was used. The dataset contained the times and locations of flashes and additional flash characteristics derived from the number, area and brightness of involved events and groups. Flash time corresponded to the time of the first group and flash location was the location of the flash centroid. Additional flash properties that were used in this study included duration, number of groups and events, radiance, area, maximum number of events per group and maximum group area and radiance.

C. Measuring ATDnet detection efficiency

LIS flashes and ATDnet strokes were compared. This approach was chosen as it had already been demonstrated to be suitable for comparing ground based networks and LIS [Rudlosky and Shea, 2013; Rudlosky, 2014 and 2015]. The locations of all LIS groups were also taken into account in order to ensure that ATDnet fixes far from LIS flash centroids but in the vicinity of LIS groups still counted as ATDnet matches. The times and locations of all ATDnet strokes corresponding to LIS flashes were saved so that it was later possible to estimate the number of ATDnet strokes per detected LIS flash and spatial and temporal distribution of ATDnet strokes relative to matching LIS flashes.

A LIS flash was considered to be detected by ATDnet if there was at least one ATDnet fix within 25 km of any group in the LIS flash (i.e., furthest groups north, south, east and west) and 330 ms before the start of, until 330 ms after the end of the LIS flash (Fig. 2). These spatial and temporal criteria were introduced by Rudlosky and Shea [2013] who examined several time and distance thresholds to determine the best matching criteria.

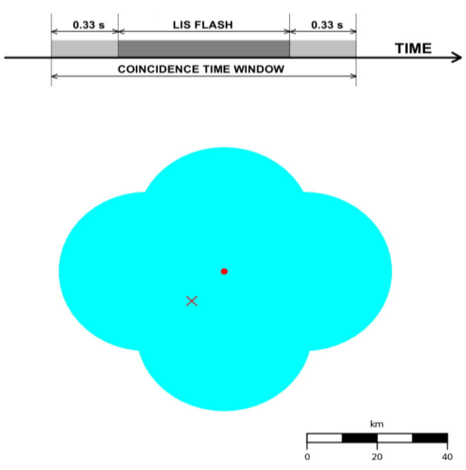

Fig. 2. Schematic representation of the temporal (top) and spatial (bottom) criteria used for matching ATDnet fixes and LIS flashes. Coincidence time window started 0.33 s before LIS flash start and ended 0.33 s after LIS flash end (top). A matched ATDnet fix had to occur within 25 km of any group in a LIS flash (area in aqua, bottom). The red dot is the centroid of the detected LIS flash and the red cross marks the location of the corresponding ATDnet fix.

Only one-to-many relationships were allowed meaning that a LIS flash could have one or more linked ATDnet fix(es) but an ATDnet fix could only be linked to one LIS flash. This approach is scientifically justified as LIS flashes can contain multiple return strokes which could be all detected as separate ATDnet fixes whereas a single ATDnet fix represents either a CG return stroke or an IC pulse that can only belong to one LIS flash. In order to avoid double counting, all ATDnet fixes with a matching LIS flash were flagged as used so that they could not be matched with other LIS flashes later.

III. Results

A. ATDnet DE

ATDnet performed best over the North Atlantic Ocean and the Mediterranean basin where it was capable of detecting approximately 20-30% of LIS flashes (Fig. 3). ATDnet DE of around 10-15% was observed in the Caribbean Sea, northern Africa and the north eastern part of South America. More distant regions of South America together with the South Atlantic Ocean had ATDnet DE values of approximately 5%. ATDnet also detected some lightning in central and southern Africa, the Middle East, Asia, the eastern seaboard of the US and the Gulf of Mexico but its relative DE was below 5% in those areas. A clear contrast between land and salty water appeared with higher ATDnet DE values over the Mediterranean basin and the Atlantic Ocean.

There were 235 593 linked LIS flashes and 288 663 linked ATDnet fixes in the study area during 2008-2014. The average number of ATDnet fixes per detected LIS flash was 1.23. Nearly 85% of the LIS flashes had only one linked ATDnet fix and approximately 10% had two linked fixes. Approximately 0.65% of all linked LIS flashes (4002 flashes) had more than four linked ATDnet fixes. The spatial distribution of the average number of ATDnet fixes per detected LIS flash is shown in Fig. 4. There were clearly more ATDnet fixes per detected LIS flash over water than over land which is very similar to higher ATDnet DE over the Atlantic Ocean and the Mediterranean basin.

B. Annual and day-to-day variations

ATDnet DE relative to LIS improved slightly during the study period. For example, in the East Atlantic Ocean ATDnet detected about 14% of LIS flashes in 2008, 20-25% of LIS flashes during 2009-2011 and 23-28% of LIS flashes in 2012-2014. The biggest improvement from 2008 to 2009 was most likely related to the change to ATDnet group velocity that was introduced at the beginning of 2009. It significantly reduced northeast to southwest oriented location errors of ATDnet fixes over the Atlantic Ocean and South America and thus increased the proportion of ATDnet-LIS matches that met the spatial threshold of 25 km. At the same time a slight decrease in ATDnet DE was observed in the West Atlantic Ocean towards the end of the study period. This was probably related to the failure of one of the westernmost ATDnet sensors in Valentia, Ireland, which was out of order from 2012 to 2015.

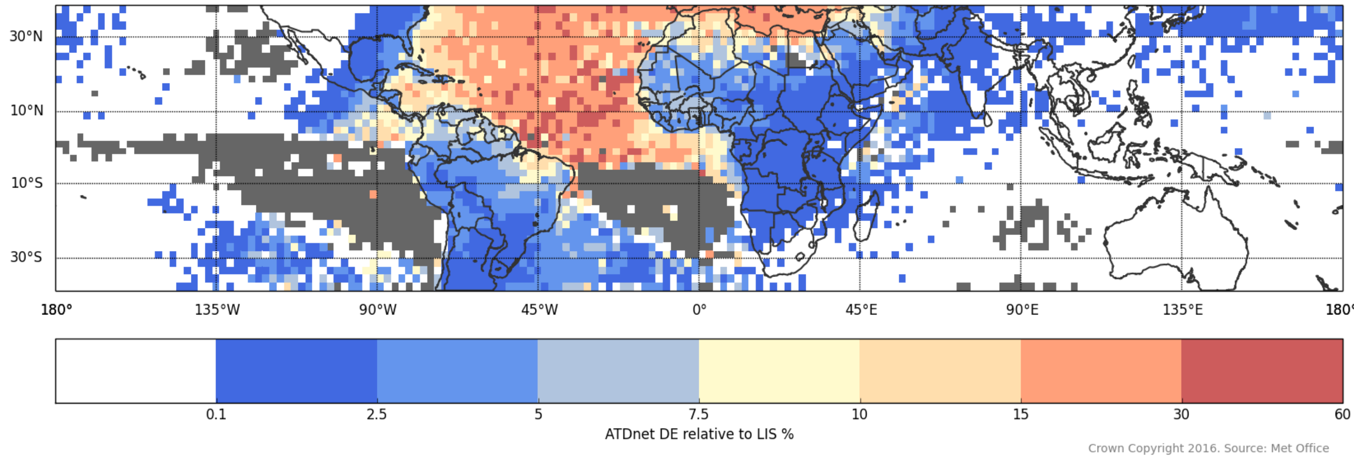

Fig. 3. ATDnet DE relative to LIS during 2008-2014. Dark gray areas represent grid cells where ATDnet DE was not computed as there were less than 10 LIS flashes during the study period.

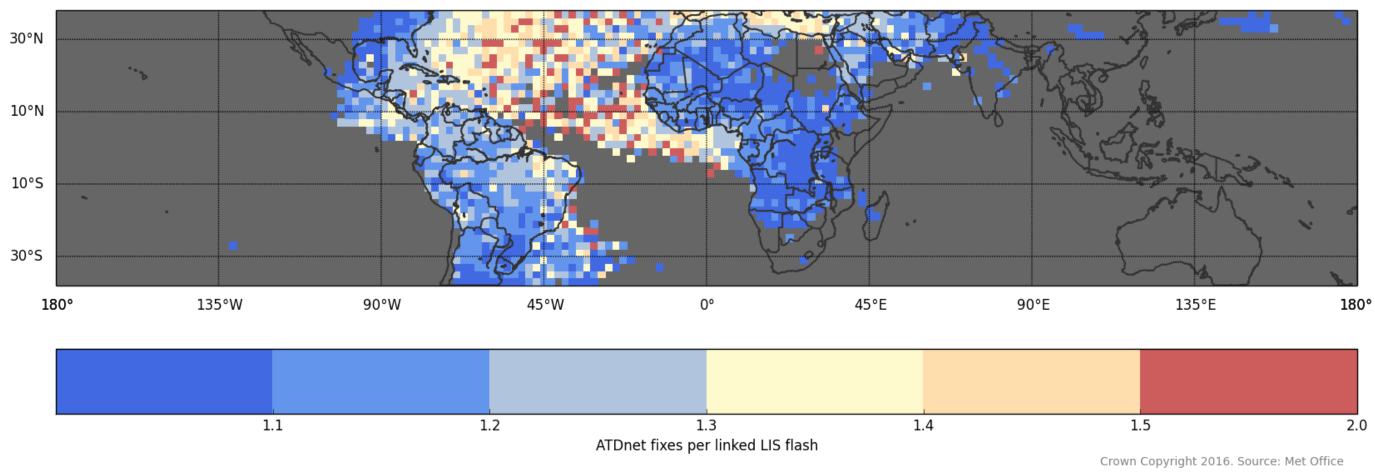

Fig. 4. The spatial distribution of the mean number of ATDnet fixes per detected LIS flash during 2008-2014. Dark gray areas represent grid cells where the parameter was not computed as there were less than 10 detected LIS flashes during the study period.

Large day-to-day and storm-to-storm variations were characteristic to ATDnet detection efficiency even if only a small study area was used and days with similar storm pattern were compared. Two sample cases with a relatively similar spatial pattern of Mediterranean thunderstorms in and around Tunisia are shown in Fig. 5. The first storm occurred on the 26 October 2008 and the second one on the 24 October 2010. Both days had 480-490 LIS flashes in the Mediterranean region. ATDnet detected 54.5% of LIS flashes in the first storm but only 3.5% in the second storm. Similarly large storm-to-storm fluctuations in ATDnet DE were observed in different regions including parts of the Atlantic Ocean and South America.

C. ATDnet DE and LIS flash characteristics

The impact of eight LIS flash characteristics on ATDnet DE was examined (Table 1). The results revealed a positive relationship between the values of all the LIS characteristics and ATDnet DE, i.e. brighter flashes with larger area, longer duration and greater number of groups and events were generally more likely to be detected by ATDnet. According to the two-sided Welch's t-test [Welch 1947], the mean values of all eight LIS flash characteristics were significantly lower for undetected LIS flashes ($P \ll 0.01$).

A more detailed examination revealed that flash area, maximum group area and maximum number of events per group had stronger impact on ATDnet probability of detection. ATDnet DE values of 15-20% corresponded to high values of those flash characteristics. In contrast flash duration, the number of groups and events per flash as well as flash radiance and maximum group radiance had a smaller impact on ATDnet DE which was only 5-10% even if the values of those parameters were high.

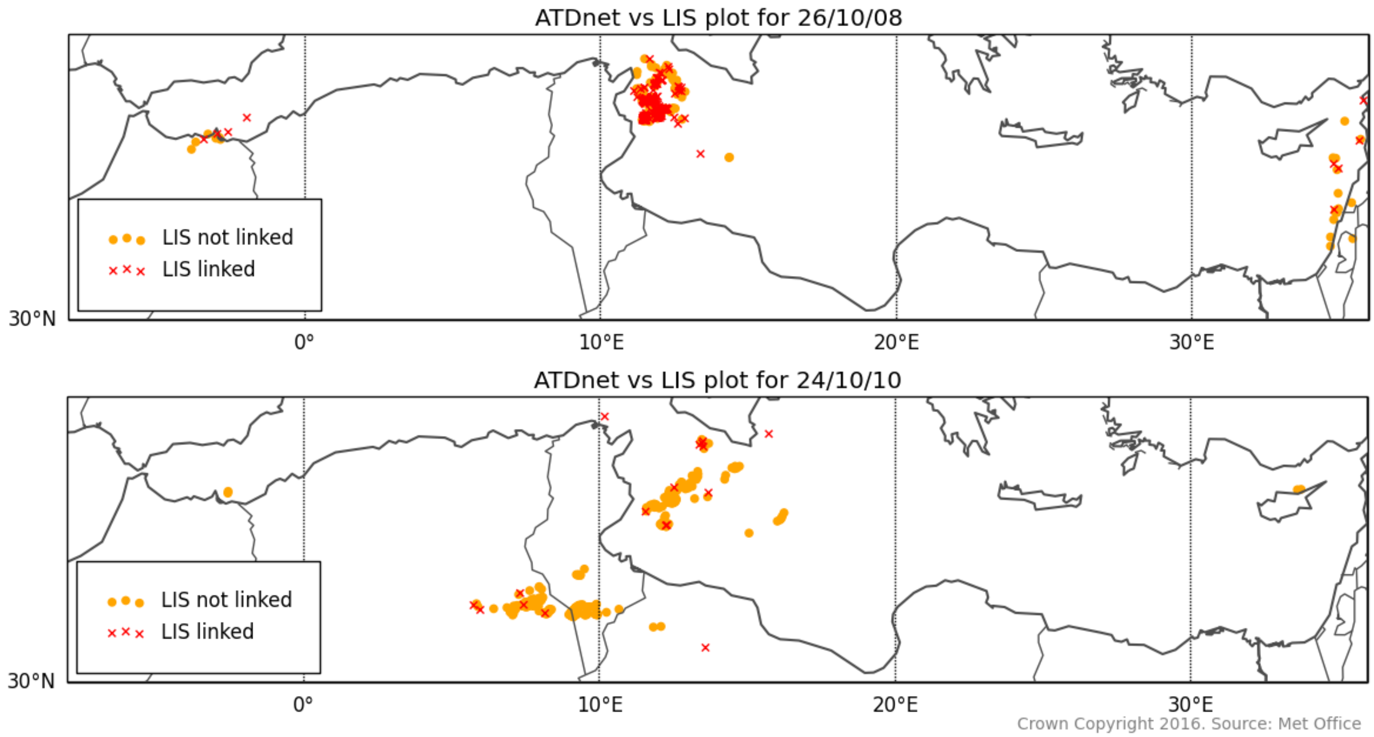

Fig. 5. LIS-linked (detected by ATDnet) and not linked flashes in the Mediterranean region on 26 October 2008 with two daytime TRMM overpasses and a total of 488 LIS flashes (top) and 24 October 2010 with four nighttime TRMM overpasses and a total of 483 LIS flashes (bottom).

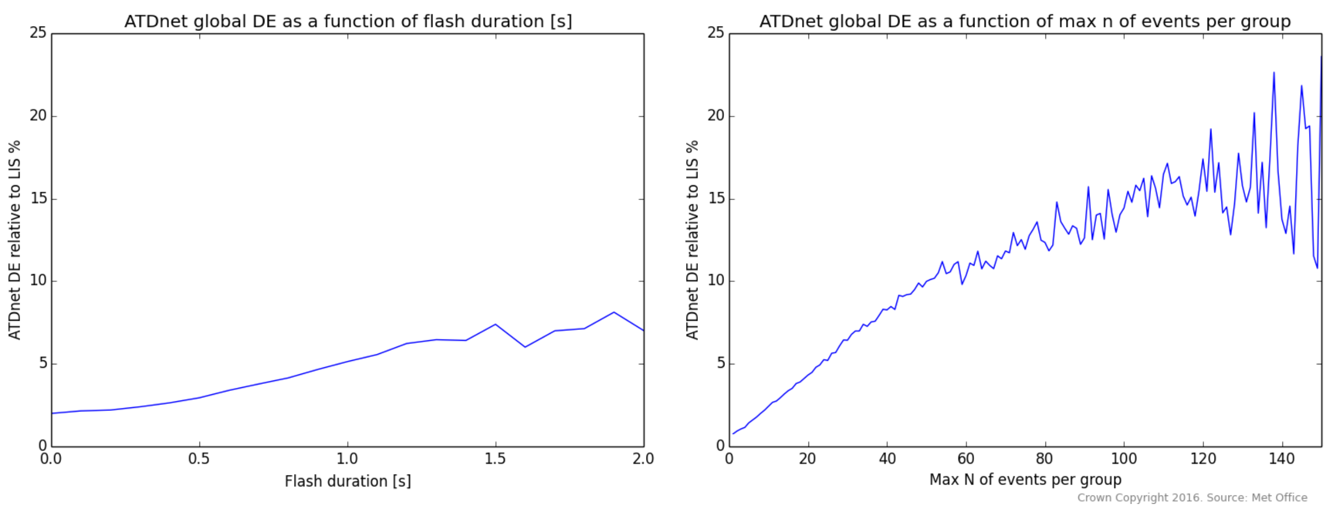

Fig. 6. ATDnet DE as a function of flash duration (left) and the maximum number of events per group (right).

Example plots of the relationships between LIS flash characteristics and ATDnet DE are shown in Fig. 6 for the maximum number of events per group and flash duration. It can be seen that the former had much stronger impact on ATDnet DE than the latter. The overall logarithmic shape of the DE graphs is likely related to the fact the global LIS dataset was used whereas ATDnet is a regional LLS. Thus, there are areas outside the range of ATDnet where even the strongest flashes are unlikely to be detected. Note that the DE data get increasingly noisier with the diminishing number of LIS flashes as is the case towards higher values of the maximum number of events per group and flash duration.

TABLE I. THE MEAN VALUES AND VARIANCES OF THE STUDIED LIS FLASH CHARACTERISTICS FOR FLASHES DETECTED AND NOT DETECTED BY ATDNET. DELTA-DURATION (s); NG-NUMBER OF GROUPS; NE-NUMBER OF EVENTS; RAD-RADIANCE (J m^{-2} sr^{-1} μm^{-1}); AREA-AREA (km^2); MNEG-MAXIMUM NUMBER OF EVENTS PER GROUP; MGA-MAXIMUM GROUP AREA (km^2); MGRAD-MAXIMUM GROUP RADIANCE (J m^{-2} sr^{-1} μm^{-1}).

	Detected LIS flashes (N=235 593)		**Undetected LIS flashes (N=9 646 491)**		**P**
	average	*variance*	*average*	*variance*	
DELTA	0.31	0.080	0.25	0.054	0.00
NG	14.9	348.1	11.0	182.7	0.00
NE	93.7	16 985.8	48.1	6 520.3	0.00
RAD	1 524 608.3	1.03e+13	653 975.0	2.94e+12	0.00
AREA	560.0	319 502.3	280.7	87 869.2	0.00
MNEG	20.2	540.0	9.9	138.3	0.00
MGA	490.6	275 459.5	247.1	74 232.3	0.00
MGRAD	495 075.7	1.15e+12	197 069.2	2.49e+11	0.00

IV. DISCUSSION

The results confirmed that ATDnet is capable of detecting lightning not only in and around Europe but also over the whole tropical Atlantic and also in most of Africa, South America and the eastern seaboard of the US. ATDnet DE values were found to be 20-30% over the Mediterranean and the East Atlantic and decrease to 5% in distant regions such as South America and the South Atlantic. These values might seem relatively low at first but it has to be taken into account that ATDnet and LIS have somewhat different capabilities and limitations.

LIS is an all lightning sensor whereas ATDnet is designed to locate cloud-to-ground lightning return strokes. It is generally known that cloud lightning is much more frequent than cloud-to-ground lightning and constitutes around 75-80% of total lightning in the world [Rakov and Uman 2003]. Even higher IC fractions have been reported in certain regions especially in tropics [e.g. Pinto et al., 2007]. Moreover, some studies have indicated that LIS is more sensitive to cloud lightning [Ushio et al. 1999; Thomas et al. 2000]. Thus, it can be assumed that ATDnet DE relative to LIS is significantly limited by a large fraction of cloud lightning in the LIS dataset.

It is also important to consider that virtually all the LIS data domain lies outside ATDnet perimeter. That means issues like attenuated and distorted waveforms caused by long propagation paths as well as larger location errors due to unfavourable network geometry. Thus, the ATDnet DE values represented here are expected to be significantly lower than in Europe. On the other hand it is remarkable that ATDnet is capable of detecting a significant proportion of stronger flashes and thus locate all significant storms even as far from Europe as South America and the South Atlantic.

Land-sea contrast in ATDnet DE and number of fixes per detected LIS flash was obvious. It is not surprising that ATDnet performs better over the oceans as flashes there are generally stronger than over land [e.g. Said et al. 2013; Hutchins et al. 2013] and thus emit stronger sferics that are easier to detect. Moreover, higher air conductivity over salty water means lower attenuation and increases the probability that sferics of less powerful return strokes are still detectable at great distances. It has been previously demonstrated that an ATDnet-like long range VLF lightning location system WWLLN detects lightning over the oceans approximately three times more efficiently than over land [Rudlosky and Shea 2013].

Large dry land areas such as deserts cause stronger attenuation of VLF waveforms. The fact that ATDnet DE is somewhat lower in central and southern Africa compared to more distant areas in South America is probably due to stronger waveform attenuation over the Sahara desert in northern Africa.

It was found that LIS flash characteristics, especially flash area, maximum group area and maximum number of events per group had clear impact on ATDnet DE. This is in line with the observation that maximum group area and maximum number of events per group are the two LIS flash characteristics most suitable for discriminating between CGs and ICs [Koshak 2010]. Thus, it can be assumed that the fraction of CGs increases towards higher values of maximum number of events per group and maximum group area and so does the ATDnet DE because the system is designed to locate CG return strokes. Large group and flash area may also compensate for ATDnet location errors.

Large variations in ATDnet DE between individual storms are probably related to variations in IC-CG ratio and flash characteristics between storms. However, there are probably also other contributing factors. For example, it was observed that daytime storms had generally higher ATDnet DE than nighttime storms. It is known that VLF propagation conditions differ between day and night and that the current ATDnet system is tuned for daytime lightning. The opposite is true for LIS which could more easily detect the optical emission of lightning against dark nighttime background. This demonstrates that ATDnet and satellite-based lightning imagers can outperform each other in certain situations and thus highlights the potential benefits of complementary data products.

V. CONCLUSIONS

ATDnet flash detection efficiency (DE) relative to the Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS) was evaluated. LIS used the same observing principles as is used by GOES-16 Geostationary Lightning Mapper and will be used by MTG Lightning Imager. Thus, the results of the present study could be used for planning complementary studies and data products.

The results revealed that ATDnet detected 20-30% of LIS flashes over the Mediterranean and the East Atlantic, 10-15% of LIS flashes over the West Atlantic and 5-10% in northern and western Africa. This is a significant fraction of LIS flashes given that virtually all the study area was located outside ATDnet perimeter and that LIS is capable of detecting all type of lightning discharges whereas ATDnet was primarily designed to detect cloud-to-ground lightning return strokes. This indicates that ATDnet has a potential to provide complementary data to geostationary lightning sensors in the future.

The findings encourage further steps towards collaboration and/or synergies with geostationary lightning data. The first opportunity will be with GOES-16 GLM launched in November 2016. The results of the present study indicate that ATDnet detects a significant number of lightning discharges within the GOES-16 footprint in South America and the Atlantic Ocean for a comparative study. A similar comparison over Europe against LIS on the International Space Station (ISS) could also provide valuable new information.

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