THE COMPARISON OF GLD360 AND EUCLID LIGHTNING LOCATION SYSTEMS IN EUROPE

Pohjola H.[1] and Mäkelä A.[2]

[1]*Vaisala Oyj, P.O. Box 26, 00421Helsinki, Finland, heikki.pohjola@vaisala.com*

[2]*Finnish Meteorological Institute, P.O. Box 503, 00101 Helsinki, Finland, antti.makela@fmi.fi*

I. INTRODUCTION

A lightning flash is not a simple spark, but it consists of many smaller scale discharges, which together produce a quantity termed "flash", occurring either inside the cloud (cloud flash) or between the cloud and ground (cloud-to-ground flash). Because of the large variety of discharges, a flash radiates in a wide electromagnetic (EM) spectrum, from Extremely Low Frequencies (ELF) to high energy radiation of x- and even gamma rays (Fishman et al., 1994). In lightning detection and location, two frequency domains Have been noted to be the most practical; Very High Frequencies (VHF), and Low or Very Low Frequencies (LF and VLF).

The chosen frequency range is up to the user: if the user wants to get as much information from lightning as possible, a VHF system is needed; if only the ground strike points and a limited number of cloud flash information is needed, an LF/VLF system is a good choice.

For lightning location systems (LLS), there are two widely used parameters for describing the network performance, detection efficiency (DE) and location accuracy (LA). The former means the ratio between the located and actually occurred strokes, while the latter indicates how precisely the occurrence point of lightning can be determined. In reality, all LLSs are imperfect; DE is always below 100% and LA is usually at best some tens or hundreds of meters (Schulz and Diendorfer, 1996; Idone et al., 1998a-b; Biagi et al., 2007), although for some individual strokes it can be only a few meters. Because a flash may contain several subsequent strokes, these performance parameters can be expressed for flashes and for strokes; for example, a flash-DE is always better than stroke-DE because to detect a flash, only one of its strokes is needed to be detected.

The absolute values of DE and LA are extremely difficult to determine, because the ground truth information is not available. For example, in Finland the ground truth is known for some tens of cases per year (Mäkelä, 2011). For instrumented towers, rocket triggering facilities (Jerauld et al., 2005; Diendorfer, 2010), and for E-field and video measurements (Saba et al., 2010; Schulz and Saba, 2009) there may be more cases, but still the numbers are low compared to the overall number of actual strokes. Also, the strokes on instrumented facilities may not be representative sample of the natural lightning.

Because of the reasons mentioned above, the comparison of different lightning location systems (LLS) is challenging. However, although the actual (absolute) performance cannot be known with certainty for any network, the relative performance of any system can be calculated. This can be done by cross-checking the lightning location data between two or more LLSs with some of the systems being the reference. A question may arise, what is the scientific value of a "relative" performance because this may not have anything to do with the absolute performance. In this paper we will show the value of this kind of comparison.

The best reference system is, of course, a system whose performance is known or can be estimated with enough certainty. Usually this is the case for a network, which has been running for several years and whose performance and data are routinely monitored and checked. In Europe, one of the most validated area within European Cooperation for Lightning Detection (EUCLID, see e.g. Diendorfer, 2010) coverage is Austria, which we will use in this paper as a reference territory.

In this study we compare the lightning location data of EUCLID to a long-range lightning location system GLD360 (Global Lightning Dataset 360) operated by Vaisala Oyj (Demetriades et al., 2010). The purpose of this study is to show the performance and the possible benefits and deficiencies of both of the networks.

II. DATA AND METHODS

European Cooperation for Lightning Detection (EUCLID) is a collaborative lightning location network in Europe. The general working principle of EUCLID is the same as that of other similar networks using compatible central processor and sensors (for detailed description see for example Cummins et al., 1998; Schulz et al., 2005; Mäkelä et al., 2010). The only practical difference is that EUCLID does not have its own sensors; EUCLID central processor receives the raw sensor data from the participating national networks and processes lightning locations in real-time to practically all of Europe. This kind of configuration is unique globally, because no other cooperative network consists of so many national networks.

Vaisala has been operating and developing the global lightning detection network GLD360 since 2009. The GLD360 network consists of VLF sensors strategically placed around the world for optimal detection of cloud-to-ground (CG) lightning strokes. These wideband sensors concentrate on detection of CG return strokes using magnetic direction finding and time-of-arrival methodologies combined with waveform recognition algorithms in the VLF band. Accurate arrival time estimates are achieved at long range by using a waveform bank, which enables the sensor to reliably identify a low time variance feature on individual waveforms that are band-limited and dispersed due to propagation in the Earth-ionosphere (Said et al, 2010). Using a receiver tuned for maximum sensitivity in the VLF band (Cohen et al, 2010), each sensor is able to detect radio impulses generated by lightning discharges out to 6000 km. Signals captured by this technology are then transmitted to Vaisala's Network Control Center (NCC) in Tucson, Arizona via a wide variety of communications methods. The NCC combines and correlates each of the raw sensor data to optimize the location estimate of the CG stroke. Data is made available or transferred through standard TCP/IP communications protocols. The GLD360 is owned, operated, and maintained by Vaisala. The expected eventual detection efficiency and median location accuracy of GLD360 globally are 70% for CG flash DE and 2-5 km median CG stroke LA. Vaisala has conducted preliminary validation of these claims through comparison to the NLDN (Demetriades et al, 2010). GLD360 also estimates the polarity and peak current of lightning discharges. Vaisala does not disclose the sensor locations (Vaisala, 2009).

The comparison period is May 5 – September 30, 2011. We have analyzed the lightning location data from both of the networks for four smaller regions in Europe which we name as Austria, Scandinavia, North Sea, and Spain. We also compare the data from a larger area defined with coordinates 35°-71°N, 10°W-35°E. The smaller areas are for showing the relative performance in high detail, and the larger area indicates the relative performance over whole Europe. The larger area comparison shows especially the outer detection boundary of EUCLID. For GLD360, the data set consists of all located strokes, mainly CGs; however, some of these may as well be cloud strokes, but we have no way of knowing this. The total number of detected strokes in this larger area is 8,525,073 for GLD360 and 6,846,690 for EUCLID. These strokes are plotted in Fig. 1 in 0.1° longitude x 0.1° latitude bins, indicating where the most abundant thunderstorms have occurred during the study period.

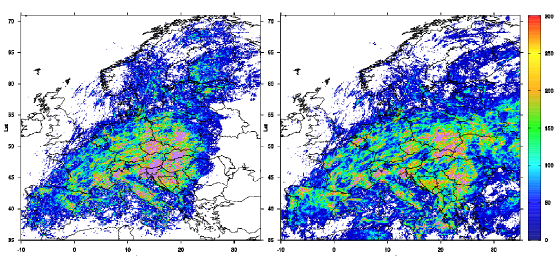

FIG. 1: Number of strokes in 0.1° longitude×0.1° latitude bins according to EUCLID (left) and GLD360 (right) during the study period. Purple color indicates values larger than 300 strokes.

For the comparison of relative location accuracy (RLA) we have used one month (July) of lightning location data from Austria. Austria has been chosen because the EUCLID performance over there is noticed to be one of the best in Europe, and because the performance has been checked and verified with tower and video measurements (Schulz et al., 2005; Diendorfer, 2010). However, merely by comparing two lightning location datasets, we cannot deduce the absolute location accuracy. If we pick up from the EUCLID data those strokes which we assume to be accurately located, we can estimate the GLD360 accuracy. In the EUCLID data there is a parameter termed as semimajor axis, which indicates the confidence of the calculated lightning location (Mäkelä et al., 2010); this means the length of the semimajor axis of a confidence ellipse, inside which the actual strike points is with 50% probability. In the RLA comparison we have neglected all EUCLID strokes with semimajor axis greater than one kilometre. Then, to find the corresponding strokes, we have used a time window of 0.1 milliseconds; if a GLD360 and EUCLID stroke are within this time window, they are considered as common. A temporal correspondence is enough here because the study area is small and it is highly unlikely that EUCLID and GLD360 detects not-related strokes during this time window in Austria. In this part, we have also made a coordinate transformation from the original WGS84 geographical coordinate system into the kilometre-based Universal Transverse Mercator system (UTM, zone 32). The total number of CG strokes in July in Austria is 26022 for EUCLID and 16566 for GLD360; the total number of temporally common events is 9418.

For peak current comparison, we use the same data set as for the RLA. The peak current of either network is not a direct measurement, but it is estimated from the lightning waveform received by the sensors with a propagation model (Schulz et al., 2005). For example with tower measurements in Austria, it has been found out that the peak current estimation with this method works well (Diendorfer et al., 2008), and the same has been noted also in Brazil (Mesquita et al., 2011). We also show how the relative detection efficiency depends on the peak current by presenting the GLD360 RDE for peak currents 0 - 30 kA.

Area	**EUCLID**	**GLD360**
Austria	146600	70892
North Sea	9987	13153
Scandinavia	185218	82801
Spain	150540	218801
Austria July 2011 [a] (the number of temporally common strokes is 9 418)	26022	16566

TABLE I: The number of located CG strokes in the studied regions in May 5–September 30, 2011. [a] Data used for the relative location accuracy and peak current comparisons.

III. RESULTS

a. Relative stroke detection efficiency

Figures 1-2 shows the detection efficiency of GLD360 relative to EUCLID in four smaller regions and in the whole Europe. The total number of strokes is shown in Table 1. In the figures, the relative detection efficiency (RDE) has been calculated if there have been at least ten strokes in the reference network data. The four regions have been chosen because they represent different performance areas in the EUCLID network: Austria is situated in the center of the network; Scandinavia, North Sea and Spain in the outer boundaries. A good EUCLID performance is anticipated in Austria, because there are plenty of sensors in the surroundings. This can be clearly seen in Fig. 2a; the RDE of GLD360 is generally below 100% in Austria, indicating that EUCLID detects more strokes. However, for some areas in Austria, GLD360 RDE reaches 100% or above. This may be linked to topography, but it is most likely related to location uncertainty of GLD360; if some GLD360 strokes fall into a "wrong" square because of location error, this may lead to a high RDE value in the analysis. The total number of strokes are 70,892 (GLD360) and 146,600 (EUCLID) which means an average RDE of about 48%. We note, that thus value would be lower if all EUCLID events (i.e., also intracloud classifications) would be included in the comparison, and the value would be larger if EUCLID CG flashes would be used as reference (i.e., taking account for only the first EUCLID CG strokes).

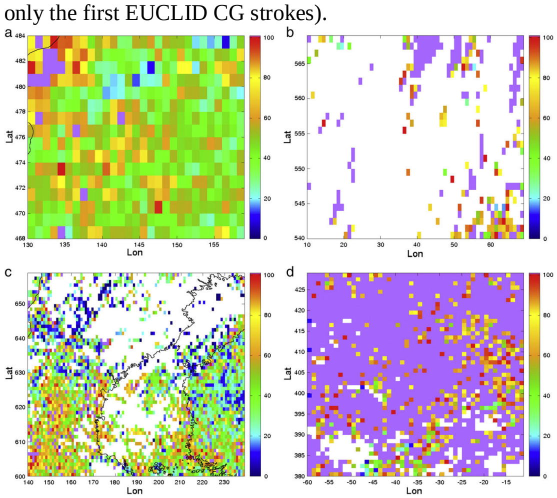

FIG. 2: Relative detection efficiency of GLD360 to EUCLID in a) Austria, b) North Sea, c) Scandinavia and d) Spain. Purple color indicates values larger than 100%.

In Fig. 2b is shown the results in the area of North Sea, which is situated in the western edge of EUCLID. Although not much lightning has been located in the area in 2011, a better performance of GLD360 compared to EUCLID can be seen with RDE values 100% or greater. In the eastern part of the area, the values decrease, indicating an increase in the EUCLID performance. This is obvious when moving away from the boundary area of EUCLID network i.e. the area of low performance of EUCLID network.

In Scandinavia, shown in Fig. 2c, the GLD360 RDE is generally below 100%. The reason is that although Scandinavia is situated in the boundary of EUCLID, the study area chosen for this study is surrounded by the Scandinavian sensors, resulting in a good EUCLID performance. Later in Fig. 3 we can see that the EUCLID performance drops rapidly to the East and West of Scandinavia.

The area of Spain in Fig. 2d shows interesting feature; the GLD360 RDE is practically everywhere above 100%. This suggests that EUCLID performance is poor in that area, although theoretically there are plenty of sensors monitoring the area. The reason for poor EUCLID performance in Spain is very likely related to communication failures during 2011, so that many sensor messages did not reach the EUCLID central processor.

Relative detection efficiency over the whole Europe is shown in Fig. 3. Fig. 3a shows the GLD360 RDE and Fig. 3b shows EUCLID RDE. We show the RDE of both systems because there can be small differences, e.g. due to the above mentioned location inaccuracy, which may put lightning locations into a wrong square. As seen in Figs. 3a and 3b generally, EUCLID has detected much more strokes in the central and southern Europe and in central Scandinavia, and the GLD360 RDE in these areas is 20% – 80%. However, over smaller regions (for example Italian Alps, parts of France, Spain, Belgium, central Poland and southern Sweden) the GLD360 RDE reaches 100% and above indicating much better performance compared to EUCLID network. What is also seen at the edge of the EUCLID coverage areas is, that the boundary between GLD360 and EUCLID RDE values below and above 100% is extremely sharp showing the sudden drop of performance in EUCLID network.

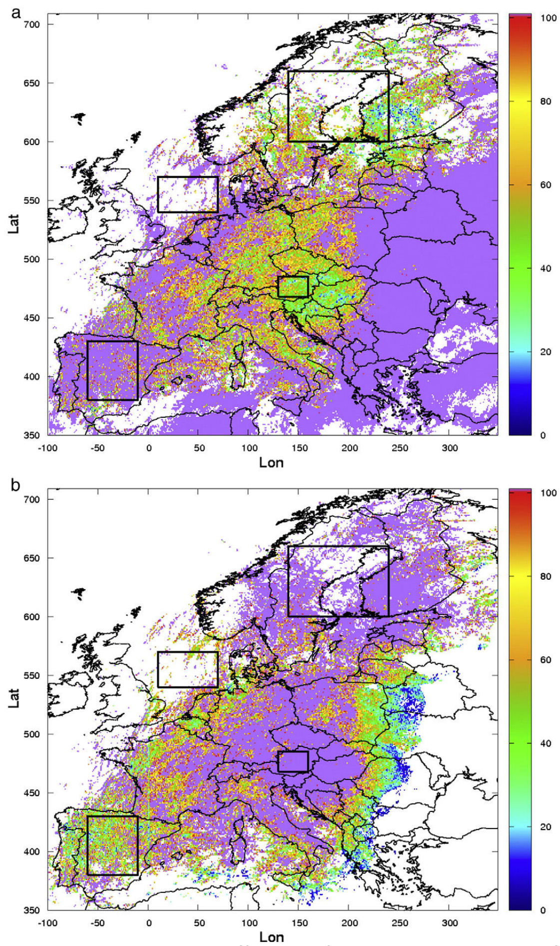

FIG. 3: Relative detection efficiency of a) GLD360 (the number of GLD360 strokes divided by the number of EUCLID CG strokes), and b) EUCLID (the number of EUCLID CG strokes divided by the number of GLD360 strokes), respectively. Study areas named Scandinavia, North Sea, Austria and Spain indicated with black squares from north to south respectively. Purple color indicates values larger than 100%.

Although Figures 1 and 2 do not reveal the absolute performance of either network, the results bring out interesting features regarding both of the networks. Especially important and interesting is to note the areas of decreased performance of EUCLID in some areas even in the central Europe. Our results suggest further and closer examinations in these areas.

To see how the detection efficiency varies according to the peak current, we have calculated the GLD360 RDE for different (integer) peak currents in Austria in July (Fig. 4). The number of GLD360 (blue columns) and EUCLID (red) events per a peak current bin (x-axis) is shown in the left y-axis, and the secondary y-axis shows their ratio (i.e., GLD360 RDE). Figure 4 shows that GLD360 RDE approaches or exceeds 100 % for peak currents above 15 kA. Below 15 kA the RDE drops so that at 10 kA it is about 70%, 60 % at 9 kA, and less than 10 % at 5 kA.

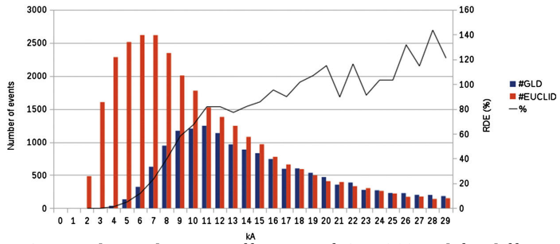

FIG. 4: Relative detection efficiency of GLD360 and for different peak currents in Austria in July 2011.

For a comparison, when looking at the temporally common strokes with peak current above 50 kA, there are a total of 321 EUCLID strokes for which a total of 233 temporal matches are found in the GLD360 data. This gives a GLD360 RDE of 73%. We note, that this value should not be confused with those of the relative peak current comparison discussed earlier in this subsection.

b. Relative location accuracy

After finding the temporally corresponding strokes in Austria, we have calculated their distance between the strike points, and analysed the data into a grid with square size of 0.1 km x 0.1 km, to see how the GLD360 lightning locations are spatially distributed (Fig. 5). The reference lightning location of EUCLID is at the origin of the density plot, and the x- and y-axis values are kilometres in the West-East and South-North directions, respectively. The majority of GLD360 lightning locations have been located within only a few kilometres from the corresponding EUCLID stroke. The error has a tendency to spread slightly more towards the south than north. Also, there is a smaller population of high-density values in the upper right-hand corner of Fig. 5. The feature is similar to that shown by Pohjola et al (2011) in the Scandinavian comparison, but not as dramatic. The reason may be caused by a systematical error in the GLD360 data processing or network design. The feature suggests further studies. The plot of EUCLID peak current versus the GLD360 location difference (not shown) indicates that on average the higher the EUCLID peak current, the smaller the location difference. This seems logical; the higher the peak current, the more sensors will generally detect it, and so the central processor has more information to optimize the location.

c. Daily and diurnal variation

In Fig. 6 we show the day-to-day and average hour-to-hour variation of located lightning in Austria in July. In the daily Fig. 6a the bars indicate the located strokes (left y-axis) of EUCLID, and the red line the daily percentage (right y-axis) of GLD360 strokes. For periods with plenty of lightning (for example, July 5 – 11 and 13 – 14) GLD360 percentage is about 50% to 90%, while for days with only a few strokes, the percentage is generally lower. Because GLD360 is a global network, the large day-to-day variation in performance may be caused by intense storms occurring simultaneously in other parts of the world, which may temporarily decrease the performance because sensors may be saturated with too many signals. The variation may be partly related to processing settings at the GLD360 central processor; especially during weak or modest thunderstorms the rejection ratio of events may increase.

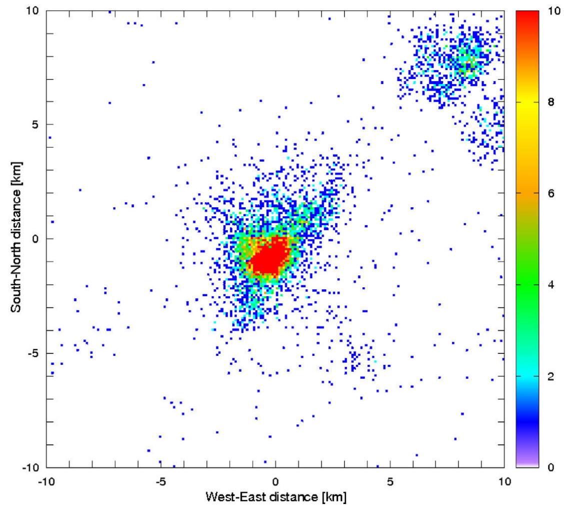

FIG. 5: Relative location accuracy of GLD360 compared to EUCLID in Austria in July 2011. The data set consists of a total of 9 418 temporally common strokes.

The diurnal variation shown in Fig. 6b is similar to both of the networks (blue and red columns); lightning activity increases at about UTC noon (local time is UTC+2 hours), and largest percentage of strokes occur in Austria at 16-17 UTC, after which there is a weakening. The larger percentages for GLD360 in the bins 15-16 and 16-17 UTC may be caused by a day-evening-night sensitivity variation, which is typical for VLF frequency and long range networks (e.g., Thomson 1993; Thomson et al., 2007). However, according to Fig. 6b, this effect is quite small. The green line in Fig. 6b shows the average hourly RDE of GLD360. The values are larger during the night hours, although in some bins (2-3, 8-9, and 9-10 UTC) there is only little data. So, although there is a large variation in the daily performance, the diurnal performance shows similar features than EUCLID.

d. Peak current

The correlation between the absolute peak currents of EUCLID and GLD360 are shown in Fig. 7 for negative and positive temporally common CG strokes. The linear correlation is strong (r = 0.91), and it has the form

$$I_{GLD360} = 1.32 \cdot I_{EUCLID} + 0.70 \qquad (1)$$

There were a total of 166 strokes in which EUCLID had reported negative and GLD360 positive polarity, and 91 strokes in which EUCLID had reported positive and GLD360 negative polarity. Even if the polarity is different, these strokes may still be common because it sometimes happens that a lightning location system determines the polarity opposite than the actual return stroke has, and this may happen more often for a long range system, because the detected lightning signal may have gone through several reflections in the Earth-Ionosphere waveguide. Luckily, the number of these strokes is very small so that they do not have large effect on our results.

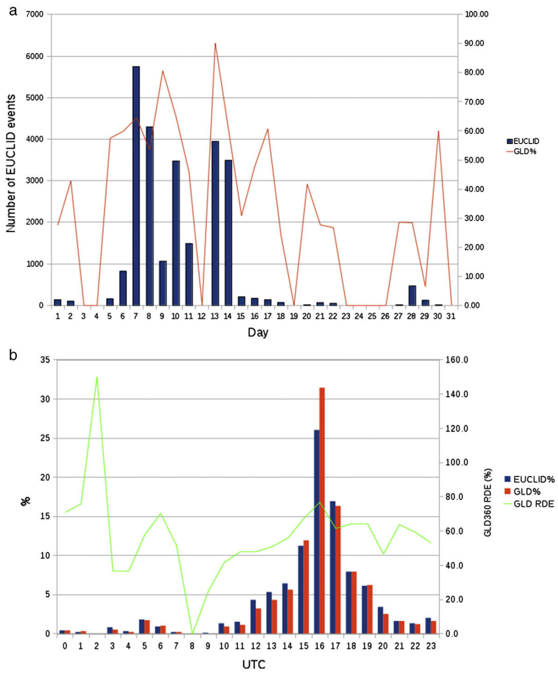

FIG. 6: GLD360 and EUCLID a) day-to-day and b) average hour-to-hour variation of located lightning in Austria in July 2011.

The distributions of peak current for negative and positive strokes in Austria in July are shown in Fig. 8a and 8b. The median (average) peak currents for negative strokes are 10 (12) kA (EUCLID) and 15 (19) kA (GLD360), and 9 (12) kA (EUCLID) and 12 (15) kA (GLD360) for positive strokes. According to the distributions, it is clear that EUCLID detects in Austria more low peak current strokes than GLD360. This is not a surprise because the EUCLID sensor density is high in Austria so that even the weakest discharges can be detected.

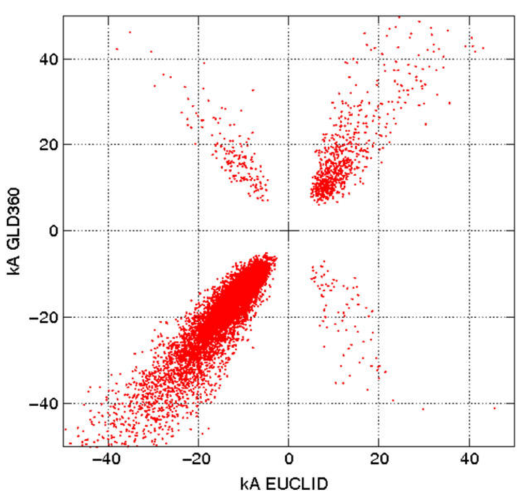

FIG. 7: Correlation between the measured peak currents of EUCLID and GLD360 for negative and positive temporally common strokes in Austria in July 2011.

IV. CONCLUSIONS

A single value for the relative cloud-to-ground stroke detection efficiency cannot be given because of the large regional variation. However, it is clear that EUCLID detects much more, especially weak amplitude strokes in the areas where the sensor density is large.

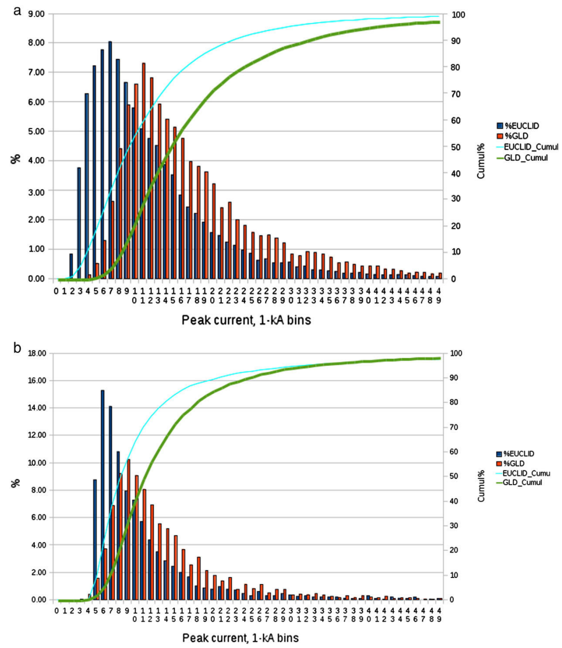

FIG. 8: The distributions of peak current for a) negative and b) positive strokes in Austria in July 2011.

This can also be seen in the stroke peak current distributions. Comparison reveals that the poor performance areas of EUCLID are relatively small, and the GLD360 RDE values below 100% are found only in a portion of central Europe and in Scandinavia. The manufacturer has stated the absolute detection efficiency to be 70% for cloud-to-ground flashes (Demetriades et al., 2010). According to our results, the GLD360 RDE for cloud-to-ground strokes in Austria in July 2011 is 48%. Therefore, the claimed 70%may be a good assumption in Europe, considering that our results here include all subsequent strokes of cloud-to-ground flashes.

The daily RDE of GLD360 in Austria in July has somewhat large variation. The RDE is better during days with plenty of lightning. The reason for this is unclear and needs further examination. The diurnal distribution of GLD360 RDE in Austria is highly similar to that of EUCLID; the largest percentage of located strokes is at 16–17 UTC. The detection efficiency of EUCLID drops rapidly in the network edge. This can be seen as a sharp increase in the GLD360 RDE values to above 100%. The sudden drop in the medium range LLS is maybe even more sudden than have been anticipated before. Also, the EUCLID performance inside its coverage area contains variation. The large GLD360 RDE values over, for example, Italian Alps, Spain and Belgium suggest a drop of EUCLID performance in these areas. This should be investigated in more detail.

The mean and median relative location accuracy (RLA) of GLD360 in Austria, i.e., the distance of GLD360 lightning location compared to a temporally common EUCLID stroke, are 3.8 km and 1.5 km, respectively. These values seem surprisingly good considering that GLD360 is a long range LLS. However, we note that the values should not be considered as absolute ones. For the peak current statistics our results show that median peak currents for negative strokes in Austria in July are 9 kA for EUCLID and 14 kA for GLD360; for positive strokes the values are 8 kA (EUCLID) and 11 kA (GLD360).

This study has shown performance statistics of a long range lightning location system, which has a global coverage. Our results indicate that GLD360 has a great potential to be used in monitoring thunderstorms in real-time with large coverage. As can be suspected, a smaller baseline LLS with many sensors close to each other is capable of detecting also strokes with low peak currents. These are largely missing from the GLD360 data. However, it seems that the efficiency of a smaller baseline system to these weak strokes decreases extremely rapidly when the sensor density gets lower. Furthermore, an important benefit of a long range LLS is that its coverage is not limited to a single country or to its proximity; a long range LLS detects thunderstorm already when they are approaching giving several hour of lead time for severe weather detection (Pohjola et al., 2011). In the future, EUCLID and long range LLS observations will be very useful when combining this information with the European wide radar coverage provided by EUMETNET OPERA project (Huuskonen et al., 2010).

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