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The verification of lightning location accuracy in Finland deduced from lightning strikes to trees

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ABSTRACT

We present a new method to determine the ground truth and accuracy of lightning location systems (LLS), using natural lightning strikes to trees. Observations of strikes to trees are being collected with a Web-based survey tool at the Finnish Meteorological Institute. Since the Finnish thunderstorms tend to have on average a low flash rate, it is often possible to identify from the LLS data unambiguously the stroke that caused damage to a given tree. The coordinates of the tree are then the ground truth for that stroke. The technique has clear advantages over other methods used to determine the ground truth. Instrumented towers and rocket launches measure upward-propagating lightning. Video and audio records, even with triangulation, are rarely capable of high accuracy. We present data for 36 quality-controlled tree strikes in the years 2007–2008. We show that the average inaccuracy of the lightning location network for that period was 600 m. In addition, we show that the 50% confidence ellipse calculated by the lightning location network and used operationally for describing the location accuracy is physically meaningful: half of all the strikes were located within the uncertainty ellipse of the nearest recorded stroke. Using tree strike data thus allows not only the accuracy of the LLS to be estimated but also the reliability of the uncertainty ellipse. To our knowledge, this method has not been attempted before for natural lightning.

1. Introduction

Trees can be analyzed from several different perspectives. First, unlike a tall mast or a rocket-triggered lightning, a tree can be viewed as a natural object to study the lightning attachment process, e.g., how the soil and tree properties, such as height, affect the attachment (Mäkelä et al., 2009). Second, lightning strike to a tree can be viewed from the biological perspective, i.e., what kind of damages are typical to certain tree types, and are the damages more related to the properties of the tree and its surroundings, rather than to the stroke properties (e.g., Anderson and Anderson, 1968). Strikes to trees can also be considered from the standpoint of the hazard they cause to humans and infrastructure (Das et al., 2009; McKechnie and Jandrell, 2008), or as sources of forest fires (Larjavaara et al., 2005). Taylor (1965) attempted to estimate the diameter of a lightning current channel by analyzing the damage occurring to the trees. Finally, as will be discussed in this paper, tree damages can be used to verify the lightning location data.

The present lightning location system (LLS) of the Finnish Meteorological Institute (FMI) has been in operation since 1998 (Tuomi and Mäkelä, 2008a; Mäkelä et al., 2010, 2014). Besides the temporal and spatial information of the located cloud-to-ground (CG) strokes, the system provides also information, e.g., about polarity, multiplicity, and peak current. Furthermore, the system provides estimate about the uncertainty related to the calculated stroke location, often termed as location accuracy. As an LLS is a remote sensing instrument, all reported values are estimates, and not directly measured values. This means, that if the performance of the LLS should be checked or verified, ground truth observations are needed.

Two parameters are often reported to represent the performance of an LLS: detection efficiency (DE) and location accuracy (LA). Location accuracy studies can be arranged into three categories: (1) comparison between two or more different LLS's, (2) comparison of video and LLS observations, and (3) comparison of LLS locations to known strike points. Method 1 (e.g., Rodger et al., 2004; Lay et al., 2004; Pohjola and Mäkelä, 2013) can be done for large data sets but it gives only the information on the relative performance of the compared LLS's (i.e., not against any ground truth). Method 2 is more objective but the comparison can be usually done only for subsequent strokes occurring in the same lightning channel, i.e., strokes having the same ground strike point (Idone et al., 1998; Ballarotti et al., 2006; Biagi et al., 2007; Poelman et al., 2013). This makes possible the inspection of the random location bias of the LLS for subsequent strokes. Method 3 is the most objective method, but it is hampered by the small number of known ground strike points, and usually needs cooperation with, for example, insurance companies.

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There are not many studies addressing the location accuracy of an LLS. One of the most detailed is by Idone et al. (1998) using video recordings and LLS data from the National Lightning Detection Network (NLDN). Besides video recordings for several hundreds of strokes in 1994–1995, the exact ground strike point was known for a total of 11 strokes, yielding a median (mean) location accuracy of 518 m (484 m), which is close to the nominal 500 m median location accuracy reported by the LLS. The magnitude of the error was noted to be larger for strokes with smaller peak current; this is because weaker strokes are usually detected with fewer sensors.

On the subject, several studies have been performed in Austria. Diendorfer et al. (2002) studied the performance of the Austrian Lightning Detection and Information System (ALDIS) with tower measurements. The median accuracy for 285 strokes was 450 m. However, they noticed a systematic shift of about 500 m to the northeast, whose cause was unclear; if correcting according to the bias, the accuracy would have been about 200 m. Later, Schulz et al. (2012a, 2012b) found the LA to have improved to a median value of 124 m with the aid of sensor and network updates. A recent study in Austria (Diendorfer et al., 2014) included in the verification also the analysis and interpretation of the location uncertainty ellipse. They found out a huge improvement in the LA from the period 2000–2013 to 2010–2013, and that in the 2010–2013 data set, more than 80% of the strokes to the measurement tower were actually within the 50% probability confidence error ellipse of the located stroke; for the 2000–2013 period, only 50% of strokes were within the ellipse.

For rocket-triggered lightning in Florida, Jerauld et al. (2005) show the median location accuracy of the NLDN to be 270 m in 2001 (17 strokes), 830 m in 2002 (44 strokes), and 450 m in 2003 (34 strokes); the 2001–2003 median was 600 m. The differences between the years are suspected to be due to the sample sizes. According to Lafkovici et al. (2008), the NALDN (North American Lightning Detection Network, i.e., NLDN plus Canadian sensors) median (mean) location accuracy based on a total of 38 strokes to the CN Tower in Toronto was 358 m (395 m). In Japan, Shinjo et al. (1999) studied lightning related faults to transmission lines (250 strokes). Their median location error was found to be about 2 km. For the LINET (LIghtning NETwork) covering large areas of Europe, Betz et al. (2007, 2008) showed that the location accuracy verified against lightning strokes to known strike points at ground (e.g., TV-masts) is approximately 100 m.

Recently, Poelman et al. (2013) investigated the performance of several LLS's over Belgium by comparing the LLS data against high-speed camera and electric field measurements. Using the method described by Biagi et al. (2007), for multistroke CG flashes with subsequent strokes occurring in the same channel, it is possible to determine the upper limit for the LA. In the study of Poelman et al. (2013), the data set consisted of a total of 8 multistroke CG flashes.

The above-mentioned studies indicate the variety of ways for verifying the LLS performance. Unfortunately, none of these are perfect. First, the ground truth data sets in question are always merely a small sample from the total absolute number of strokes collected from a small area. Second, most of the LA verifications have been dealing with non-natural objects, namely, towers or masts and rockets for which the stroke tends to be upwardly propagated, i.e., they are a special case of lightning. Further, in the case of triggered lightning, the first stroke is missing completely. Thus, it is possible that the results from these experiments may not be completely generalizable for *natural* lightning flashes to the ground. However, whether the lightning-type (i.e., natural vs. triggered) has an effect for the location accuracy, is a topic for another study.

We present a verification method that involves only natural lightning attachment: lightning to trees. Preliminary results have been published regarding the lightning attachment to trees, presenting also the method for collecting the data set (Mäkelä et al., 2009).

As discussed by Fernando et al. (2009), trees are not good conductors and therefore do not provide a good path for the lightning to travel; however, they are often the highest objects in their vicinity and in addition have sharp tips which favor the initiation of upward leaders. Particularly in a highly forested country like Finland, trees are in fact the most likely object to be struck.

The attachment of lightning to trees is not well understood (Fernando et al., 2009). It is known that a strike to a tree can cause a variety of effects, ranging from no effect to bark-loss damage (vertical strips of bark are torn off) to wood-loss damage (inner wood material is ejected) to complete annihilation of the tree (see e.g., Taylor, 1964a, 1977; Orville, 1968; Mäkelä et al., 2009). Mäkelä et al. (2009) showed that the amount of damage is inversely correlated with rainfall; that is, a wet tree surface has higher conductivity than dry one and therefore the flash is able to proceed along the trunk rather than entering deeply inside the tree. It is currently not known whether the fine structure of the damage has any effect on the attachment process. In this study, the effects on the tree have been left out of the analysis, and the tree is simply considered to be the point of attachment.

In this study, lightning location data are analyzed against a total of 36 lightning strikes to trees on measurement campaigns during summers 2007–2008. The analysis is divided into two categories: (i) analysis of the absolute location accuracy and (ii) reliability analysis of the location uncertainty reported by the LLS. From a total of 73 cases, for 36 cases the probable corresponding stroke has been found; the remaining 37 cases are ambiguous, i.e., there have been several candidates in the lightning location data (this is often the case if the damage time is not known exactly). The data and acquisition methods are discussed in Section 2 and the results in Section 3. The conclusions are presented in Section 4.

2. Data and analysis methods

2.1. Lightning data

The FMI LLS is part of the NORDLIS (NORDic Lightning Information System) cooperative network depicted in Fig. 1: the individual national central processors in Norway, Sweden, and Finland receive the lightning data from all of the sensors from the collaborating countries, process the data, and provide to the end users. Although the sensors are not identical, they are from the same manufacturer (Vaisala Inc.), which makes the data exchange possible. More about the sensor operation can be found in Cummins et al. (1998) and Cummins and Murphy (2009). The characteristics and the performance of the NORDLIS network for first strokes are estimated to be about 95% in Finland (Tuomi and Mäkelä, 2008b; Mäkelä et al., 2010). The network has improved considerably since 2008, but here we refer to the status of 2007–2008.

Two kinds of methods are used to determine the lightning strike point: direction finding (DF) and time of arrival (TOA). Both information are measured at the sensors and analyzed at the central processor to find the strike point. If at least two sensors have reported the azimuth of an event, the strike point can be calculated. In the case with more than two azimuths, the most probable (optimized) location is achieved by minimizing a χ^2 function (Cummins et al., 1993). The TOA information is used along with the azimuths to calculate range circles, which further adjust the location. Central processor uses all available sensor information and their deviation from each other to calculate an optimized location, which is reported as the most probable strike point. The uncertainty of the calculated location is expressed as a 2-dimensional confidence ellipse inside which the location is with 50% probability. Also, other probability ellipses can be used (e.g., 99%). The semimajor axis of the ellipse is reported to represent the accuracy, and the direction of the semimajor axis is oriented towards the largest uncertainty. Because the semimajor axis of the 50% probability ellipse is used operationally to quantify the uncertainty of the located stroke, it is useful to study its operational applicability.

There is always some uncertainty in the calculated strike location, and the magnitude depends on several factors:

— Azimuth errors, which can be either systematic or random. Systematic errors are constant for a certain sensor site, and these errors can be corrected with statistical methods by analyzing large data set and