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EUCLID Located Strokes to the Gaisberg Tower – Accuracy of Location and its assigned Confidence Ellipse

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***Abstract*— In this paper we analyze LLS located discharges (return strokes and superimposed ICC pulses) to the Gaisberg Tower (GBT) in terms of their location accuracy and assigned confidence ellipse (often also called error-ellipse). From 2000 to 2013 EUCLID (ALDIS) located 681 return strokes and 779 ICC pulses in upward initiated flashes from the GBT. We found that for 49 % of the return strokes and for 48 % of the ICC pulses the true tower location was inside the 50% confidence ellipse assigned by the LLS to the LLS estimated striking point. After implementation of several improvements in the location algorithm median location accuracy for strokes to the GBT is in the range of 100 m. For the most recent years (GBT data since 2010) we observe a significantly higher than expected percentage of GBT location being included in the assigned confidence ellipse. Most likely this is a result of the discretization of the length of the semi-major axis of confidence ellipse in 100 m steps, which is in the same range as the median location accuracy.**

***Keywords*— lightning, confidence ellipse, location accuracy**

I. Introduction

Lightning location systems (LLS) provide coordinates for the most probable location of a lightning strike determined from reports of a number of sensors. These sensors report time of arrival and angle of incidence of the electromagnetic wave radiated by the highly transient current in the lightning channel. Those sensor reported times and angles are of limited accuracy as any other measurements of a physical property.

In principle, sensor reports are subject to both random and systematic errors where the magnitude of these errors may depend on the particular sensor site, on propagation paths between sensor and source of the electromagnetic wave, etc. Any inaccuracies of the sensor reported angles and times result in a misplacement of the LLS estimated strike position from the real strike position, the so-called location error of a LLS.

A first statistical approach of the problem of locating an object of unknown position, on which reports of angle of incidence are taken from two or more stations (direction finders) whose positions are known, was done in by Stansfield in [1]. It was assumed that no systematic error is present in the data, and that the errors in the reported angles from each direction finder can be adequately described by a Gaussian, or "normal," error probability distribution with zero mean as given in Eq.(1). The probability that a given sensor will report an angle between θ+ψ and θ+ψ+dψ is

$$P(\psi) \cdot d\psi = \frac{1}{\sigma_{\psi} \cdot \sqrt{2\pi}} \cdot e^{-\frac{\psi^2}{2\sigma_{\psi}^2}} \cdot d\psi \qquad (1)$$

where θ is the true angle to the lightning strike position and ψ is the error in the sensor reported angle. The same applies to the error distribution of the sensor reported times.

With this we can calculate a 50 percent confidence (error) ellipse, under the assumption that the distributions of angle and time errors are Gaussian. A detailed discussions of these models, along with assumptions used, are given by [1], [2].

The median (50%) confidence ellipse circumscribes a region centered on the computed (optimum) location, within which there is a 50% probability that the stroke occurred. The describing parameters of the confidence ellipse (length of semi-major axis, eccentricity and orientation) are provided by the LLS for each stroke. Confidence ellipse is determined by the number and relative position of sensors contributing to a given stroke location as well as by the standard deviation of the time and angle measurements for each of the used sensors.

Although theoretical models can be used to evaluate the performance characteristics of a LLS (location errors, accuracy of peak current estimates, as well as detection efficiency), ultimately ground-truth data are required to verify the true performance of a LLS network. Such data should include the measured time, position, and peak current of lightning events in a specific region. The time, position, and peak current measurements can be obtained using instrumented towers [3] or rocket triggered lightning [4]

II. DATA

Direct lightning strikes to a 100 m high radio tower at Gaisberg, a mountain next to the City of Salzburg in Austria, are measured since 1998. Gaisberg Tower (GBT) coordinates are 47.805 N and 13.112 E, and the mountain top is 1287 m above sea level, which is about 800 m above the surrounding terrain of the city of Salzburg. For a detailed description of the experimental setup and characteristics of the measured lightning currents see [3], [5], [6].

Some of the upward initiated flashes from the GBT are located by EUCLID LLS system, the European Cooperation for Lightning Detection. EUCLID is a multinational cooperation of LLS operators and employs currently about 150 sensors, most of them are providing angle and time information.

For the analysis presented in this paper we are using return strokes and ICC-pulses measured in upward initiated negative lightning from the GBT in the period from 2000 – 2013. On average about 65 flashes are recorded at GBT per year with annual values ranging from 10 to about 100 (see Fig. 1). During this time period EUCLID has located 779 return strokes and 681 ICC pulses in flashes upward initiated from the GBT.

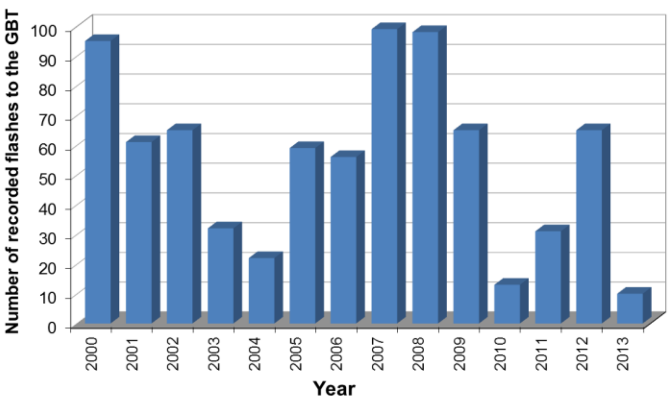

Fig. 1. Annual number of flashes to the GBT including all types of discharges (positive discharges and negative ICC_{Only}, ICC_P, and ICC_{RS} type discharges as defined in [3]).

III. RESULTS

For all strokes to the GBT located by EUCLID since 2000 we checked if the actual GBT position is within the assigned confidence ellipse or not. This allows us to validate the 50% probability value for the confidence ellipses assigned to each of the estimated strike positions. By theory in 50% of the events the true tower location, which is the true striking position, should be within the area of the 50% confidence ellipse. We have to note that the maximum resolution of length of the semi-major axis is 100 meters. Length of semi-major axis together with axis ratio and inclination of semi-major axis are the three parameters provided by the central processor (LP2000, TLP) for each located stroke to describe the assigned confidence ellipse.

Fig. 2 shows an example of a flash to the GBT with 3 located strokes and their assigned confidence ellipses. For 2 out of the 3 located strokes the true tower location was within the confidence ellipse (orange lines) and for one stroke the tower location was outside the confidence ellipse (purple line).

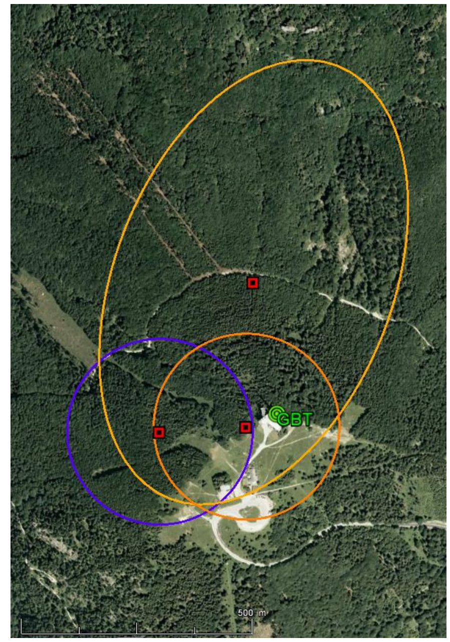

Fig. 2. ALDIS locations of 3 strokes in GBT Flash #783 (05/07/2010 08:13:16 UTC). Two confidence ellipses include the GBT site (orange line) and one ellipse does not (purple line).

The confidence ellipse can be calculated for any desired probability level other than 50% by scaling the semi-major and semi-minor axes of the 50% confidence ellipse according to Eq.(2).

$$SC = \frac{\sqrt{-2 \cdot \ln(1-P)}}{1.177} \tag{2}$$

where *SC* is the scaling factor and *P* is the desired probability given as a fraction rather than a percentage (e.g. 0.3 for 30%) [7]. For more frequently used probabilities of 90% and 99% the scaling factor *SC* is 1.82 and 2.57, respectively.

In order to evaluate the confidence ellipse for different probabilities we have done the described analyses for probability values 10%, 20%, 30%, ….. 80%, 90%, and 99%. Results of this analysis for located return strokes are shown in Fig. 3. The red line in the figure indicates the perfect match with the model assumptions.

Interestingly there is almost perfect match at the 50% confidence value (49% of the assigned ellipses included the GBT location). For probabilities higher than 50% the observations at GBT are slightly below the model estimates, for probabilities smaller than 50% the GBT results are better than predicted.

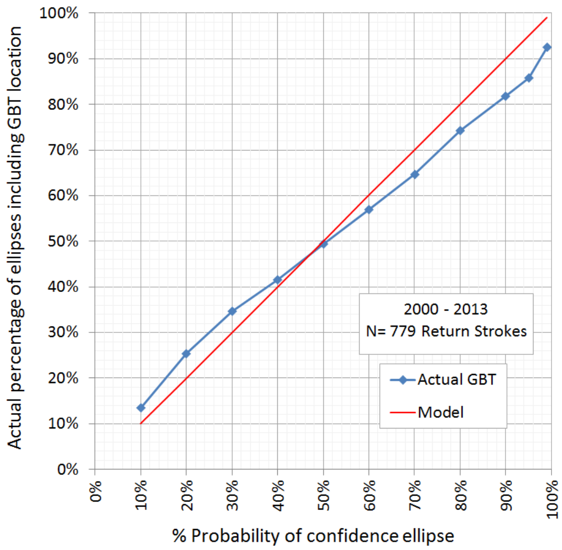

Fig. 3. Percentage of located return strokes assigned confidence ellipses that include the true GBT location.

Sometimes upward initiated lightning from high objects show strongly inclined or almost horizontal channel branches at low altitudes. Superimposed ICC pulses with short current risetimes are the result of return strokes attaching to an existing channel branch at some height above the tower top [8]. In this case the LLS may actually locate the merging point of the return stroke to the existing channel branch rather than the tower location and consequently we are expecting a larger location error. In order to test this hypotheses we have evaluate also the validity of the confidence ellipse for the 681 located ICC pulses. Results shown in Fig. 4 are very similar to Fig. 3 and therefore no difference in the location accuracy of returns strokes and ICC pulses is indicated.

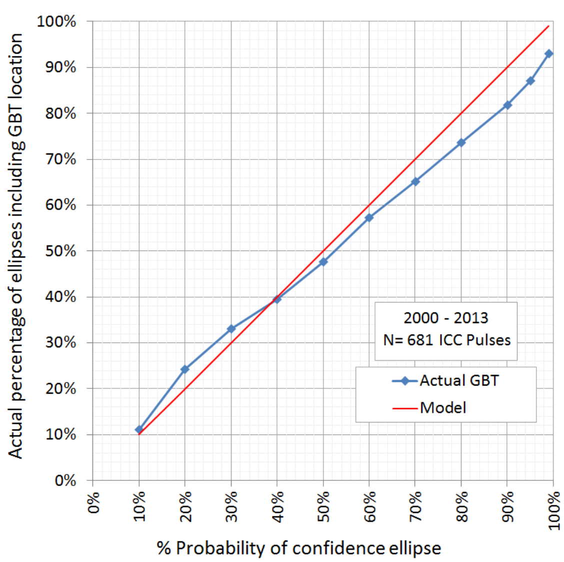

Fig. 4. Percentage of located ICC-pulses assigned confidence ellipses that include the true GBT location.

We have to note that from 2000 to 2008 for all sensors the same default value of 1.5 µs was set as the time standard deviation of the sensor measurements in the configuration files of the lightning processor. A number of changes have been made in recent years affecting the standard deviations of time and angle measurements and therefore the accuracy of the LLS. Reduced standard deviations also affect the dimensions of the estimated error ellipses. In 07/2011 sensor based onset time correction [9] was implemented at all the EUCLID LS700X type sensors and since 2009 the random errors for time are determined for each sensor and set individually instead of using a default value. In November 2012 propagation correction was implemented the first time and random error values of sensors were reviewed.

Basically parameters needed for the determination of the confidence ellipse (random errors for sensor reported times and angles) are derived from historical sensor data by the following procedure.

The time random error of each sensor is determined from a preselected set of located strokes fulfilling following criteria;

- more than 4 sensors (including the sensor under investigation) participated in location of the stroke,
- semi major axis of the confidence ellipse is less than 0.4 km, and
- Chi-square value, which is a measure of how well sensor measurements agreed, is less than 2.

For time differences (difference between LLS estimated stroke time and sensor reported time) RMS values are calculated to obtain a value for the time error. RMS value is used instead of the standard deviation in order to include any residual systematic error in the random error.

The angle random errors are determined as part of the site error correction, which needs to be done for any sensor on a more or less regular base for all sensors in a network. As the angle random error is strongly dependent on the signal amplitude, the angle random error used for error ellipse calculation is not a constant but is given as an approximated function of signal amplitude. The parameters of this function are determined during the site error correction.

In 2013, after implementation of all above mentioned improvements at the LS700x type sensors and in the TLP lightning processor, most of the values of time errors of sensors are in the range from 0.2 µs to 1 µs for LS700x and IMPACT type sensors. In the currently used EUCLID configuration we determined for the 10 sensors closest to the GBT, all of them are LS700x type sensors, a median time error of 0.35 µs, which is lower than the default value of 1.5 µs and reflects also the improvements in location accuracy achieved in recent years. In order to test if smaller probability ellipses, as a result of improved location accuracy, are still including the GBT location we have performed the same analysis as shown in Fig. 3 and Fig. 4, respectively, for the time period 2009 to 2013. The results for this more recent time period are shown in Fig. 5 and Fig. 6 for located return strokes and ICC pulses, respectively.

For both types of discharges (return strokes as well as ICC pulses) we obtain a much higher than predicted percentage of events that include the GBT location in the corresponding confidence ellipse. As an example, for the 103 located return strokes more than 80% of assigned 50%-confidence ellipses included the GBT location. We have to note, that this is a preliminary result as it covers a period when several changes were made and the number of detected lightning events at the GBT was relatively low. The observed discrepancies to Fig. 3 and Fig. 4 are likely caused by the discretization of the error ellipse dimensions in steps of 100 m. This step size seems to be too large in view of today's achieved location accuracies in the same range of 100 m. In the future a smaller discretization of the error ellipse dimensions should be provided by the TLP.

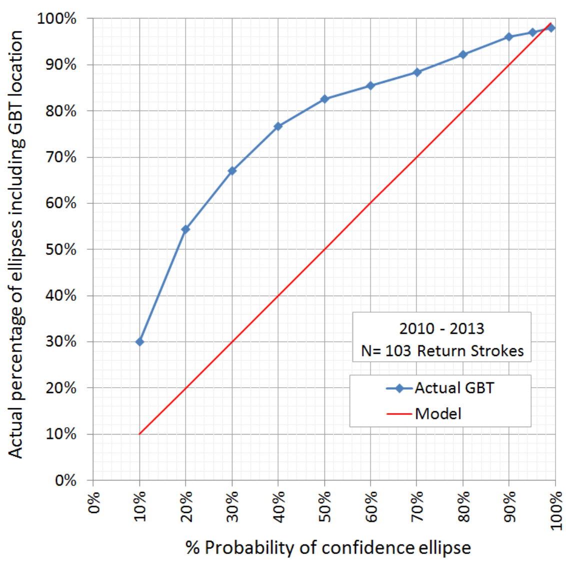

Fig. 5. Percentage of located return strokes assigned confidence ellipses that include the true GBT location for the period 2010 –2013.

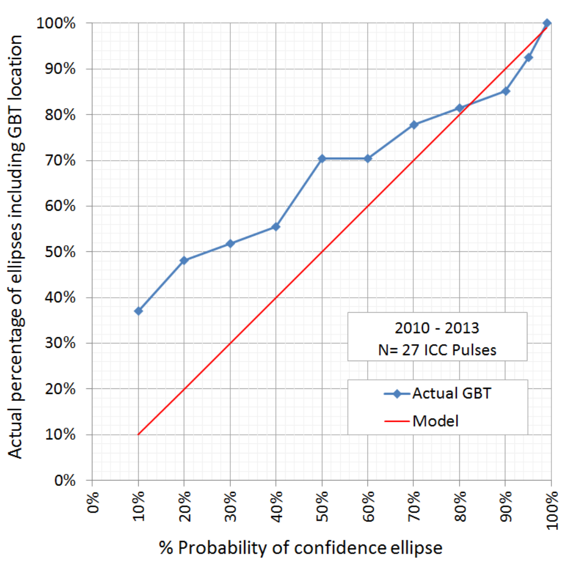

Fig. 6. Percentage of located ICC pulses assigned confidence ellipses that include the true GBT location for the period 2010 –2013.

An example of a recently recorded flash at GBT with 8 return strokes located very accurately by EUCLID is shown in Fig. 7. All stoke locations are all within 100 meters of the true GBT location and 7 of the 8 confidence ellipses are circles (excentricity is 1) of radius 100 m, which is the minimum reportable length of the 50% semi-major axis.

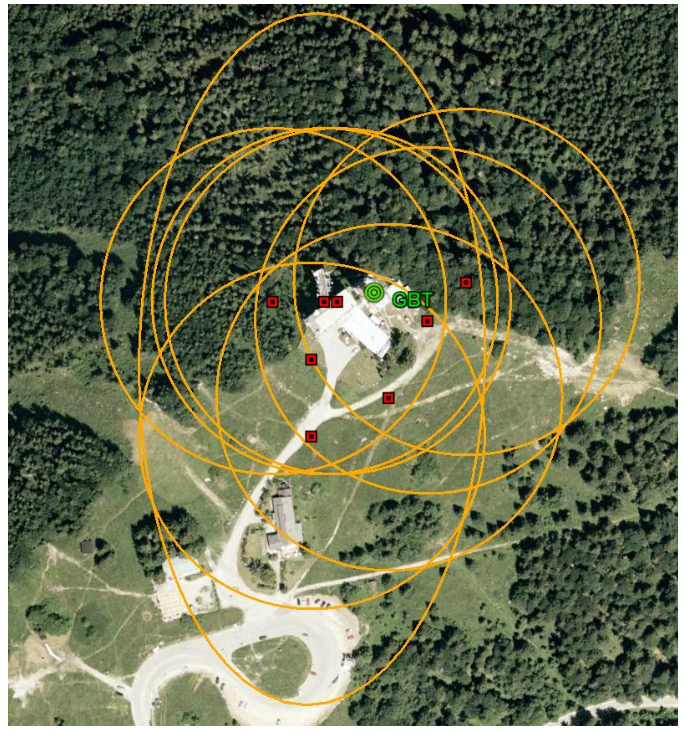

Fig. 7. Locations of 8 return strokes in GBT flash #885 from 02-06-2013 at 05:20:42 (UTC) with their assigned 50% confidence ellipse.

IV. DISCUSSION

A confidence ellipse (often also called error ellipse) is assigned by LLS to each located lightning stroke. The length of the semi-major axis of the 50% confidence ellipse is used as a measure to describe the median location accuracy of a LLS. The confidence ellipse is also used in different applications to support decisions whether a located stroke has hit a certain structure or not (e.g. real time correlation of lightning and power line outages [10]).

Several upgrades were made in the EUCLID network since 2007. Sensor based onset time correction was implemented in LS700x type sensors, which more accurately determines the arrival time of electromagnetic waveforms from lightning events at a sensor. Propagation correction accounting for field propagation across uneven terrain, varying ground conductivity, and the accurate speed of electromagnetic waves propagating over ground was also implemented. This has led to an improvement in the median location accuracy (given by the median of semi-major axis) of EUCLID to about 100 m in the interior of the network as shown in Fig. 8. These results also agree well with recent studies of location accuracy at GBT [11] and in video studies in different regions of Austria [12].

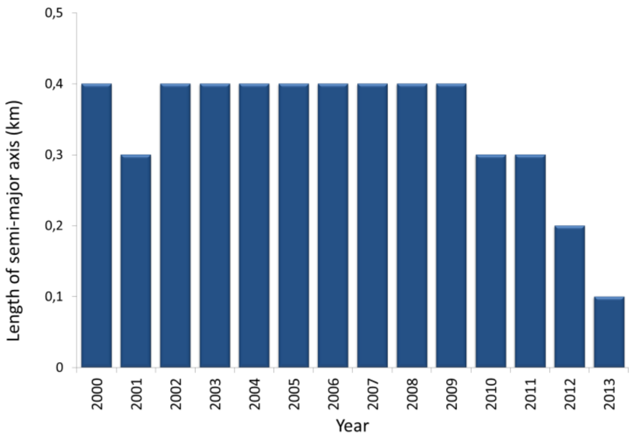

Fig. 8. Median length of semi-major axis of 50% confidence ellipse for EUCLID located negative strokes in a 100 km radius circular area in Austria centered 14.0°E/47.5°N (Calculation is based on about 100.000 Strokes per year)

Validity of using the dimension of the confidence ellipse as a measure to describe the median location error of the LLS is confirmed by the GBT data analyzed in this paper. The ground truth data analysis shows excellent agreement between the error ellipses assigned to located strokes and their actual location error.

As the median location error has reduced from about 350 m to about 100 m the discretization of the error ellipse in steps of 100 m results in larger disagreements in the evaluation as shown in Fig. 5 and Fig. 6.

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