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on Lightning and Power systems

France

Status of lightning detection

Performances and limitations of existing systems

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SUMMARY

This paper is intended to be an introduction to the capabilities of lightning detection networks and to provide guidelines to understand the type and quality of data that can be expected from those measurement systems. It first introduces the principle of lightning detection then covers the performances and limitations of the various technologies in use. A review of the knowledge on the lightning phenomenon gained through the analysis of the data provided by those networks is then presented. Typical values for lightning parameters are finally reviewed.

This paper is not the result of a new scientific study, but rather a synthesis of the material that can be found in recent scientific literature.

KEYWORDS

Lightning, Lightning Location Systems, Performance Evaluation, Validation methodologies, Lightning parameters.

CITATIONS

This paper is mostly based on existing literature (see bibliography). In particular it is extensively using work done by Dr. Ken Cummins, Dr. Wolfgang Schulz and Graeme Anderson and I want to thank them for their contribution and authorization to quote their publications.

A) Principle of lightning detection

The lightning phenomenon is, basically, a sequence of current discharges that are established rapidly in the atmosphere and produce so much heat that the air channel will explode, emitting light and sound. A “Cloud to Ground Flash” is composed of a least one first stroke to the ground that exhibits a very high peak current, and eventually followed by subsequent strokes with lower peak currents. Each lightning flash generates various signals in the audio, visual and electro-magnetic spectrums.

Lightning detection is based on the measure of one or more of those signals with ad-hoc equipment. It can be the ear of a human observer, the plate of an electric field antenna, the sensors in a camera or a radio electric receiver such as an FM radio or a sensor used in a detection network.

It is rather easy to obtain traces of lightning events, through burnt trees, far away thunder or static in an FM radio. But it's much more difficult to actually measure all the parameters of all the flashes. The main reasons for this are:

- Lightning flash are discrete and rare events (typ. 1 flash per km² per year in France)
- Lightning strikes in different place. There is a popular saying that “lightning never strikes the same place twice”, not to be trusted
- Lightning flashes occurs at random moments
- Each lightning flash is a different event as can be seen in high speed videos, with a different path of current in the air, various attachment point and different time parameters,
- The current flowing to ground varies from a few kilo amperes to some hundreds kilo amperes, positive or negative

The main challenge of lightning detection is to resolve as many parameters as possible, at least the lightning location (latitude and longitude) and time stamp. The measure of the lightning current as well as other parameter such as rise time, width, polarity, continuing current ... may also be of interest.

For the above mentioned reasons, a complete measure of lightning events cannot be achieved with a single instrument and a network of sensor is deployed.

Acoustic detection, mostly human based, is limited by the sound wave propagation to few tenths kilometers and only provides timing and direction with some level of confidence. However acoustic and infra-sound system has been developed.

Electro static detection, done with electrostatic field measurement by fast fields antennae or field mills, is limited to some tenths of kilometers and only provides information on the timing and signal amplitude of the lightning events.

Optical detection can be performed “at ground level” with strike cameras or high speed models. The former will give a time integrated view of the discharge showing its branching to ground. The later will provide a very detailed view of the discharge with high time resolution. It also helps identifying ground contact points and classifying intra cloud versus cloud to ground discharges. Cameras can be manually operated or automated and remotely controlled, but both setups are limited in their field of view and do not measure distance along their focus line.

Optical detection can also be performed “from above” with lightning imagers onboard non- satellites. Non-geostationary satellites such as LIS and OTD require collecting data for many years in order to provide a sufficient coverage of any part of the globe, but they have been in operation for many years. Geostationary lightning imagers require more sensitive equipment due to their higher distance from ground; such equipment will be launched in the near future in Europe and the USA. In both case the measuring device looks for transient events produced in the visible (or electromagnetic) spectrum by the lightning discharges in the atmosphere. They measure predominantly intra-cloud discharges and resolve their timing and position.

Electromagnetic detection is today the most used, most capable solution for lightning localization. Although some stand-alone equipment is available, it does not provide such a complete set of measure as networked solution. In those Lightning Detection Networks a set of sensors is connected to a central computer, and each lightning flash that is detected by several sensors can be located and measured. As the frequency spectrum of the lightning event is very large, different kind of antennae can be used.

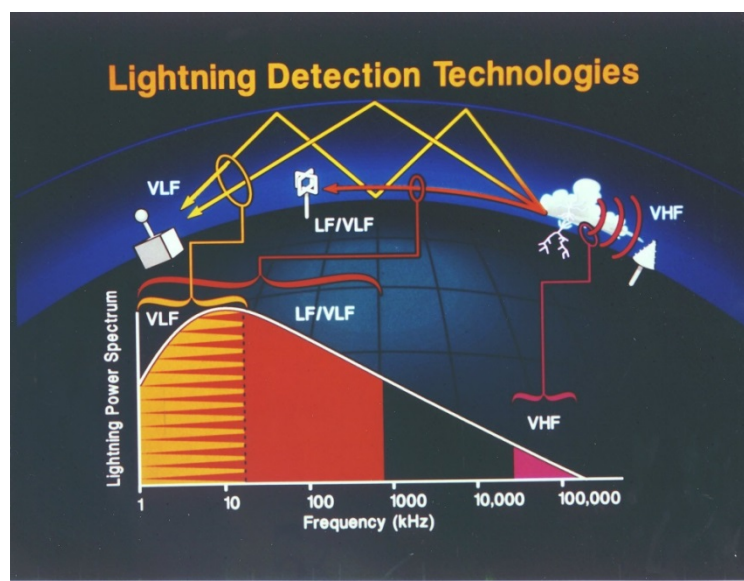


Fig. 1 Electro-magnetic frequency spectrum

B) Performances and limitations of lightning detection networks

VHF detection allows capturing the electrical breakdowns that occur within a cloud and trace the steps taken by a current discharge. Time and angle can be obtained from each sensor allowing triangulation or differential time of arrival methods to compute the location of the sources. If enough sensors are used the altitude can also be computed. As VHF detection is limited by optical line of sight, VHF detection networks are mostly used over small areas (Typ. 200x200 km²); they provide a very detailed information on intra cloud discharge and on the storm dynamic. They are used mostly for research and very high impact areas (space launcher facilities, large airports ...)

In addition to the line of sight limitation that imposes small baseline between sensors (max 150 km), an additional constraint is the need for “clean” sites with no background noise in the sensor frequency range. Ad-hoc filtering is required to get rid of the noise and allow for the use of low thresholds; and high speed data processing is required. Depending on the technology in use, the cost of the antenna

can be high thus limit the number of antennae to be deployed which leads to reduced coverage, low resolution and 2D only capability. A VHF network detects electrical breakdowns in the air, but cannot measure the current flowing in a discharge.

Sample products using VHF detection are the SAFIR system originally designed by Dimension, the TLS200, its digitalized evolution proposed by Vaisala and the Lightning Mapping Array developed at New Mexico Tech.

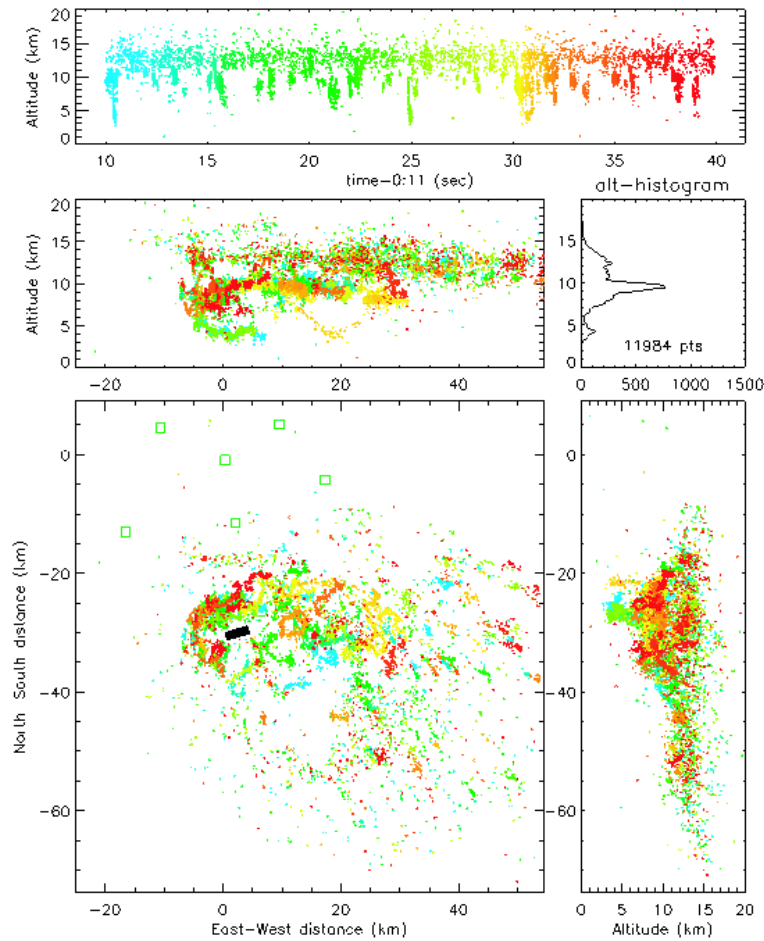


Fig.2 Sample flash as seen by a VHF network (Lightning Mapper Array using time of arrival)

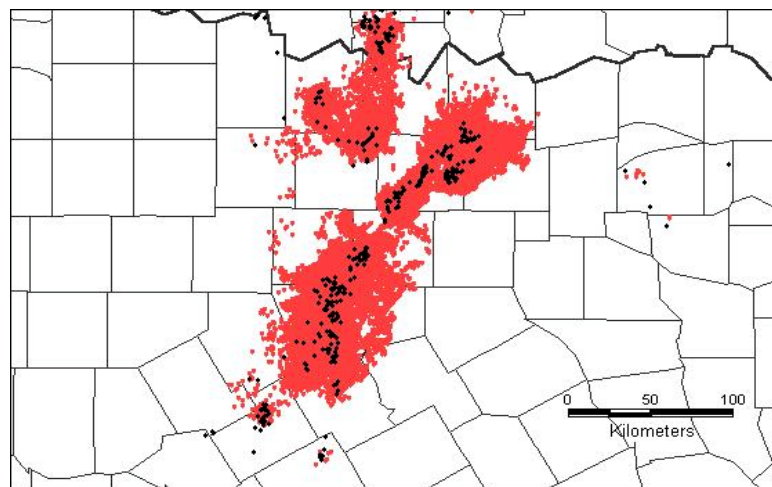


Fig. 3 Lightning sources (red) detected by an interferometric VHF network, and LF detected Cloud to Ground flashes (black) during 5 minutes in Texas

LF detection

LF detection works in a frequency range (typ. 30 to 300 kHz) where the electromagnetic signals propagate as a ground wave to large distances (typ. up to 1000 km) without being overly affected by the terrain. The technology for sensors and data processing algorithm is fairly simple, resulting in affordable solutions. This allows for example to cover an area of 1 million km² with 16 sensors and provide a very good and homogeneous detection efficiency if the goal is to detect cloud-to-ground flashes or strokes. The distance between sensors (the baseline) will vary from 200 to 400 km depending on the sensor sensitivity and required performance level. The sensors can measure key parameters such as an angle of incidence, time of arrival and signal strength or record a full waveform; they transmit their data to a central processor that runs the location algorithm. Those types of networks detect both strokes to ground and intra-clouds with high levels of detection efficiency (Typ. 90% for CGs and 50% for ICs), they locate the events with a resolution in hundreds of meters. The measure of the electromagnetic field at an antenna allows, once the distance to the source is known, to compute the peak current of the discharge; it is then possible to apply propagation model in order to estimate the actual peak current in the discharge. The accuracy for this current amplitude is in the 10-20% range. LF lightning detection networks are typically used on country or continental scale and provide a very operational information.

The limitations of LF based networks are shown by the benefits of VLF and VHF solutions: limited range of detection and detection of intra-cloud events limited to vertical discharges carrying enough current.

Different manufacturers provide LF based solutions for lightning localization. Vaisala combines time and angle measures in their solution, they use threshold values to discriminate IC and CGs. The NLDN is a 100+ sensor network covering the USA and operated by Vaisala. TOA systems, as its name implies, propose a time of arrival only solution. Earth Network has sensors operating in an extended frequency range to detect more intra cloud events, they use timing information for localization and record waveforms to provide discrimination and current measurement. They have a 700 sensor network covering the USA. LINET uses measurement techniques and filtering mechanisms that allow for very low thresholds at the sensors, so that even weak lightning strokes (< 5 kA) can be detected and located. With short enough baselines, the network can provide altitude information for intra cloud events. Blitzortung is a world-wide non-commercial low-cost community-based Time-of-Arrival lightning detection and lightning location network. They managed to deploy a large quantity of inexpensive sensors operated by their members in many parts of the world. Lightning data is available for the members on a non-commercial basis, and on some public web sites.

VLF detection takes benefit of the very long signal propagation in the Schuman resonance band, between the ground and ionosphere. Events located thousands of kilometers away can be detected by a sensor. Most systems use time of arrival location algorithms. Using some tens of sensors it is possible to obtain a worldwide coverage.

Long range detection performed in VLF will be limited to the most energetic lightning events; low current flashes as well as intra-cloud discharges will be hardly detected. The variation in the altitude of the ionosphere between day and night changes the distance travelled by the electromagnetic signal, causing error in the location. The overall detection efficiency of VLF system is generally low compared to LF systems, somewhere between 20% and 70%. Depending on the installed sensor base, and due to the difficulty to install sensors in the middle of oceans, there may be a strong spatial variation of the detection efficiency.

VLF lightning detection network are used at continental or world wide scale and provide an overview of the thunderstorm activity.

Sample systems using VLF detection are the ZEUS network operated by the University of Athena, the ATDnet developed by the Met Office in the UK and mostly centered on Europe, the WWLLN created by the University of Washington and the GLD360 developed and operated by Vaisala.

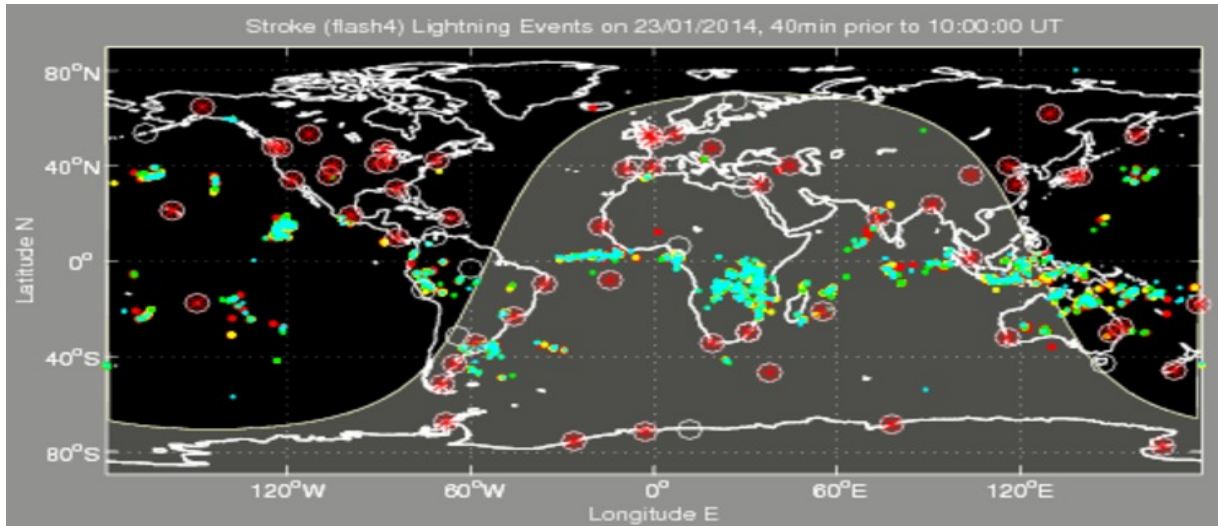


Fig. 4 The sensors of the WWLLN network and some lightning activity (live snapshot from WWLLN website)

It is possible to mix different detection technologies in order to gain benefit from various systems. For example, Earth Network combines the data of its own LF network with the WWLLN data set, and Vaisala offers to their LF network owners the possibility to combine VLF data of the GLD360 with the local LF data set. It is also possible to superimpose LF and VHF data, but merging them is much more problematic as they belong to different physical phenomenon.

Operational performance

The lightning detection technology will set the capabilities of a given network in terms of coverage, collected data, accuracy and delay. But the real world capability of a production system is also determined by its operational condition. For a lightning detection network the key parameters to be taken in account are:

- The sensor uptime. As the lightning data is mostly needed in real time, any sensor or communication failure has a non-recoverable impact on the quality of the delivery. The reliability of the sensor as well as the availability of the telecommunication links are key parameters, but the organization of the maintenance and self-redundancy of the detection network are also essential.
- The timely delivery of data. The nowcasting applications of lightning data for safety and asset management require that the information be delivered without delay to the end-users. Reliable communication links, redundant processing centers and end to end supervision are required in the implementation of a solution.
- It is also required that the system is able to provide optimized data in real time without the need of a reprocessing or post-processing stage.
- An homogeneous coverage is needed for all the region of interest. Areas of lower detection efficiency will provide a bias in the information that is misleading.

- A long term data base is required to perform any kind of statistics or climatology. Managing the sensor meta-data, being able to trace all the configuration changes and to replay the data are essential steps to provide useful long term data sets.
- A fully calibrated network requires a sufficient amount of data and the proper data analysis. For example the redundant information provided by the simultaneous detection of lightning strokes by many sensors will allow computing correction parameters for various phenomenon such as site errors and propagation delays due to the topology. Those parameters can be introduced in the data concentrator to produce better locations.

C) Validation techniques for lightning detection networks

As lightning is made of different, rare, and random events it is difficult to validate a lightning measurement system, and probably impossible to fully calibrate all the parameters provided by one network. Furthermore, each detection system being different in coverage, terrain, number of sensors; the characteristics of one network do not apply readily to another one. And lastly thunderstorms themselves are different from place to place and time to time; a single storm does not follow a universal distribution for lightning peak current.

But the existence of very different kinds of measurement system based on different physical principles, the existence of overlaying systems and the availability of large data sets allow to perform intercomparisons and cross validation that provide a good knowledge of the performances of each system.

Performance characteristics, what shall we measure

The main characteristics of the operation of lightning detection network, hence the more important for evaluation are:

- The Detection Efficiency (**DE**), the ratio of detected events to the number of actual events. It is defined for Cloud to Ground flashes, for Cloud to Ground strokes, and Intra-Cloud flashes. Practically, an Intra-Cloud flash is assumed to be detected if one current discharge (in LF) or one source (in VHF) is emitted. There is no practical definition of a “source Detection Efficiency”. The DE is the key performance parameter for a given lightning detection network, but it cannot be measured across the whole network nor in a continuous fashion. The detection efficiency is a function of the flash current, it increases with the peak current. A poor detection efficiency will produce bias on the Location Accuracy and errors on other parameters, for example:
 - o The flash multiplicity will be reduced by a low detection efficiency
 - o The current distribution will be shifted to higher values (going from 100% to 90% DE will raise the peak of the distribution by 1 kA, going to 75% will raise it by 2.3 kA. [10])
- The Location Accuracy (**LA**) which is composed of random and bias errors
- The Peak Current whose measurement is affected by the peak field estimate in the sensor, the propagation loss and the field to current conversion
- Polarity that can be affected by noise and long range propagation
- The Classification between CGs and ICs, also affected by noise and propagation.

For a given network, those characteristics are space dependent and should ideally be represented over a map. It is also acceptable to propose a typical value that is valid within the network boundary. In any case it is important to describe the method, the data and the period of the study.

Evaluation techniques

- Self-assessment done through the data provided by the network is the easiest and simplest way to evaluate a network. It takes benefit of the redundant information provided by many sensors and can provide a measure of the random Location Accuracy and an evaluation of the Detection Efficiency using the Number of Sensor Reporting. They are valid all across any existing network.
- Human observers and video cameras can be used for the estimation of the Detection Efficiency, Location Accuracy and Classification errors. Streak images can be used for DE and classification, while high speed videos identify strokes using the same attachment point and thus help in determining the relative location accuracy. Measurement campaigns can be manned or made automatic, but in any case the geographic scale of the study is limited.
- Tall objects, instrumented towers and triggered-lightning allow measuring the current, and as they are located at known position they allow an evaluation of the Location Accuracy. Such experiments require a costly instrumentation for each single site, and they can be coupled with video observation.
- Intercomparisons of similar systems have the drawback of having a common bias in the data, but with LF system it allows getting large volumes of data over wide areas. Comparison can be realized between different technologies using one system as a reference. In this case a preliminary normalization step is required to make sure the data set can be compared. Such comparisons have been done with VHF and LF networks, VHF and Satellite data or with VLF and LF systems. [6], [10]. Depending on the system in use they can provide a relative detection efficiency and a relative peak current calibration.
- Using external data such as radar or ground truth reports is also possible, depending on the availability of the data. Radar images may help identifying outliers or flashes spread away from the convective core of a storm, but they don't provide practical information for calibration. Ground truth collected from claims and damages need to be confirmed for their own accuracy, but they provide an easy way for a rough assessment of the DE and LA.

Performance level

Some figures are given below as reference of the current performance level of a lightning detection network.

For LF networks, the performance level mentioned in the literature for different networks in different areas range as follows:

- The flash Detection Efficiency is in the 90-100% range
- The stroke Detection Efficiency is in the 75-85% range
- The Location Accuracy can reach values as low as 100 meters
- The peak current measured for the subsequent negative return stroke is accurate within 10-20%, the peak current for the first stroke or positive stroke couldn't be calibrated

The next section is for VLF networks, based on published studies.

The WWLLN compared to LF regional networks gives (see [6]):

- 26% CG relative strokes DE,
- 10% IC relative strokes DE in Australia.
- Relative Location Accuracy 4.2 km in Australia, 15 km in Los Alamos.

The ATDnet compared to video recording in Belgium (see [9])

- 88% Relative Flash DE
- 58% Relative Stroke DE
- Relative Location Accuracy 1km

The GLD360 compared against the NLDN in the USA (see [13]):

- 2.5 km median location error (17.5 km 90th percentile)
- 57% ground flash DE
- 21% mean peak current error
- 96% matched polarity

D) Climatology of lightning

Lightning detection systems have been in operation for more than 30 years and techniques exist to check the homogeneity of the data they provide. It is thus possible to analyze the mid to long term evolution of thunderstorm activity at different geographic scales.

1/ Worldwide lightning distribution

The LIS and OTD imagers have been collecting data for more than 8 years. On board non-geostationary satellites they can't be used for real time detection but they allow the study of spatial distribution of lightning over mid to long term period. The map below shows the lightning density around the globe computed from this data set.

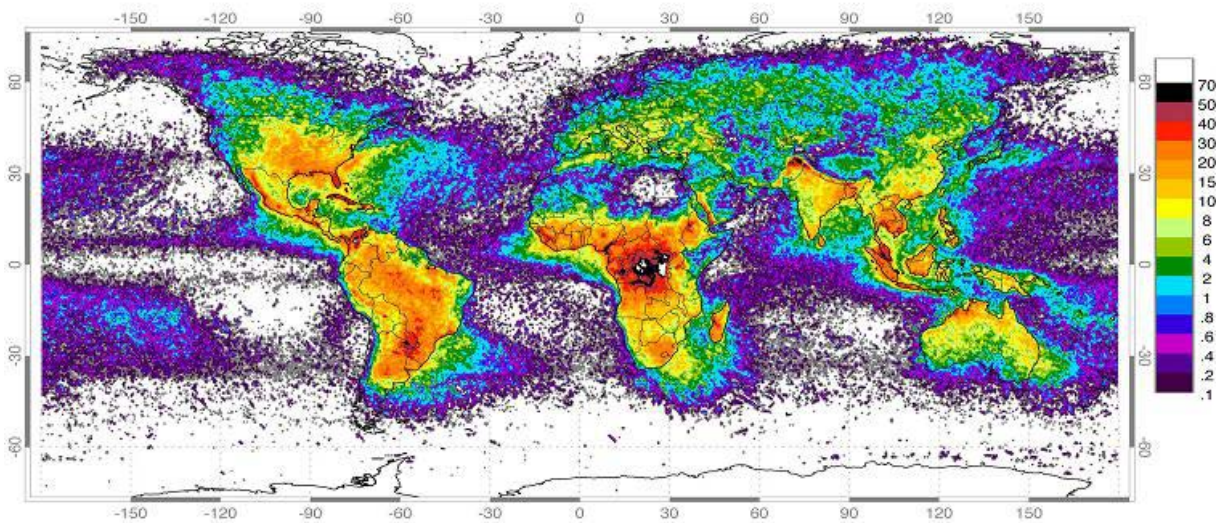


Fig. 5 Annual flash rate from April 1995 to February 2003 combining LIS and OTD

2/ Worldwide diurnal variation over land and sea.

(This section uses material from Lay et al using WLLN data[6])

Ground based lightning detection network having a continuous detection capability can provide more detailed information on the short term variations of lightning and storm dynamic. Studies done with the World Wide Lightning Detection Network operated by the University of Washington give the following results:

More variability of the lightning activity is seen over land, with a peak at 18h local time (versus 8h for sea)

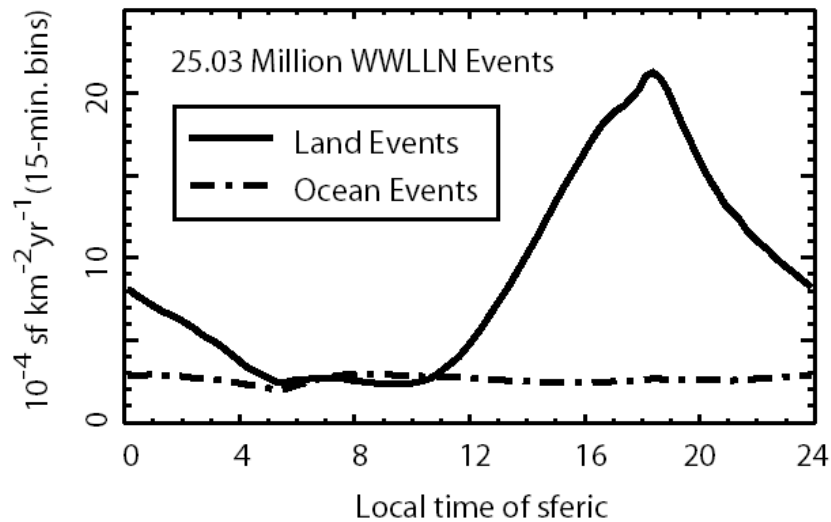


Fig. 6 Continental variation in daily peak amplitude as seen by the WLLN

The daily peak amplitude varies across regions, from about 16h UTC in Europe to around 20h UTC in North America

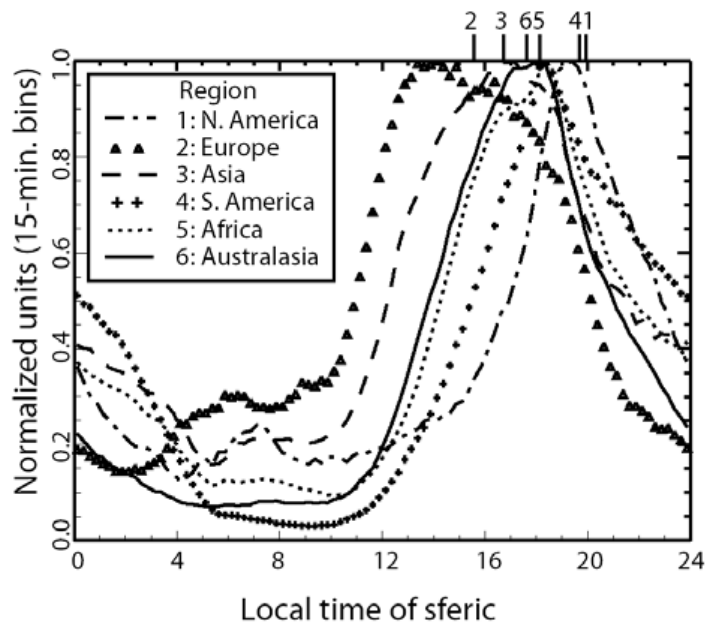
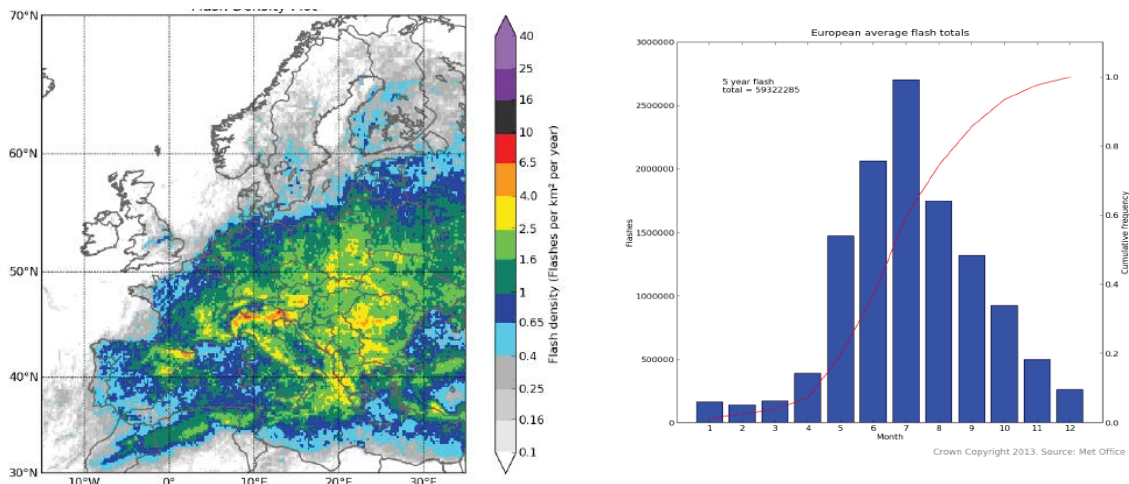


Fig. 7 Regional variation of the daily peak amplitude seen by the WLLN

3/ European climatology

(The following sections use material from G. Anderson and D. Klugmann using ATDnet data [1])

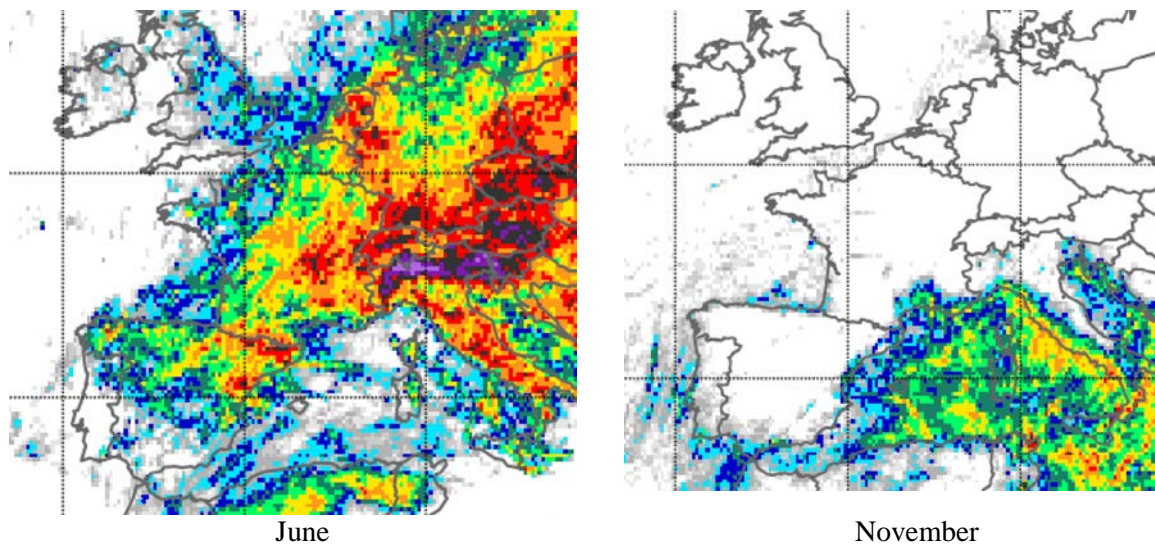
5 years of data collected by the ATDnet system allow the presentation of a climatology of lightning over Europe. In winter the lightning activity is predominantly over the Mediterranean, in early Spring, when the land begins to warm, the activity switches to the southern part of the continent. In Summer the majority of lightning is over land and extends to the north of Europe. There is a peak of activity in July and then a slight decrease in August followed by an extension of the activity on the Western Mediterranean in September. Until the end of the year the activity decreases and the higher density area in the Mediterranean shifts to the east.



Annual detected lightning flash density.2008-2012 Monthly average flash detections across all of Europe
Fig. 8 Annual flash density and Monthly variation in Europe shown by ATDnet

Land/Sea contrast

On a yearly basis, there is more lighting activity over land than over sea, but the transition between both terrains is quite smooth as can be seen in Fig. 7. Looking at the monthly variation the contract is sharper. In summer, along the western coast of Italy and southern coast of France, the lightning density plot perfectly matches the land/sea boundary with higher values in the land. In Winter a similar effect exists, even if less contrasted, around Greece, Turkey and Balkans and eastern shores of Italy. But at this time lightning activity is higher on the sea.



June November
Fig. 10 Land-Sea contrast in June and November, ATDnet

Springtime Alps

During spring, solar heating increases and the warming air near the surface starts the convection process that causes more lightning activity. A different pattern is anyhow observed in the central Alps with a region of low lightning density in Spring.

One explanation is that moisture from the Mediterranean and southerly winds will cause a lot of lightning activity on the southern slopes of the Alps. Once over central Alps, the moisture content is lower and the upward forcing is reduced, so the condition for storm development are weaker.

This local phenomenon is also described by Schulz et al[12] using 10 years of data from the ALDIS network.

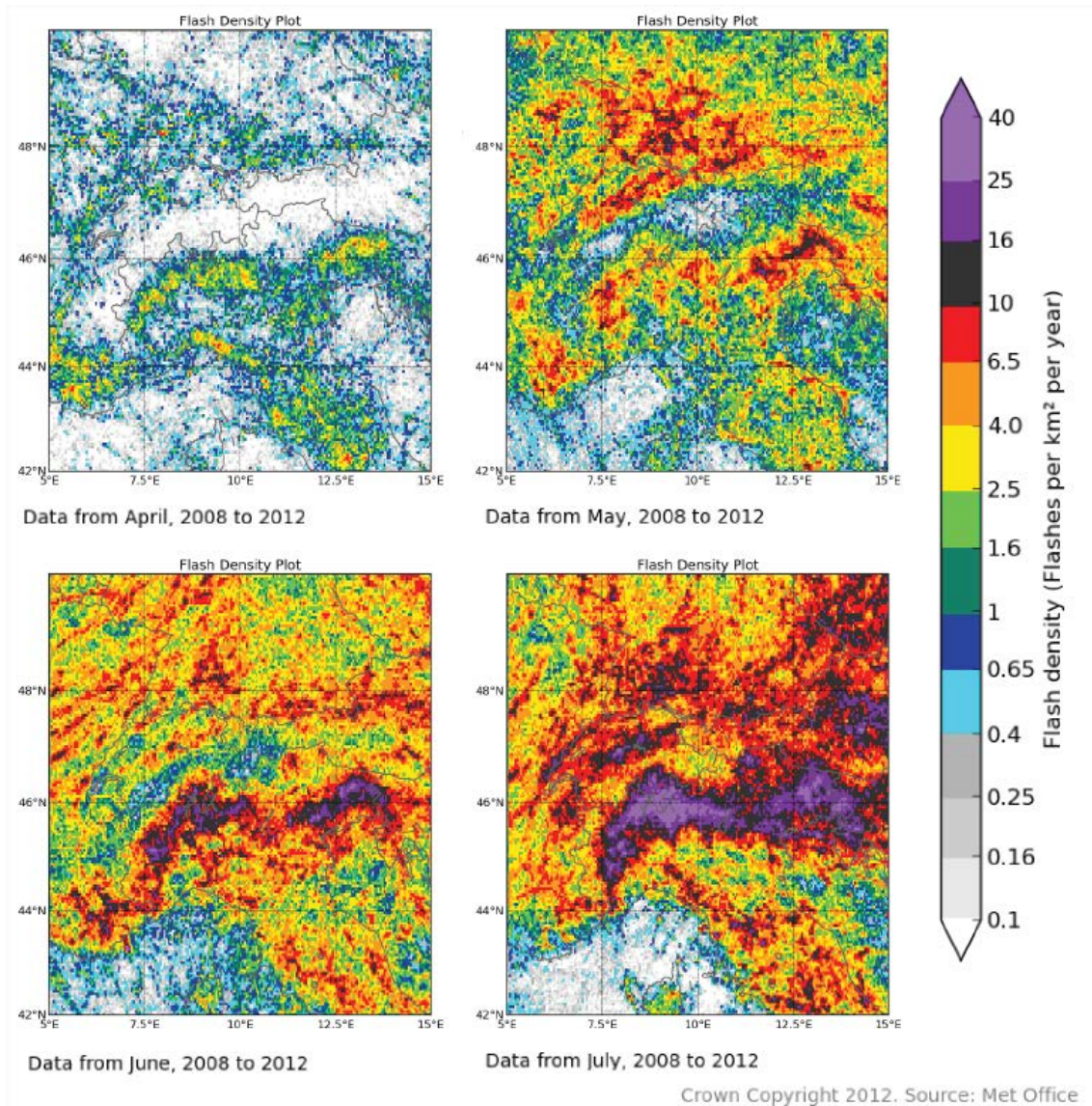


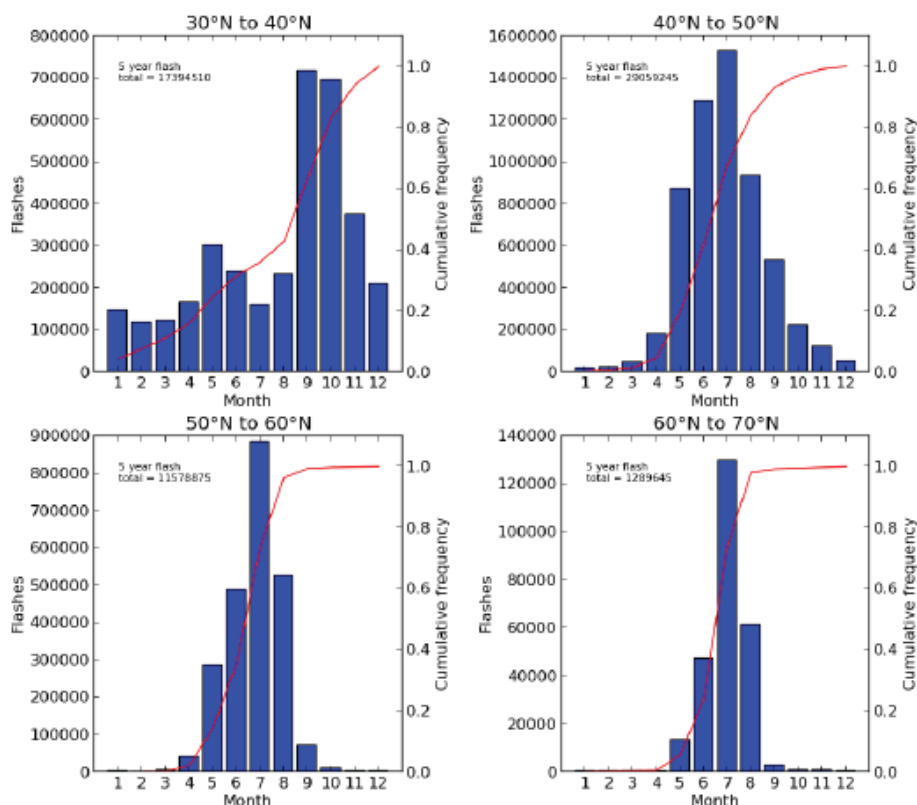
Fig. 9 Lightning density over the Alps in spring, by ATDnet

Refined climatology by latitude bands

Lightning distribution is different in the south or north of Europe, for example lightning density increases toward the north in Spring but remains high over the Mediterranean in winter when it has already dropped across the continental landmass.

The study cited above, using ATDnet data sliced over four 10° latitude bands shows the regional variation.

European average flash totals in latitude bands



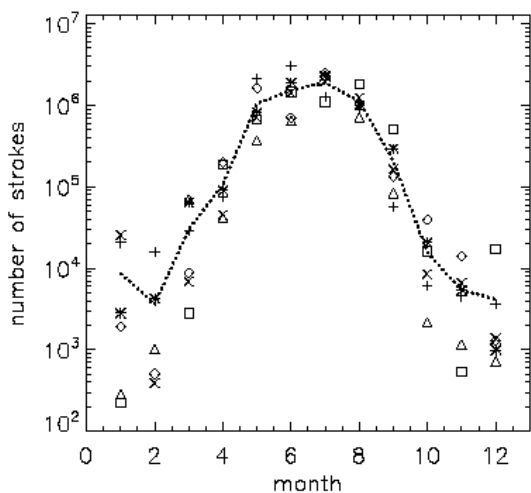
Crown Copyright 2013. Source: Met Office

Fig. 12 Yearly variation of lightning for different European latitude bands, ATDnet

4/ Annual variability

This section uses material from Kathrin Wapler using LINET data (see [5]) and Météorage data

The following diagram show the month by month variability for different years and using two different networks, one in Germany [5] and one in France. It can be seen that month to month flash count can vary from 1 to 2, that the peak value is not always at the same month, and that the patterns for each years are different.



... shows mean / Symbols: individual years
Fig. 13 Annual cycle over Germany (DWD, 6 years)

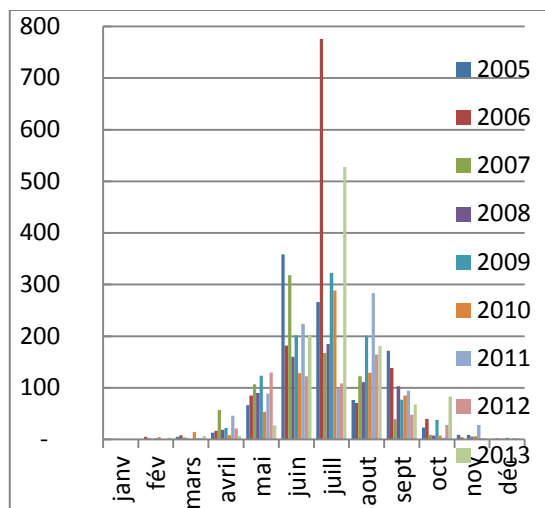


Fig. 14 Annual cycle over France (Météorage, 9 years)

5/ Comparison with the iso-keraunic level

This section uses material from Kathrin Wapler [5] and Maxime Brissard [15]

The maps below show the value for the “number of day with thunderstorm” as reported by human observers in Germany and the “number of days with more than 2 strokes closer than 15km” computed from LINET data [5]. The accordance between the values is good, the later providing a continuous coverage.

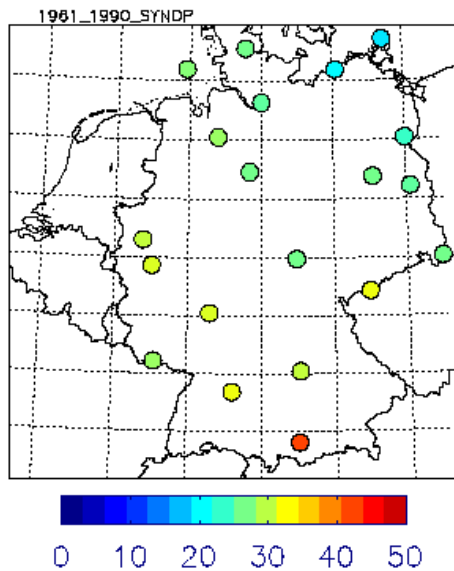


Fig. 15 Mean annual number of days with thunderstorm

As part of a study on the spatial and temporal homogeneity of the Météorage lighting archive, students from ENM in Toulouse have shown that the keraunic level was well matched with the lightning density when using 2 strokes closer than 20 km. The study mentions that out of the 100+ stations reporting the number of thunderstorm days, only 13 were producing continuous reports that could be used for comparison and calibration.

The study shows that the number of sensor contributing to each location is a key parameter for the quality of the data, and that increasing this number from 6 in 1996 to 12 in 2009 produced an improvement of the correlation between human observations and events detected by the LLS.

6/ Orography

(This section uses material from Cummins [7])

The availability of homogeneous high resolution data on different types of terrain allows studying the variation of lighting occurrence and lightning parameters with the topology. A recent paper by Ken Cummins focuses on regional areas in the USA and look for the correspondences between variation of

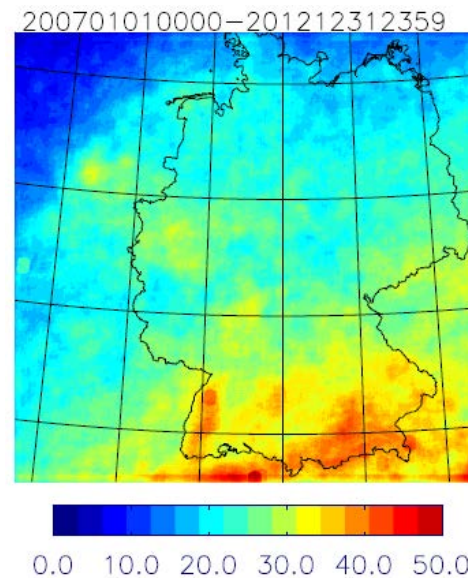


Fig. 16 Mean annual number of days with more than 2 strokes closer than 15 km

the lightning density (computed for negative ground strike stroke density: GSD) with the terrain.

Cloud-to-Ground Lightning Incidence in the Continental U.S. (1997 - 2010)

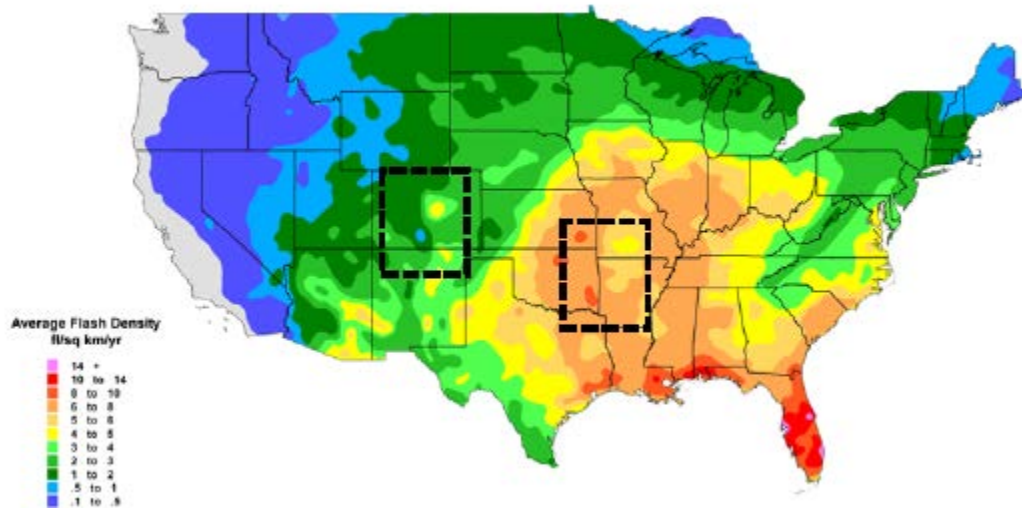


Fig. 17 Lightning density over the USA, Vaisala

Lightning density and terrain elevation

It is expected that large area terrain gradient will impact the lightning flash density due to the orographic effect on the development of deep convection. The region facing the preferred direction of arrival of warm moisture will receive more lightning.

For the eastern area on the map above, the lightning density generally matches the regions of highest terrain gradient (depicted by close isoclines) and specifically in areas of uniform slope and increasing altitude. But some of the large-gradient regions appear to be “protected” from high lightning incidence, while a few of the lower gradient regions to the west and northwest exhibit some the highest incidence. Overall the lightning density is consistent with orographically-driven thunderstorm development and propagation, with winds preferentially arriving from the south and south-east.

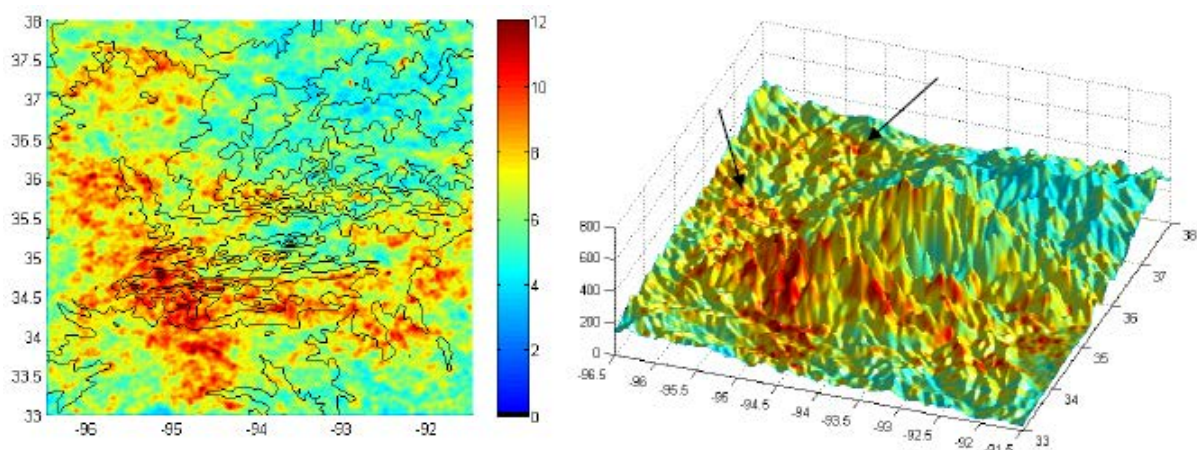


Fig. 18. 6-year ground stroke density (GSD) for negative flashes near the Ozark Mountains. (Left) Data overlaid by 100m isoclines. (Right) viewed from an elevated viewing and, with solar illumination at that same angle. Vaisala

Number of Ground Strike Points and terrain variation

An additional study of was done on the variation of the number of contact point per flash. This newly introduced object (see [14]) reflects the attachment process of the various strikes to the ground.

The number of ground contact point per flash varies between 1.4 and 2 with higher values generally occurring in areas of high terrain and high terrain gradient. But the pattern of CPF and GSD show different behaviors with respect to local terrain.

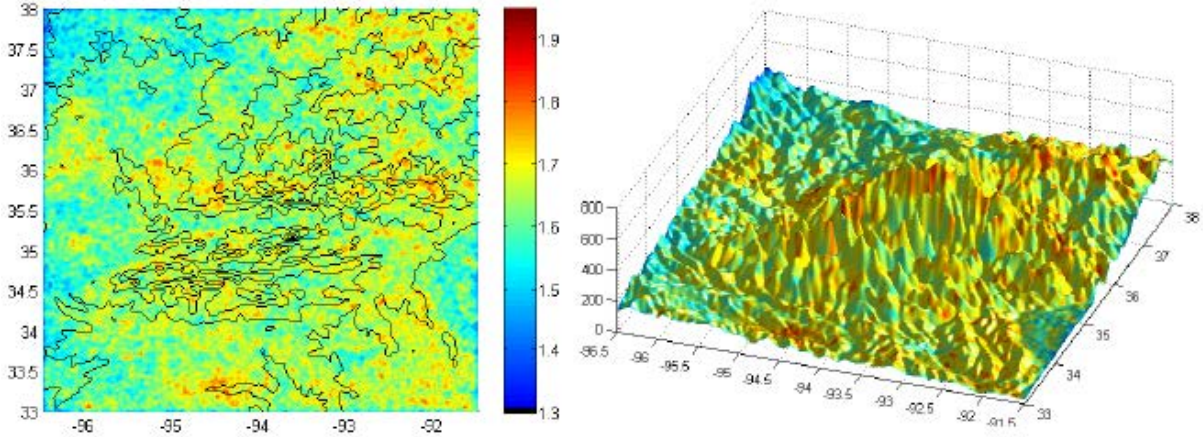


Fig. 19. 6-year average number of ground contacts per negative flash (CPF) for negative flashes near the Ozark Mountains, (a) overlaid by 100m isoclines, (b) viewed from an elevated viewing and, with solar illumination at that same angle. Vaisala

Additional elements need to be introduced in order to explain difference between CPF and GSD, the terrain roughness (defined as the signed peak amplitude of the terrain variations for spatial wavelengths less than 2 km) is one candidate. The image below shows the terrain elevation and the local roughness. The large CPF values observed in the southeastern region is not well-correlated with terrain elevation, but it appears to be generally consistent with peak roughness values greater than 10-15 m.

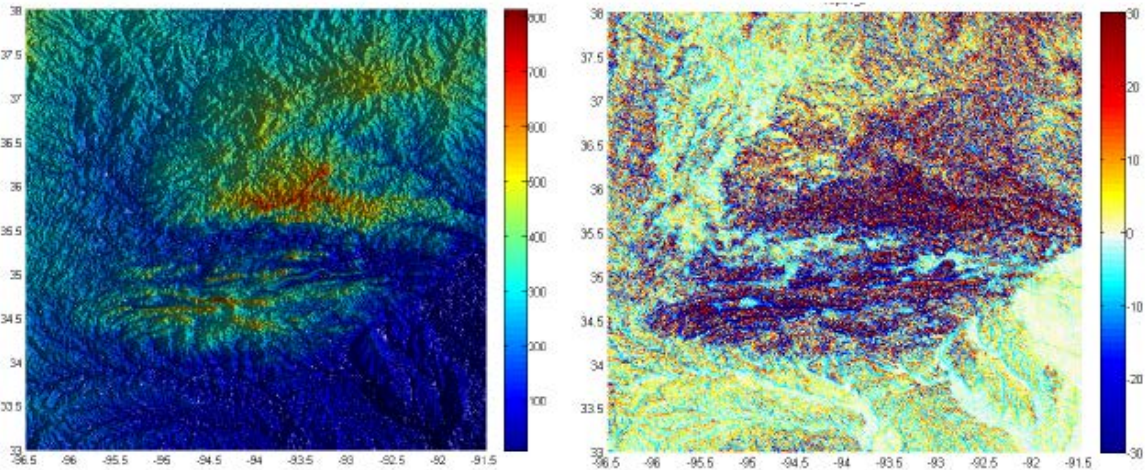


Fig. 20. Terrain elevation (left panel) and local roughness (right panel) near the Ozark Mountains. Elevation is in meters. Roughness is the signed (+/-)peak amplitude (meters) of the terrain variations in the spatial wavelengths less than ~2 km. Vaisala

There are several possible reasons for terrain and local terrain roughness to affect lightning attachment to ground. A likely factor is surface-driven turbulence, produced by variations in aerodynamic drag, that disturbs space charge homogeneity underneath an electrified cloud and within the planetary boundary layer. There may also be an effect associated with spatial variations in the near-surface electric field brought about by height and slope variations of the surface electrical boundary condition (ground). This would produce competing areas of higher (and lower) electric field near the surface during leader propagation towards ground. Finally, sloping ground (related to terrain gradient and not to local roughness), when spatially interacting with the end-points of the leader “tree” approaching ground, can produce many more “equally likely” high-field ground attachment options, which may increase the likelihood of multiple ground attachments within a flash.

E) Physics of the lightning phenomenon

The following sections use material from G. Ballarotti et. All (see[4])

Typical values for the lightning parameters were collected from different network and by different researchers. Only negative cloud to ground flashes were used. The values are presented as probability distribution [4].

1/ Continuous Current duration

Some flashes to ground exhibit a continuous current after the initial discharge. These are classified as Very Short < 10 ms, Short, or long > 40 ms.

About 50% of negative downward flashes have some CC, but very few multiple strokes flash exhibit long CC.

Some maximum values measured for CC were higher than 700 ms, in a study 0,28% of the flashes had long CC longer than 500 ms which is used in standards for lightning protection.

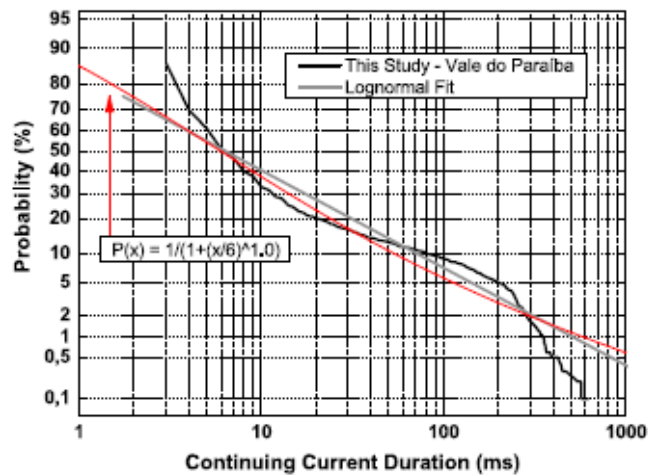


Fig. 21 Probability distribution of the Continuing Current Duration

2/ Interstroke interval

The interstroke interval is the time measured between the various strokes of a single flash.

The geometric mean value for the interstroke interval is between 60 and 65 ms. Previous values from Berger were at 33 ms because he accounted for Continuing Current between flashes. In 95% of the studied cases the interstroke interval exceeds 13-16 ms, and in 5% of the cases it was above 270-226 ms.

Only 1.1% of flashes exhibit interstroke interval above 500 ms which is the value used by LLS to group strokes in the same flash. There are some observed cases with interval higher than 700 ms; there is an hypothesis that such long interstrokes occur only if there is a very long continuing current to sustain the lightning channel in the ground.

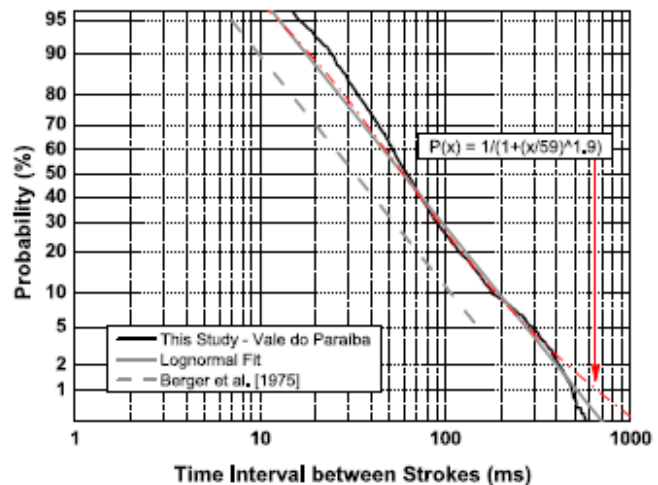


Fig. 22 Probability distribution of the Time Interval between Strokes

A study by Rakov and Uman [11] found 18% of the flashes with sub-millisecond intervals. Those flashes can have a single ground termination or be forked; the latter case would cause more damage to equipment or power lines.

3/ Flash multiplicity and number Of Ground Contact Points

The Stroke Multiplicity is the number of subsequent strokes in a flash. This parameter is known to depend on storm type and varies from day to day, so it must be studied for a large number of storms. 75 to 80% of all negative CG have more than one stroke. The average value is between 3 and 5.

The number of Ground Contact Points is the number of different points hit by the various strokes of a single flash. It can be measured with video analysis and its average value is around 1.7. There are undergoing projects to propose this parameter for the computation of risk in engineering studies.

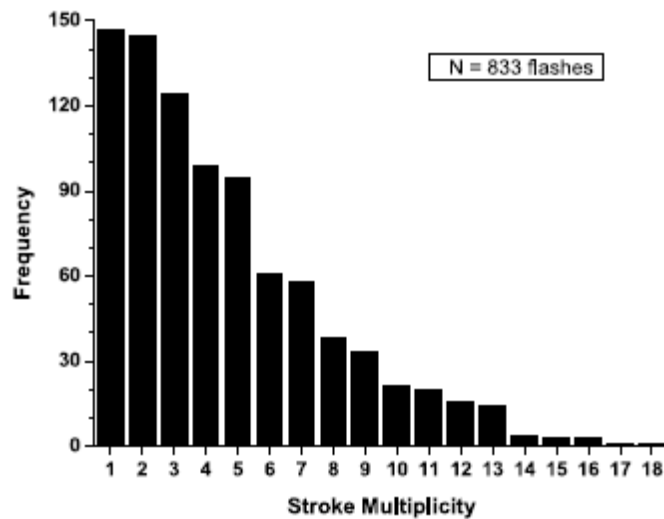


Fig. 23 Frequency distribution of the Stroke Multiplicity

4/ Total flash duration

The total flash duration is the time between the first stroke and the end of an eventual CC following the last stroke.

The values found in recent studies are higher than the findings of Berger, because of the high percentage of single strokes in Berger's data, and because of different definitions and higher time resolution of the measuring equipment.

Some observed maximum values are given:

- 1,356 ms for a 16-stroke flash,
- 1,699 ms for a 12-stroke flash,
- 1,928 ms for a 26-stroke flash.

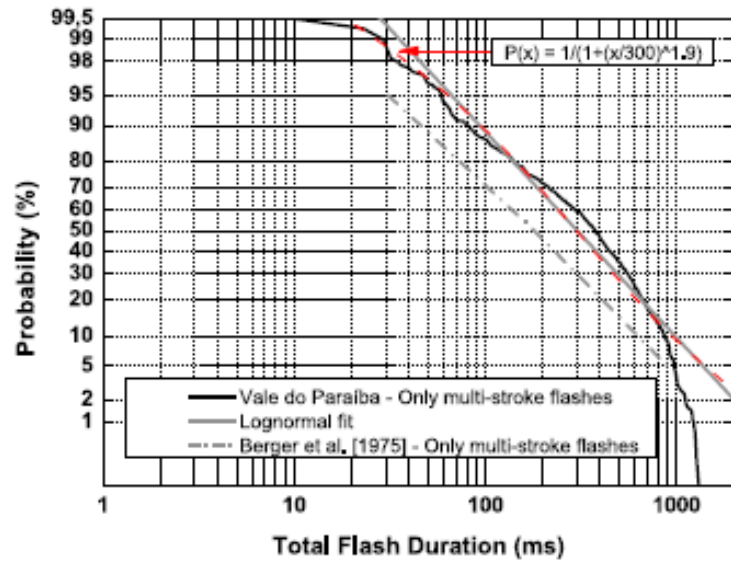


Fig. 24 Probability distribution of the Total Flash Duration

There is a good correlation between the flash duration and the number of strokes per flash.

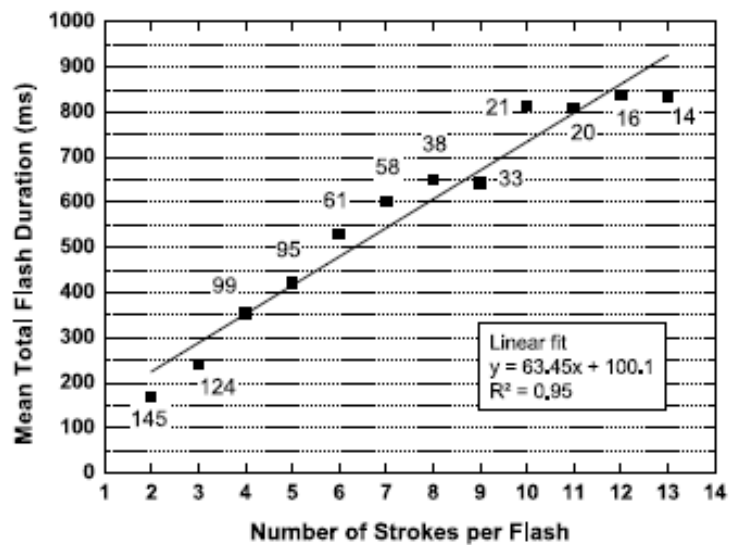


Fig. 25 Total Flash Duration as a function of the Number of Strokes per flash

5/ Storm dynamic

(This section uses material from N. Demetriades [8] and T. Rigo et al [2])

The intra-cloud events detected by VHF and recent LF networks provide a lot of information on the development and intensity of a storm, this information can be used in Nowcasting. Comparing radar and lightning information, the IC rate has been shown to be a good proxy for the storm phase, putting in evidence the growth, maturity and decay stages.

The average durations of the development and dissipation stage are quite similar, while maturity is notably longer and variable. As much as 80% of the IC and CG flashes are registered during the maturity stage. Only 2 to 5% are observed during the development stage and 10 to 15% during the dissipation. Most CG flashes are negative but the dominance of positive CGs could be associated with severe weather.

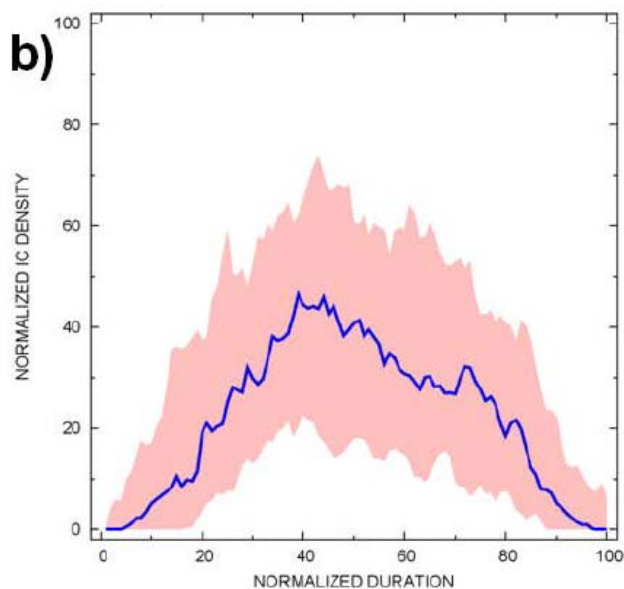


Fig. 26 Temporal evolution of the normalized density of intra-cloud flash. The diagram shows the area between the 25 and 75 percentile curves shaded and the 50 percentile curve (median) as a thick line

Studies in Catalonia and Florida show a clear positive correlation between the duration of the maturity stage and the logarithm of the CG flash observer during the same phase.

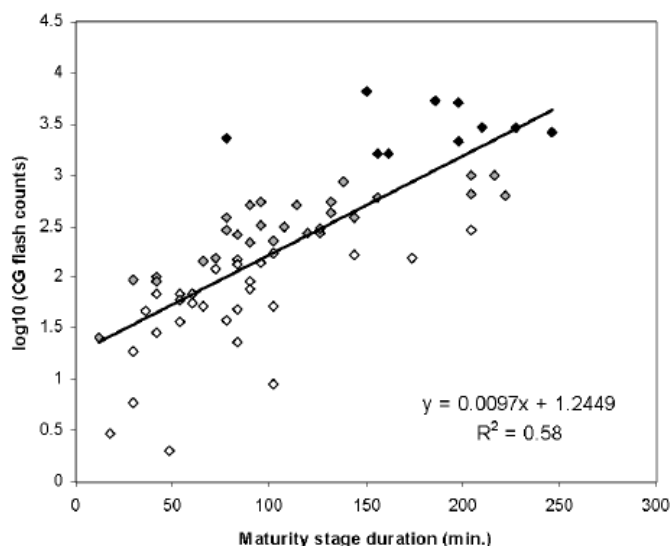


Fig 27. Positive correlation ($R^2 = 0.580$, $n=66$) between the duration of the maturity stage and the logarithm of the CG flash counts observed during the same phase.

6/ Ground strike points

(This section uses material from S. Pédeboy and W. Schulz [14])

A side benefit of the high speed video analysis has been to help define the ground strike points (GSP) as a new lightning object. Those videos show that a flash to ground will hit the ground at different places, the GSPs, each place being impacted by one or more return stroke. The interest of this newly defined object is that it shall be the right parameter for the lightning risk assessment.

The accuracy of current lightning detection networks (down to 100 m) is an order of magnitude smaller than the separation between different contact points (1.8 km), it thus allows to distinguish the GSP within the set of stroke data. An algorithm has been designed and validated to produce those GSP from a lightning data base.

The validation study, based on intercomparison of videos with two different detection networks, give the following results:

- GSP detection efficiency : 94%
- Number of GSP per flash, from video measurement 1.75
- Number of GSP per flash, from LLS measurement varies from 1.50 to 1.84 with an average of 1.71

CONCLUSION

This paper presented the various technologies that can be used to detect and locate lightning, and the methods to be employed in order to evaluate the performance of a given detection system. With this background on the possibilities and limitations of the measurement systems, we presented the knowledge that has been gained on the lightning phenomenon itself. Typical values for the main parameters of the lightning flashes were given as well as some examples of studies on the climatology of thunderstorms. We hope this material will be useful for engineers and users of lightning data in order to better understand the information they get and to develop its use.

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