Detect and Locate Lightning Events from Geostationary Satellite Observations

Report Part I

Review of existing lightning location systems

EUM/CO/02/1016/SAT

U. Finke and O. Kreyer

Institute für Meteorologie und Klimatologie
Universität Hannover

September 2002
## Contents

1 Introduction .................................................. 3

2 Lightning Location Basics .................................. 3
   2.1 Lightning Process and Emissions ............................... 3
   2.2 Atmospheric Influences on EM-Wave Propagation ............... 5
   2.3 Lightning Detection ........................................... 5
   2.4 Lightning Location ........................................... 6
   2.5 Noise .......................................................... 8

3 Ground Based Operational Networks ......................... 8
   3.1 LF Sensors and Networks: Vaisala-GAI .......................... 8
   3.2 VHF Sensors and Networks: Vaisala-Dimensions ................. 11
   3.3 British VLF ATD .............................................. 12
   3.4 Operational Networks Worldwide ................................ 13
   3.5 Long Range Lightning Location ................................ 14
   3.6 Data Characteristics .......................................... 15
   3.7 Lightning Products and Services ................................ 17
   3.8 Network Summary ............................................. 17

4 Satellite Based Lightning Location .......................... 18
   4.1 Optical Location: OTD and LIS .................................. 18
   4.2 Combined Radio-Optical Observation: FORTE ...................... 21
   4.3 VHF-Sensor: ORAGES ........................................... 22
   4.4 Satellite Summary .............................................. 23

5 Use of Lightning Location Data ................................. 23
   5.1 Comparative Studies ............................................ 23
   5.2 Climatologies .................................................. 25
   5.3 Weather Forecast and Nowcasting ................................. 25
   5.4 Total Lightning .................................................. 26
   5.5 Atmospheric Chemistry ......................................... 27
   5.6 Non–Weather Service Applications ............................... 27
   5.7 Applications Summary ......................................... 29

6 Summary and Conclusion ....................................... 30

7 Acknowledgements .............................................. 31

A Abbreviations .................................................. 42

B Related Internet Links ......................................... 43
1 Introduction

Lightning is a dangerous and destructive atmospheric phenomenon. The strong currents associated with the lightning discharge cause severe damages in the stroked object but also in its close vicinity by electromagnetic induction. Lightning can kill and injure people and animals. Enormous economic losses are caused by ignition of fire or damaging structures and facilities. Lightning is the main natural origin of forest fires. With the constantly increasing use of electronic devices in the industrial and the consuming sphere the vulnerability to lightning damages is growing.

Lightning is an indicator for convective activity in climatology and on the cloud scale. The lightning rate of a thundercloud is correlated with other storm related phenomena like precipitation, hail and gust. Lightning is an important natural source of nitrogen oxides contributing about 10% to the global budget.

All these implications keep the high interest in lightning location data. This study reviews the current state of operational lightning location systems (LLS). Special emphasis is given to the meteorological applications of lightning data.

A comprehensive review of LLS was given by Holle and Lopez in 1993. Another overview is contained in MacGorman and Rust (1998).

This study starts in section 2 with a description of the basic concepts of lightning location. A review of the existing operational ground based networks is given in section 3, while section 4 describes the space based location techniques. Finally, section 5 discusses the applications of the lightning location data.

2 Lightning Location Basics

2.1 Lightning Process and Emissions

Lightning is a spark-like electrical discharge produced in thunderstorms. The various forms of lightning are discriminated by their location and by polarity of the transported charge into Cloud-to-Ground lightning (CG) of positive or negative polarity and intracloud lightning (IC).

A lightning flash builds up in successive phases (Uman, 1987). In the following the phases of a typical negative cloud-to-ground flash are described. The initiation of lightning (preliminary breakdown) takes place in cloud regions with sufficient strong electrical field. A barely visible discharge (stepped leader) moves stepwise towards the earth. When the leader approaches the ground, an upward leader is released from elevated objects near the ground and closes the lightning channel. This initiates the return stroke, which transports charge between ground and cloud in currents of several 10 kA. Due to Ohmic heating the temperature in the core reaches 30,000 K. This produces the visible lightning flash and the thunder.

The first return stroke may be followed by subsequent return strokes each introduced by a 'dart leader' using generally the same channel. This series of return strokes composes the lightning flash. The number of subsequent return strokes gives the 'multiplicity' of the flash. Total flash duration is normally less 1 s, the time intervals between the return strokes are in the order of few 100 ms.

Intracloud discharges take place between space charges inside the cloud. The leader process is followed by several recoil streamers which are normally of less amplitude than CG return strokes.
Lightning detection and location bases on the detection of the radiation emitted by lightning. During the lightning process electromagnetic and acoustic radiation is generated in various forms:

**radio** by accelerated charges during the fast changing current steps. Radio emissions occur in form of short pulses, the corresponding broad band frequency spectrum is roughly $\sim 1/f$ (Uman, 1987). Low frequency components are generated by the return stroke. The spectrum of the other processes is concentrated in the higher frequency ranges. The time series of the magnetic and electric components of radiation field exhibit a characteristic shape. The receiving systems identify lightning by this wave form and distinguish between CG return strokes and IC lightning.

**optical** by thermal radiation of the hot (up to 30,000 K) lightning channel. Contributions to this continuous spectrum come from the excited ionized and dissociated gases and compounds of the atmosphere. The luminous period lasts a few milliseconds.

**acoustical** thunder, generated by the shock wave of the expanding hot air.

![Radiation from lightning](image)

Figure 1: Radiation from lightning (schematically). The return stroke of Cloud-to-Ground lightning emits strong LF radiation. Leader processes and recoil streamer in intracloud lightning generate predominately VHF radiation. All discharges emit optical radiation.

For the purpose of lightning location the electromagnetic radiation in the optical and radio range is used. Most of the ground based operational lightning location systems operate in the radio frequency ranges (Sec. 3) while the optical signal is employed in space based lightning sensors (Sec. 4).

Strong lightning flashes excite the ‘Schumann’ resonances of the ground-ionospheric cavity (Schumann, 1952; Volland, 1995). These resonances are of extreme low frequencies at 7.8, 14, 20, 26, 33, 39 and 45 Hertz with variations of 0.5 Hz. The analysis of the signals at only few globally distributed points permits a lightning location with accuracy of a few 100 km.
2.2 Atmospheric Influences on EM-Wave Propagation

The propagation of the electromagnetic waves in the atmospheric medium is affected by a number of factors. They are listed below without detailed discussion. See e.g. Volland (1995) for the theory of electro-magnetic wave propagation in the atmosphere.

**Attenuation** decrease of the wave’s amplitude due to increasing distance $R$ from the source. The amplitude decreases approximately with $1/R$.

**Ground reflections** (not really an atmospheric effect) depending on the properties of the soil and water bounding the propagation space. The propagation is also affected by large mountain ridges, which delay the radiation signal (e.g. Rubinstein et al., 1994). Large obstacles may obscure a part of the sky and thus limit the detection sector. Additionally, metallic objects close to the antenna can distort the magnetic field.

**Ionospheric reflections** Electromagnetic waves interact with the upper atmospheric layer of high conduction (Ionosphere). For waves with frequencies $f$ smaller than the ionospheric cutoff frequency ($f_c \approx 5$ MHz) this results in reflexion back towards the ground. Thus long waves propagate in a wave guide formed by the ground and the ionosphere and can travel over long distances with low energy loss. Waves with higher frequency can penetrate the ionosphere.

**Dispersion, scattering, refraction, absorption** cause distortion of the wave front and change the frequency spectrum.

For frequencies higher than 80 MHz the waves propagate in good approximation along the line of sight. If the wave’s frequency is lower than 5 MHz, then the energy is trapped in the atmospheric wave guide and long range propagation is observed.

The main propagation effect is the distance attenuation, which mainly reduces the amplitude. The other propagation effects depend on frequency and lead to changes in the frequency spectrum and the waveform of the signal. Particularly wave pulses become less steep.

2.3 Lightning Detection

Lightning detection sensors receive the electric and/or magnetic components of the radiation field in certain frequency ranges. Low frequency (LF, 30 kHz – 300 kHz) and very high frequency (VHF, 30 MHz – 300 MHz) bands are employed, avoiding thereby the communication and radio transmission bands. The used detection frequency (center and bandwidth) determines the detection range and accuracy. Also the size of the antenna and the sensitivity to the various propagation effects depend on the detection frequency.

2.3.1 Detectable Discharge Processes

Low frequency (LF) systems detect the signal from the return stroke of Cloud-to-Ground (CG) lightning. The strongest radio emission is generated, when the downward leader meets the upward going streamers approximately 100 m above the ground.
High frequency (VHF) antennas detect single discharge processes from stepped leader, recoil streamer, and other processes which comprise the intra-cloud discharges (IC). Hence a more complete picture of the discharge process is provided. On the other hand the ground striking point has to be determined by data processing.

### 2.3.2 Detection Efficiency

Detection efficiency (DE) is defined as the fraction of lightning flashes (or return strokes) which is detected and located by the sensor or network. The ability to detect a flash depends on the amplitude of the signal, which must be within the dynamic range of the receiving system. The amplitude of the lightning signal must be high enough to be discernable from the internal and external noise. On the other hand receivers may distort signals with too high amplitude.

Since the signal’s amplitude drops with increasing distance from the source the DE is a function of both location relative to the station and lightning amplitude. With typical frequency distribution of lightning amplitudes an effective detection range can be calculated for each station. The DE differs for different lightning types (CG, IC) and polarity.

For a network of receiving stations the DE is also a function of antenna spacing. Taking advantage of the ambiguity due to multiple receiving stations a constant DE inside the network is aimed. Generally it drops outside the network polygon with increasing distance. Most modern operational LLS have DE of 70-90% (see below).

Signals arriving with high event rate (per time interval) can saturate a receiving station. This may limit the DE during intense thunderstorms which are very close to the receiving station.

### 2.3.3 Detection Capacity

The location of lightning is limited by the detection capacity of single sensors and the total network. It is quantified as the number of lightning events which can be detected and located per time unit. This limit arises from sensor (e.g. re-arm time) or data transmission restrictions. In situations with heavy storm activity a part of the lightning events cannot be processed by the system and is lost.

### 2.4 Lightning Location

For the location of lightning the signals detected at more than one station (network) are analysed. Predominantly two location methods are applied: direction finding and 'time of arrival’.

**Time of arrival:** The exact time of the signals arrival at the antenna stations is compared for the different locations. The position of the signal source is given by the intersection of the hyperbolas for equal time differences.

**Direction finding:** The direction of the incident wave is determined at the antenna stations. The intersection of these directions gives the source location.

In modern networks a combination of both location methods is used, thus minimizing the geometric uncertainty in location accuracy.
2 LIGHTNING LOCATION BASICS

2.4.1 Time of Arrival

This method is used for 2D and 3D location. More sophisticated systems take into account propagation effects. A high time synchronisation of the sensors is required. This was realized in the past using highly stabilized oscillators and the synchronisation signal of telecommunication satellites (Loran-C). All the modern systems employ the GPS signal.

To determine the 3 unknown parameters (time, longitude, latitude) of the signal source, at least 3 independent measurements are necessary. Due to the ambiguity of the intersection of 2 hyperbolas in the general case 4 measurements of arrival time are needed. The uncertainty in the determination of the time is in the order of the time uncertainty of the single sensors ($\Delta t_i$). The location uncertainty inside the network is in the order of $\Delta t_i \cdot c$. Hence for location uncertainty lower than 1 km a time resolution higher than 3 $\mu$s is necessary. Outside the network polygon the uncertainty becomes large because the hyperbolas intersect at a small angle.

2.4.2 Direction Finding

The comparison of the phase lag of different oriented or dislocated antennas permits the determination of direction of the wave. This is realized by various methods of antenna arrays, e.g. crossed loop antennas in magnetic direction finders. Dipole arrays are used in interferometric antennas.

For 2D location only 2 receiving stations are necessary, for 3D location at least one antenna must determine the elevation angle. The uncertainty in location determination depends on the angular difference $\phi_i - \phi_j$ and is largest for differences close to 0° or 180°. Operational networks consist therefore of at least 3 stations.

2.4.3 Location Accuracy

The location accuracy is an important characteristic of LLS. It is determined by resolution and accuracy of single antennas, location principle and the network geometry, i.e. the spacing and distribution.
of the single antenna stations. In modern LLS the location accuracy is better than 1 km.

2.5 Noise

Lightning emitted radio signals are superposed by noise originating from natural and anthropogenic sources. Natural noise sources are remote thunderstorms which lightning signals can propagate over extraordinary long distances under favourable ionospheric conditions. Another high frequent noise source is radiation from corona discharges at objects close to the antenna.

Anthropogenic noise sources are communication (TV, radio, cell phone, etc) and control transmissions. Usually these signals are modulated and confined to narrow frequency bands. Additionally random broadband noise arises from various electric equipment, causing e.g. sparks. This type of noise is eliminated by waveform and amplitude criteria. Signals not matching a certain wave form which is typical for lightning are discarded. However, the application of this criterion may reject some lightning signals as well. The amplitude criterion takes advantage of the fact, that the amplitude from lightning is usually stronger than artificial noise. Again, the weaker lightning events are lost, especially intracloud lightning. In strong noise conditions the limited detection capacity of the sensor or network can cause data loss.

3 Ground Based Operational Networks

Lightning location systems (LLS) consist of 2 components: sensor and network. The sensor detects the lightning by it’s signal and records relevant parameters (direction angle or arrival time). A combination of several sensors – the network – determines the location using the transmitted parameters. Larger networks, which have been grown over many years, consist usually of different sensor types and use different location principles in combination, sometimes with redundancy.

The majority of today’s operational networks originate from the two worldwide leading manufactures of LLS: 1. GAI (Global Atmospherics Inc., USA) with sensors operating in LF range and 2. Dimensions (France) employing VHF sensors. Since 2002 both companies are incorporated in the Vaisala Group.

3.1 LF Sensors and Networks: Vaisala-GAI

3.1.1 LF Sensors: ALDF, LPATS, IMPACT

**ALDF - Advanced lightning direction finder:** Direction finding with magnetic loop antennas. These sensors were originally used in Lightning Location and Protection (LLP) networks (Klider et al., 1976).

The sensor consists of 2 vertically oriented crossed magnetic loop antennas for direction determination and a horizontal electric plate for resolving the ambiguity in direction. The detection bandwidth is 1 kHz to 1 MHz. Only signals with certain electric wave form are recorded, this discriminates electromagnetic noise from the lightning signals. The quality of detection of the magnetic signal is sensitive to distortions of the magnetic field by obstacles and metallic objects. Hence the installation site must be carefully chosen. The detection range for lightning signals is 200 km and more.
The sensor’s output is time, angle, signal amplitude and polarity of the first return stroke, and number of return strokes in the flash. If two or more sensors report a flash within a time interval less than 20 ms (programmable) the flash location is computed. Due to the applied principle only 2 sensors are necessary for location. However large errors occur for intersection angles close to 0° or 180°, therefore more sensors are used for optimized calculation.

**LPATS - time of arrival:** In the Lightning Position And Tracking System (LPATS) (Bent and Lyons, 1984) the lightning location is determined by the TOA method using the electrical signal.

A simple electric whip antenna is used with a detection band of 2 to 500 kHz. Detection by this method is less sensitive to environment conditions than the magnetic direction finder. The wave form of the signal is recorded and the ‘arrival time’ is fixed. This arrival time is compared between the different sites and the impact point is calculated.

The sensor reports for each return stroke: time, location and peak amplitude estimation. Intra-cloud lightning is also detected, but with much lower detection efficiency. The time between single detections is 15 ms, more than 50 strokes per second can be discriminated. The maximum sensor detection range is 200–300 km. For lightning location at least 3, generally 4 sensors are necessary. The network operation depends crucially on exact time synchronisation of the sensors. Since the 1990s this is accomplished by GPS time stamps.

**Latest sensor generation:** LPATS IV and IMPACT-ESP (Enhanced Sensitivity & Performance). IMPACT ESP combines magnetic and electric field measurement in the frequency range 0.4 kHz – 400 kHz. Magnetic field is measured with 2 crossed loop antennas for the determination of the waves incident direction. A plate antenna detects the electric component of the wave field for the fixation of the arrival time of the signal. For discrimination between CG and IC a wave form criterion is used. A crucial element for the quality of the whole network still remains the thoroughly choice of the sensor location place with respect to noise condition and orography (Diendorfer, personal communication).

### 3.1.2 NLDN

The world wide largest LLS is the North American Lightning Detection Network (NALDN) (Cummins et al., 1999) created in 1998, which comprises the National Lightning Detection Network (NLDN) in the United States and the Canadian Lightning Detection Network (CLDN). The NLDN as of 1991 uses 47 Advanced Lightning Direction Finders (ALDFs) in combination with 59 LPATS III electric field sensors (Fig. 3). The CLDN uses 26 IMPACT-ES sensors and 55 LPATS-IV sensors. The total area covered by the NALDN is 20 Million km².

The network location range extends a few hundred kilometers into the adjacent Oceans and the Gulf of Mexico. All sensor data are centrally processed in the Network Control Center (NCC) in Tucson. The location calculation is optimized employing both direction and arrival time information (Cummins et al., 1998). The ground stroke lightning data includes information on latitude and longitude, time, polarity, and amplitude.

Data from the NLDN are used for a long time (Orville and Huffines, 1999). First results from the combined network NALDN were given e.g. in Orville et al. (2002) or Burrows et al. (2002).
Figure 3: Location of the lightning sensors comprising the NLDN. The red triangles are impact sites; blue circles are TOA sites.

3.1.3 European GAI-networks, EUCLID

EUCLID (EUropean Cooperation for LIghtning Detection) is a compound of national lightning detecting networks with the aim to locate lightning all over the European area.

Since the end 1980’s many LLS were installed in the European countries. These LLS were national networks and operated by weather services, power utilities, etc. The performance of the network generally decreases outside the bounding polygon. Since storms can have life times of a few hours, they travel over several 100 km. It is evident, especially for smaller countries, that storms may develop outside the country, i.e. the polygon of the national network. A simple patch of the national networks data is unsatisfactory due to methodical problems with double detection, different location methods and sensor types. To overcome these problems in 1999 the operators of the European LLS basing on the GAI-technology created the EUCLID compound. The countries involved are Germany, Austria, Hungary, Czech Republic, Slovenia, Holland, Belgium, Luxembourg, Italy, Poland, Slovakia, Norway, Finland, Denmark, Sweden and France. The networks from Portugal and Greece are being joint recently. In the near future Spain will be added (S. Thern, personal communication). Each network retains its national independence and provides lightning data for individual user applications in their own country as well. EUCLID covers almost the whole Europe (except Russia) and the adjacent oceanic areas: North Sea, Mediterranean Sea, Biscaya. At the moment the complete network consists of 75 sensors of 4 different types (LPATS3, IMPACT, LPATS-IV, IMPACT-ESP). Figure 4 shows the countries covered by the EUCLID compound.

The raw data from every sensor station are transmitted to the data centres in Karlsruhe (Germany) and Vienna (Austria) where the data are archived and processed for location calculation. This central processing allows an optimized calculation of the location points.

The detection efficiency of the network is above 90% for CG-lightning with amplitudes >5 kA. Location accuracy is < 1 km. IC-lightning is detected only partially with a low detection efficiency.

With EUCLID a significant progress has been made towards a uniform homogeneous LLS. This is achieved by the central processing of the raw data and also by a step-by-step addition of new sensors at crucial locations which improve the performance of the total network. The benefit from this compound is evident also inside the national networks: the lightning location at the country’s border is supported by the adjacent sensors. Hence the detection efficiency and location accuracy remain more uniform.
There are several other LLS compounds in Europe, mostly between neighbouring countries (BLIDS, CELDN, BLDN) which are partly included in EUCLID. E.g. a Mediterranean network involves the French, Italian, and Spanish networks employing GAI sensors (Montariol, 2000). This is advantageous for storm observation in the coastal areas of these countries and even more over Mediterranean Sea, which is poorly covered by each single network.

3.2 VHF Sensors and Networks: Vaisala-Dimensions

3.2.1 SAFIR Sensor

The SAFIR (Surveillance et Alerte Foudre par Interférométrie Radioélectrique) lightning location system was originally developed by a research group of the ONERA, the French space research institution (Richard and Auffray, 1985).

The SAFIR detection station operates at a detection frequency in VHF in the worldwide protected frequency band at 110 – 118 MHz. This high frequency allows to detect signals from the single steps of the leader process and from recoil streamers of cloud discharges. These processes emit presumably in the high frequency range. Another consequence of the VHF range is the line-of-sight propagation of the lightning signals. Thus the earth curvature limits the detection range of the antennas. A ray arriving at a detection station from 200 km distance was emitted at least in an altitude of 3 km. The antenna represents an array of 5 electric dipoles comprising an interferometer.

Additionally to the VHF registration a second antenna at LF (300 Hz – 3 MHz) is used for the detection of return stroke signals. The combination of both antennas enables the discrimination between IC- and CG-lightning. All detected and located VHF events, which meet certain distance-time criteria are combined into an IC or CG flash.
SAFIR networks locate lightning by direction finding. The mean distance of antennas in SAFIR networks is at about 150-180 km. With the angular resolution of 0.25° this yields a location accuracy better than 1 km. The detection efficiency is about 90% for IC and CG for distances smaller than about 150 km.

The detection capacity is limited currently to 100 events per second. Since SAFIR detects many signals from a single lightning channel this limit can be reached easily on intense storms. This low value was chosen to meet the slow data transmission lines. It is expected that this limit will be moved in sensor upgrades (P. Richard, personal communication).

The SAFIR LLS is less affected to atmospheric propagation conditions. On the other hand any obstacle in the line of sight prevents signal detection from the corresponding sector. This imposes additional installation efforts for SAFIR sensors in mountainous areas.

### 3.2.2 SAFIR Networks

SAFIR lightning location networks are installed now in 7 European countries (Netherlands, Belgium, France, Germany, Hungary, Slovakia, Poland) as schematic displayed on Fig. 5. Several countries with SAFIR networks are cooperating in exchange of raw data for central data processing. Other SAFIR systems operate in Asia: e.g. in Singapore and in Japan, the latter consisting of over 30 stations. The launch place of the European Space Agency (ESA) in Kourou, French Guyana is equipped with a SAFIR network (Molinié and Pontikis, 1995).

![Figure 5: Area covered by SAFIR networks in Europe (left) and the sensor locations of the British long range network ATD (right).](image)

### 3.3 British VLF ATD

The UK Met. Office operates a LLS which detects lightning in the VLF range and utilizes an ‘Arrival Time Difference’ (ATD) method for lightning impact location (Lee, 1986). It was recently upgraded significantly as described by Nash et al. (2000). Currently it consists of 7 stations: 5 in the range of
the British Islands, completed by stations in Cyprus and Gibraltar (Fig. 5). The detection frequency is 10 kHz. The resulting long detection range enables the system to detect and locate lightning surely over the whole Europe, the Northern and the Mediterranean Sea. As the developers report lightning is also detected from thunderstorms at large distances in South America, Africa and eastern Russia.

The location accuracy is best inside UK with 1-2 km, in the bounds of Europe it reaches 5 km. The location accuracy reduces with increasing distance from the network. For South American lightning the location error may reach 100 km. The strong variations in propagation parameters such as ionospheric height and ocean and soil conduction properties cause strong errors in location for the distant flashes. An improved wave propagation model will be utilized to reduce these sources of uncertainty. A further consequence of the changes in propagation conditions is a large variation in DE with daytime.

The upgrade of the system also increased the detection capacity of the sensors from former 400 per hour to present 4000 per hour and is expected to increase up to 10,000 after the upgrade finished. Additional lightning parameters such as flash strength, polarity, type (cloud to ground strike, or cloud to cloud) and multiplicity (number of strokes per flash) will be provided.

Compared with the LPATS/IMPACT type systems the ATD detects only about 5% (Finke, 2000), i.e. only the return strokes with the strongest amplitudes.

### 3.4 Operational Networks Worldwide

Lightning location systems are in operation worldwide in most of the industrialized countries. Depending on the local situation the ownership of the network and the distribution of the data varies from country to country. Typically, the networks are operated by national meteorological services, power utility companies, environmental services, flight security agencies, aerospace, or military.

Table 1 summarizes the basic parameters for the operational network types.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>SAFIR</th>
<th>GAI</th>
<th>ATD</th>
</tr>
</thead>
<tbody>
<tr>
<td>location frequency</td>
<td>VHF</td>
<td>LF</td>
<td>VLF</td>
</tr>
<tr>
<td>location method</td>
<td>interferometry, DF</td>
<td>DF and TOA</td>
<td>TOA</td>
</tr>
<tr>
<td>detection range</td>
<td>150-200km</td>
<td>200-300km</td>
<td>500-1000km</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>90%</td>
<td>90%</td>
<td>10%</td>
</tr>
<tr>
<td>location accuracy in Europe</td>
<td>&lt; 1 km</td>
<td>&lt; 1 km</td>
<td>&lt; 5 km</td>
</tr>
<tr>
<td>detected lightning type</td>
<td>total lightning (CG+IC)</td>
<td>CG lightning</td>
<td>CG lightning</td>
</tr>
</tbody>
</table>

Table 1: Parameters of operational lightning location networks.

The worldwide coverage with LLS is confined however mostly to the industrialized countries. Particularly in the tropics where most of the thunderstorms take place lightning location data are missing. Also the oceanic areas are not covered by LLS except of the first few hundred km from the coasts. Recently there are activities by GAI to create a Global Lightning Detection Network which integrates the worldwide operating LLS and employs the long range detection capabilities (Cramer and Cummins, 1999) to cover the Oceans.

It follows an incomplete list of the countries with operational LLS. As mentioned earlier (Sec. 3.1), the majority of LLS is equipped with either VHF SAFIR sensors or LF sensors from GAI. In some countries networks of both types work in the same area.
Europe: France, Germany, Austria, Switzerland, Great Britain, Sweden, Norway, Denmark, Finland, Iceland, Poland, Hungary, Slovakia, Czechia, Belgium, Netherlands, Luxemburg, Spain, Portugal, Italy, Slovenia, Croatia.

Africa: South Africa, Tunisia, Morocco

North America: USA (NLDN) and Canada (CLDN)

South America: Brazil (Beneti and Sato, 2000), Colombia (Torres et al., 1996), Costa Rica, Venezuela

Asia: Japan (Ishii et al., 2000), South Korea (Woo et al., 2000), Indonesia (Laksimwati, 1998), Thailand, Singapore, Hong Kong

Australia: Australia Sharp (1999), New Zealand (Pannett, 2000)

3.5 Long Range Lightning Location

Recently attempts are made to extend the detection range of LF location systems into the oceans areas by a method which employs the signal from waves reflected at the ionospheric rather than the ground wave in normal processing. A test configuration with the NLDN sensors was used by Cramer and Cummins (1999) to estimate the data quality parameters of such a long range detection. The authors found a detection efficiency of 10-25% during the night and a few percent during the day. For lightning with amplitude > 45 kA the DE is about 50%. This strong variation with the time of the day is caused by the diurnal changes in the ionosphere structure. To reduce these variations it is proposed to place more sensors at larger latitudinal distances. The location accuracy is approximately 5-10 km.

Several methods for long range detection and location are currently investigated and operate in several research organisations.

3.5.1 VLF Arrays

The Los Alamos Sferics Array (LASA) was installed in 1998 in support of the FORTE satellite mission (sec. 4.2). It represents an array of now 11 electric field changes sensors located in 3 sub-arrays in stations in New Mexico, Texas, Florida, and Colorado (Massey et al., 1999; Heavner et al., 2000). The sensors detect in the frequency range 300 Hz to 500 kHz with high time resolution and GPS time synchronization. The network detects the waveform and locates CG and also IC using a time of arrival method with a location accuracy at about 2km within 130km of the New Mexico and Florida sub-array.

A VLF-array operates in the South of Germany (Betz et al., 1996). This network consists of 3 stations and is used for storm nowcasting (Oettinger et al., 2000).

3.5.2 ELF and Schumann-Resonance Lightning Location

Strong lightning flashes excite 'Schumann resonances' (SR) in the earth-ionospheric cavity. SR detection stations are located around the world mostly at research institutions (e.g. Lyons et al., 2000; Boccippio et al., 1998). Using inversion calculations the global detection and location of lightning is possible (Heckman et al., 1998; Burke and Jones, 1995) with accuracy of a few 100 km (Füllekrug et al., 1996). The detection efficiency is only a few percent compared with the operational LLS. In
view of the low DE and the large location uncertainty the use for operational purposes is limited. However the SR location method may be a very useful instrument for global and climatological studies (Williams, 1992).

3.6 Data Characteristics

Lightning data are available in near real-time with delays less than a few minutes. This is sufficient with regard to typical evolution times of storm cells. The data contain time, spatial location in geographical coordinates, peak current amplitude, polarity and flash multiplicity (number of single return strokes per flash).

Lightning location data are usually represented as points on geographical maps with colour-coded time information (Fig. 6). Averaging and integrating produces lightning densities for certain time intervals and time series of lightning totals for some areas. The point structure of the data makes it easy to overlay lightning data on other geographically distributed data, e.g. from radar and satellites.

The IC lightning data detected by the SAFIR networks contain for every lightning flash many single point locations. These are assembled by data processing algorithms into complete lightning paths.

3.6.1 Quality Parameters

Important quality parameters of the networks are: detection efficiency, false alarm rate; the quality of location determination and amplitude estimation. Another characterising network property is the ability to detect and to discriminate between different lightning types, i.e. CG lightning or total lightning (CG and IC).

Detection  The detection efficiency in modern networks is 90\% but drops down with increasing distance from the network. For instance, at a 200 km distance outside of the NLDN the DE is less than 40\% (e.g. Nierow and Showalter, 2000).

Consistency tests and comparison with cloud data show, that the rate of false alarms is very low (less than 10 per day (Diendorfer, personal communication)). In some special constellations bogus mapping of flashes to far locations is possible. These cases are however easily recognized by the forecaster and can be eliminated by special filters.

Accuracy  Comparisons with ground truth observations (see below) showed that in thoroughly installed networks the location accuracy is better than 1 km.

CG and IC lightning  For distinction between CG and IC a wave form criteria is used in LF systems. In the past this method classified some of the IC flashes wrongly as positive flashes (Cummins, 1996 personal communication). In SAFIR systems the signal from the additional LF antenna is used for discrimination of the ground flashes.
Flash multiplicity  For organising the single detected return strokes into flashes, usually a distance and time criterion is applied. Return strokes which follow a short time (1 s) after the first stroke and are located closer than 10 km are assigned to one flash. Finke (1999) suggested from a correlation analysis of LPATS lightning data distance interval of 5 km and a time interval of 1 s for the subsequent return strokes.

3.6.2 Validation Studies

Much validation efforts have been made by operators and users of the ground based LLS (Diendorfer et al., 1994). Validation studies use for ground truth impacts of lightning in towers (Hussein et al., 1995; Heidler et al., 2001) or optical video observations of lightning (Idone et al., 1998a,b).

Recently Diendorfer et al. (2002) presented a validation study comparing lightning detection of the Austrian ALDIS with tower impacts. Additionally high-speed video observations were made. Analysing 463 strokes with peak amplitudes > 2 kA the authors derived a detection efficiency of 94%
and a average location accuracy of about 500 m. Comparing the peak current estimate with direct tower measurements a linear regression \( I_{\text{ALDIS}} = 0.95 \cdot I_{\text{Tower}} \) was established with a correlation coefficient of 0.95. These findings demonstrate the high quality of today’s ground based LLS.

### 3.6.3 Network Intercomparisons

For areas which are covered by 2 networks the intercomparison of the data is possible. The data are compared with respect to the lightning distribution statistics and coincident events detected by both system. In Europe (Ruffieux and Rast, 2001) compared the data from 2 LLS (BLIDS and Meteorage) covering the area of Switzerland with lightning counter detections. Tzanos and Senesi (1998) presented a comparison of the Meteorage-network (IMPACT sensors) and a SAFIR-system around Paris in France.

For an 8-week period during the field experiment EULINOX Finke (2000) compared the data from LPATS and ATD over the range of Germany. He established detection efficiency for the ATD of only about 5-10%. A i.e. only the return strokes with the strongest amplitudes were detected. A high percentage of coincident events was found, 84% of all ATD flashes could be identified in the LPATS data. Thery (2000) compared the LPATS data for the same time period against observations with a 3D SAFIR type system. She found a slight overestimation of CG flashes by LPATS due to wrongly identified cloud flashes.

### 3.7 Lightning Products and Services

Various products and services are offered by the network operators: full access to lightning location data, lightning distribution maps, climatologies for sub-areas. A broad spectrum of warning services are available via different communication lines.

Online lightning information with reduced resolution in time and space is provided free of charge from the various LLS operators:

- **EUCLID compound** [http://www.euclid.org](http://www.euclid.org)
- **BLIDS Germany+Switzerland** [http://onweb.blids.de](http://onweb.blids.de)
- **Meteorage in France** [http://www.meteorage.fr](http://www.meteorage.fr)
- **Vaisala GAI** [http://www.lightningstorm.com](http://www.lightningstorm.com)

### 3.8 Network Summary

Ground based LLS operate in the most high industrialized countries now. Europe, North-America and Australia are continuously covered by LLS. In many countries operate more than one LLS. E.g. in Europe and Japan operate SAFIR and GAI-networks simultaneously. Additionally, Europe is covered by the long range British ATD system. Currently the national networks are combined into large compounds with central data processing. Outside Europe and North-America the LLS operate mostly isolated in the national bounds.

Newly installed and upgraded networks working with the latest sensor generation are able to detect approximately 90% of all CG flashes with amplitudes larger than 5 kA. The location accuracy in these networks is normally better than 1 km. The LF networks (from Vaisala-GAI) are designed to locate
only the CG flashes, while the total lightning information is provided by the SAFIR systems (Vaisala-Dimensions).

Lightning information from ground based LLS is generally missing over the oceanic areas far from the continental coasts. Large continental areas without LLS are met in Africa, many Asiatic countries and also in Russia. A continuous coverage of these regions with the existing technology networks cannot be expected for the near future due to the missing technical and financial preconditions in these countries.

Long range detection methods are being currently developed e.g. by special processing of the LF sensor data. This may extend the detection range to over 1000 km, however with low detection efficiency, a location accuracy of about 5 km and strong variations with daytime.

A further improvement in location accuracy and amplitude estimation can be expected from the implementation of wave propagation models which take into account orography and different ground conductivity.

In contrast to the majority of other meteorological information, LLS are owned and operated in many cases by private, non-governmental companies. This implies great differences in the data distribution policy. The complete lightning location data are restricted in access and have to be paid. Reduced information however, is made available to the public via internet.

4 Satellite Based Lightning Location

Satellite based lightning detection and location methods are not operationally implemented, but a few platforms are in work now since the middle of the 1990s. These include the NASA development of optical lightning sensor arrays (OTD, LIS) and the multisensor (RF and optical) satellite FORTE launched by the Los Alamos National Laboratory.

4.1 Optical Location: OTD and LIS

First satellite based lightning location data were derived from the Operational Linescan System (OLS) on board of the sun-synchronous U.S. Air Force DMSP (Defense Meteorological Satellite Program) (Goodman and Christian, 1993). Observation was limited to night time, the geographical and spatial coverage was very sparse. The data were processed by NASA MSFC for 13 years between 1973 and 1997. The first dedicated observation of lightning from space in the optical range was started by NASA with the OTD (1995) and the LIS (1997) sensors (Christian, 1999). It is planned to install a geostationary lightning mapper (LMS) on GOES (Weber et al., 1998).

4.1.1 Emission and Propagation of Optical Radiation

Lightning emits optical radiation during its hot phase. This thermal radiation is described by Planck’s law and the total intensity is proportional to the 4th power of the channel’s surface temperature.

The optical radiation is scattered in the atmosphere by gases, aerosols and cloud particles. Most significant is the multiple scattering by cloud particles. According to Christian et al. (1989) the energy loss by this process due to absorption is low. Most of the optical energy is conserved and the part
scattered into the upper hemisphere can be detected from a satellite based sensor. More recently Light et al. (2001) simulated the optical signal in satellite based lightning detection.

The optical arrays are sensitive to high energetic particles (e.g. protons) which cause non-lightning detection and can saturate the sensor. This hampers the lightning detection in regions like the South Atlantic Anomaly (SAA) with unusually high proton levels caused by a minimum of the geomagnetic field.

4.1.2 OTD Sensor

The Optical Transients Detector (OTD) was developed by NASA and was launched into space in 1995. It is carried by the Microlab satellite, which is on a 70° sun-synchronous orbit at an altitude of 740 km above the ground.

The optical radiation of lightning is detected with a 128 × 128 pixel CCD matrix. The field of view projected onto the earth surface is 1300 km × 1300 km. The radiation is passed through a narrow interference filter which is centred at the wavelength of ionized Oxygen at 777.4 nm.

Special data processing (the Real Time Event Processor) was developed in order to address the specific problems such as short time of the flash, daylight conditions, optical noise form many other sources. An instrument description is given e.g. by Christian et al. (1996). Figure 7 shows an example plot of lightning detected by OTD.

Figure 7: OTD lightning observation on 21 July 1998 during all ascending passes. (From NASA webpage)
4 SATELLITE BASED LIGHTNING LOCATION

4.1.3 LIS Sensor

The Lightning Imaging Sensor (LIS) was launched on board of the Tropical Rainfall Measuring Miss­ion (TRMM) satellite in 1997 (Kummerow et al., 1998). According to the objectives of the TRMM the satellite’s orbit limited the observation area to the latitudes ±35°. The construction of the LIS in­strument resembles the OTD with several improvements in sensitivity, design and electronics (Chris­tian, 1999).

4.1.4 Data Characteristics

The data sets from both sensors along with the data analysis software library are freely available for the scientific community. The data include for every detected event location data and radiation energy. This is completed by ancillary information about the orbit, observation conditions, noise, instrument status and also the background images.

The orbital parameters of both sensors are listed in table 2.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>OTD</th>
<th>LIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>70°, 740km</td>
<td>35°, 350km</td>
</tr>
<tr>
<td>Field of View</td>
<td>1300 km × 1300 km</td>
<td>550 km × 550 km</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>10 km</td>
<td>5 km</td>
</tr>
<tr>
<td>Observation time for a fixed ground location during overpass</td>
<td>1-270 sec</td>
<td>90 sec</td>
</tr>
</tbody>
</table>

Table 2: Orbital parameters of OTD and LIS sensors

The sophisticated primary data processing performs a hierarchical clustering of data into events, groups, flashes and areas.

OTD and LIS detect both CG and IC flashes, i.e. total lightning. However, basing on the optical data alone, it is difficult to discriminate between both types, i.e. to discern the ground strikes.

The big advantage of the OTD and LIS data is the global homogeneity of the observation. Some external influences (sun glints, SAA) depend however on satellite position or viewing angle.

The short observation time for fixed locations at the ground during the overpasses limit presently the use of these data in forecast and nowcasting. The main applications are in climatology, comparing studies and single case studies on storm cloud scale. It was a major aim of NASA to perform intensive tests and validations on these sensors data to develop various algorithms and methods for future sensors in space.

Data from OTD and LIS have been investigated by many scientific groups worldwide. Comparative analyses have been performed with ground based data from operational LLS (NLDN) and total lightning systems (e.g. LDAR). The detection accuracy was found to be within 10 km (OTD) and 3-6 km (LIS). Due to non-perfect geolocation of the satellite the location data may be biased by few km. The detection efficiency for CG lightning is about 45-70%, slightly higher for IC lightning (Boccippio et al., 2000).
4.1.5 Scientific Results and Applications

The observations with the both sensors made it first possible to observe lightning continuously on the whole globe. Since OTD operated almost continuously from 1995 until 1999 the data set is suited for a 5-year global climatology. A lot of scientific facts about global lightning distribution could be established firstly or have been proved (Boccippio et al., 2001). This includes the land-ocean distribution, latitudinal variations, and the global lightning flash rate (Christian et al., 1999).

The global OTD data set found use in other application, e.g. for the parameterisation of lightning produced NOx in Chemical Transport Models (Allen and Pickering, 2002).

The LIS being an integral part of TRMM made it possible to interrelate the electric discharge activity in clouds to their particle content as observed by the radiometers and radars. This also enables the investigation of cloud electrification. Figur 8 displays a 3 month lightning summary from LIS.

![LIS Lightning Observations](image)

Figure 8: LIS lightning observation summary for 3 months: Dec 1997 - Feb 1998. (From NASA webpage)

Basing on the experience gathered with the both sensors NASA is prepared to the launch of the Lightning Mapping Sensor (LMS), which will be on a geostationary orbit.

4.2 Combined Radio-Optical Observation: FORTE

4.2.1 FORTE Sensors

The Fast On-Orbit Recording of Transient Events (FORTE) satellite is a joint Los Alamos National Laboratory (LANL) and Sandia National Laboratories project. The satellite was launched in 1997 in a circular, 825-km-altitude orbit with 70° inclination. It was designed to test technologies to remotely monitor compliance with arms control treaties (nonproliferation) and for lightning and ionospheric research.
The satellite carries 3 sensors:

**Broadband VHF receivers** with a total frequency range of 26 – 300 MHz. Two independent receivers both with 22 MHz bandwidth can be used. For lightning detection usually a lower band (26–48MHz) and upper band (118–140 MHz) is employed. The receivers record at high sampling rate (50 MHz). The used 35 ft antenna has an aperture of 80\(^\circ\).

**Broadband photodiode (PDD)** in the visible – near infrared wavelength interval (400–1100 nm) for the record of the optical waveform during 2 ms with 15\(\mu\)s resolution. The viewing angle is approximately 80\(^\circ\), which corresponds to an area of 1200 km diameter on earth surface.

**Narrow band CCD-array** of 128\(\times\)128 pixels – the Lightning Location System (LLS) with an observing wavelength of 777.6 nm. The pixel size projection gives a 10 km\(\times\)10 km footprint on the earth.

The payload was described e.g. Massey et al. (1998). The optical lightning sensor (OLS) is based on the design of NASA's detectors OTD and LIS described above with electronics developed by the Sandia National Laboratories.

FORTE’s instruments detect, record, and analyze transient radio frequency and optical signals that arise from near the Earth’s surface. It can operate in various modes, RF ranges and trigger conditions. The geometrical orbit parameters are nearly the same as for the OTD sensor on the microlab satellite.

### 4.2.2 Scientific Results and Applications

The FORTE lightning data have been compared against various ground based LLS: with the LASA VLF-array (Massey et al., 1999), the NLDN (Jacobson et al., 2000) and the ATD (Jacobson and Williams, 2001).

New results were gained in lightning research investigating strong IC discharges, which are detected from space such as trans-ionic pulse pairs (TIPP) (Holden et al., 1995). It was established that these events originate from narrow-bipolar events within the clouds: the compact intracloud discharges (CID) which emit fast and isolated bipolar electric field change pulses (Smith et al., 1999).

FORTE has provided a better understanding of the relationship between optical and RF lightning events. There exists a strong correlation of optical and RF power for CG events, almost proportionality. The combined analysis of the RF and the optical signal enables the identification and distinguishing between CG and IC lightning and also leader processes (Suszcynsky et al., 2000).

It is proposed to provide global lightning and severe storm monitoring information which would be continuously downlinked from the GPS Block IIF satellites (Suszcynsky et al., 2000).

### 4.3 VHF-Sensor: ORAGES

ORAGES is a project of a space-born VHF lightning locator which will localize intra-cloud and cloud-to-ground lightning flashes. Basing on the SAFIR antenna technology lightning will be localized by interferometry at a receiving frequency of about 200 MHz (Bondiou-Clergerie et al., 1999). The sensor is planned to be launched in 2004 onto a low orbit (700 km altitude) with an inclination of 13\(^\circ\), which allows an intense observation of the tropics. The antenna system will be experimented on a stratospheric balloon flight. The project is directed by the French aerospace research institution ONERA in scientific collaboration with the Laboratoire d’Aerologie (Toulouse).
4.4 Satellite Summary

Detection and location of lightning from satellite based sensors have been developed to high quality during the last 5 years. Optical location sensors (OTD, LIS and OLS) detect total lightning (CG and IC) with a location accuracy of approximately 5-10 km. With these sensors for the first time lightning can be observed globally. The data were validated against ground based LLS, mainly for the USA, but also outside the US.

The additional VHF broadband sensor on the multi-sensor platform FORTE opens new possibilities in lightning observation. A combined analysis of VHF and optical data permits the discrimination between the lightning types.

The data from both systems are available for the scientific community and are intensively explored currently.

The platforms are intermediate steps towards continuous global observation of lightning from geostationary platform (NASA-MSFC) or a family of low orbit satellites (LANL). A lightning mapper (LMS) is scheduled to be launched on GOES-East and GOES-West for continuous lightning observation over America.

5 Use of Lightning Location Data

Lightning location data are widely used now in research and in various application fields. A part of applications make operational use of the real-time data for all kind of warning purposes (weather services, power plants, aviation), while other applications use the archived data (insurances, climatologies, research). This section gives an overview of typical applications of lightning data in atmospheric research, meteorological services and other applications.

5.1 Comparative Studies

Lightning data from all the described LLS have been analysed in various fields of thunderstorm research on the various scales in combination with other cloud data from radar and satellites.

5.1.1 Radar and Satellite

Identification and characterisation of thunderstorms is accomplished by cloud satellites and radars. Cloud observing (IR) satellites provide images of the cloud top temperature and height with spatial resolution of 5 km and repetition rate of currently 30 min. Precipitation and cloud radars use the reflectivity information for determination of rain rate or in terms of particle density and size. Spatial resolution ranges form 100 m – 2 km, the sampling rate for operational radars is about 10-20 min.

Lightning data add value to this information by indicating the most active parts of the storm clouds. Thus lightning data help to narrow the potentially hazardous regions. Another advantage is the real time availability of lightning information. Thereby lightning can bridge the time between successive scans and fill the gaps caused by failures of the scanning systems.
This is valuable in any stage of the storm development. In the growing phase it helps to recognize the fastest growing cells. During the mature phase the storm cloud is large and not homogeneous. Lightning marks the most active part, when satellite images show largely extended anvil clouds. Lightning data help to distinguish active cells from dissipating regions in clouds with uniform high radar reflectivity. Furthermore, the development tendency - intensification or ceasing - goes along with characteristic changes in the total lightning activity. Lightning also identifies embedded convection in stratiform clouds, which is sometimes difficult to accomplish with radar alone.

Various quantitative studies have been performed which relate lightning rate and density to cloud parameters. We give here a short summary after MacGorman and Rust (1998):

- CG lightning occurs when the cloud’s reflectivity at a height corresponding to \(-10^\circ\)C exceeds 35-40 dBZ and the cloud top extends at least to 9 km (corresponding cloud top temperature of \(-40^\circ\)C).

- Lightning is located closely to the reflectivity maximum, but more frequent at the border of this area.

- High IC lightning activity is correlated to the volume of large reflectivities cloud regions.

### 5.1.2 Lightning and Precipitation Data

Lightning activity and precipitation amount of a storm cloud is in close relation. There is a large number of publications on this topic (Goodman and Raghavan, 1993; Richard and Lojou, 1996; Cheze and Sauvageot, 1997; Areitio et al., 1999; Anderson, 2000; Soriano et al., 2001; Soula and Chauzy, 2001). Petersen and Rutledge (1998) compared the data for different latitudes and geographical locations.

Generally a good correlation is found between lightning density and rain amount. Some authors present empirical regressions functions (mostly potential law): the rain-yield per flash. Remarkable is the large scatter in these relations for different storms and locations, which limits the practical use of these regressions. This suggests to include in the analysis additional atmospheric data such as moisture content, precipitable water. The storm type must be considered as well as synoptic scale lifting and orographic influences.

A high lightning rate is always a reliable indicator for heavy precipitation. In the absence of radar or in mountainous regions, where radar coverage is obstructed, lightning data can be a useful indicator for flash floods.

### 5.1.3 Lightning and Other Storm Characteristics

The relation of lightning activity and other storm related phenomena have been studied. This includes hail (MacGorman and Burgess, 1994; Hohl and Schiesser, 2001), tornados (Buechler et al., 2000; McCaul et al., 2002), gust and microburst (Laroche et al., 1991) and flash floods (Petersen et al., 1999). These case studies established characteristic signatures in the flash rate time series preceding the occurrence of e.g. hail or tornados.

Positive lightning is less frequent (<10%) in the average but occurs to high percentage in winter storms (Shimura et al., 1999) and at the end of storms (MacGorman and Rust, 1998).
Lightning activity also varies with the dynamic organisation of the storm. Supercell storms were observed with an unusual large percentage of IC lightning (Ray et al., 1987). High lightning densities are observed in squall-lines and in Mesoscale Convective Systems (MacGorman and Morgenstern, 1998).

### 5.2 Climatologies

Various statistical analyses of lightning data have been published mostly for the national networks. (e.g. Orville and Huffines, 1999; Finke and Hauf, 1996; Tuomi, 1996; Hidayat and Ishii, 1998). Lightning climatologies show the geographical distribution of the lightning density, time series of lightning totals for various regions, such as annual and diurnal cycles, frequency distribution of number of lightning impacts and other parameters.

A common feature of these climatologies particularly for the middle latitudes is the high variability of the annual mean values. The reason is the concentration of most of the lightning events on few days in certain thunderstorms. This ‘fractal’ property of the lightning distribution requires a long observation time in order to get statistically significant mean values.

The network’s DE is not uniform in space and changes with time (with various improvements of sensors and network). Statistics from different networks can hardly be compared due to the many differences between them. With the tendency towards network integration a more homogeneous spatial DE will be achieved and climatologies of larger regions will become available.

The relation between lightning density and the synoptic observations of thunderstorm days has been investigated (Changnon, 1989, 1993; Finke and Hauf, 1996). A good correlation has been found, in general with deviations due to varying acoustic conditions at the synoptic stations.

Another application is the use of lightning data for derivation of storm parameters. Hagen et al. (1999) applied a semi-automatic method for a statistical analysis of storm motion parameters. An automated tracking of lightning and radar data was presented by Steinacker et al. (2000).

Global distribution of lightning can now be calculated from the satellite (OTD) data (Christian et al., 1999). It turned out, that most of the lightning activity is concentrated over the tropical land masses with an expressed diurnal cycle, while lightning over the oceans is more constant in time. The mean global flash rate was established to amount 37 flashes per second.

Lightning statistics are the base for lightning risk assessment. Changes in lightning distribution may indicate regional and global manifestations of global climate change (Price and Rind, 1994). This suggests the use of lightning statistics for climate monitoring.

### 5.3 Weather Forecast and Nowcasting

The value of lightning data for nowcasting of severe convection is evident and methods for integration of lightning data in various algorithms have been developed (e.g. Goodman, 1991; Morel and Senesi, 2000).

Lightning data report uniquely the electric activity in clouds and lightning strike hazard. Combined with other cloud observations from radar and satellite it adds value by indicating the most active parts in the cloud.
Lightning data are easy to display and to interpret. The sequence of lightning location points gives the forecaster a fast overview of the development of convective activity in the whole region. The data arrive practically without delay, hence lightning information fills the gaps between sampling times of other instruments.

The synergistic effects of combining lightning, radar and satellite data support the early detection of convection, the detection of intensification or ceasing, and a qualified tracking and motion forecasting. Forecast of convective storms can benefit from additional information provided by the IC lightning data. Total lightning gives a more complete picture of the electrical activity. It requires however more interpretation effort and the development of proper display techniques which reduce the amount of data to useful information.

In the COST Action 78 (COST = European Co-operation in the Field of Scientific and Technical Research) a special task was dedicated to the use lightning data for early detection, nowcasting and classification of thunderstorms (COST-78, 2001).

An algorithm for tracking and nowcasting of motion and evolution of storms on various scale was recently developed by Morel and Senesi (2000). The authors use satellite (Meteosat) data together with lightning data from a ground based LLS for identification of storms. Each identified storm is treated as an 'object' with the properties: size parameters, motion vectors, cloud top temperature structure and lightning content.

In Jacobs and Raatz (2001) numerical model output is combined with observed data from radar, satellite and lightning detection system for a pixel-wise nowcasting for 3 hours in advance. Knüpffer (2001) presented a method for predicting lightning with a MOS (Model Output Statistics)-schema. The input data are observed lightning data and forecast from the numerical model GMS of the German Weather Service.

5.4 Total Lightning

Total lightning includes the Cloud-to-Ground flashes and the intracloud lightning. Generally the IC discharges precede the CG lightning in the life cycle of convective clouds. It was shown in comparative studies that the time difference between the first detection of IC lightning and the first CG flash varies strongly (Tzanos and Senesi, 1998). For fast developing clouds this time may amount only a few minutes (Richard and Kononov, 2001), while other clouds exist long time without producing any CG flash. Among the currently employed operational LLS only SAFIR detects IC lightning.

For many applications the total lightning information is of significance, since total lightning gives a more complete information about the electric activity in the storm. A cloud with IC lightning is potentially dangerous, because lightning can be triggered by objects close enough. Furthermore, the cloud may intensify and produce after some time CG lightning. Residual clouds left from convective systems may be electrified and represent a hazard for aviation.

For practical applications it is important to reduce the IC lightning information into proper products which can be easily used by the end users (Richard and Kononov, 2001). The usefulness of total lightning information for aviation was demonstrated with the LISDAD product (see sec. 5.6.1).
5 USE OF LIGHTNING LOCATION DATA

5.5 Atmospheric Chemistry

In the hot lightning channel at temperatures above 3000-4000 K nitrogen oxide NO is created in high concentration (Chameides et al., 1977). Due to the fast cooling of the lightning channel this high concentration remains 'frozen' after the return to ambient temperatures (Zeldovich and Raizer, 1966; Hill, 1979). The created NO is in fast establishing photochemical equilibrium with NO₂ under tropospheric conditions. The sum of both gases is named NOx. This NOx is partially transported, together with NOx from other sources, by the strong updrafts in thunderstorms up to the tropopause level (Huntrieser et al., 1998). The contribution of lightning produced NOx is currently investigated both on the cloud scale of single thunderstorms (Ridley et al., 1996) as well as on regional and global scale (Lee et al., 1997; Price et al., 1997).

Of crucial importance for these estimations is the knowledge of the distribution of CG and IC lightning. Lightning detection systems on the various scales contribute these data. On the cloud scale the 3D lightning path relative to the up- and downdrafts is reconstructed from local VHF system observations (Defer et al., 2000; Thery, 2001). For regional analyses the operational LLS can be used (Höller et al., 1999; Finke, 2000).

The absence of lightning data in most parts of the globe, especially over the tropical regions disabled global studies on lightning NOx production. Only recently, with the OTD and LIS sensors, lightning data became available for these areas even though discontinuously in time. Nesbitt et al. (2000) used OTD data for calculation of seasonal global lightning NOx production. In global chemical transport models the OTD data provide parameterizations for lightning NOx (Allen and Pickering, 2002), while total NOx columns can be gathered with other satellites (e.g GOME).

5.6 Non – Weather Service Applications

The lightning based forecast and climatology products provided by weather services and LLS operators are used in many applications. The following section describes the use of lightning location data in a few application fields where lightning data are of special interest.

5.6.1 Aviation and Flight Security

Lightning is a hazard for airplanes and can cause severe damage of the construction, fuel ignition and damages of the electronic equipment or harm the crew members. Halsey and Patton (1999) reported on the lightning hazard for helicopter operations over the Northern Sea. Military flight operations are coordinated taking into account lightning hazard.

Airplanes normally avoid thunderstorms due to the prevailing strong air motions and icing hazard. However the lightning hazard in non-thunderstorm clouds is often underestimated and lightning strikes are triggered by the aircraft itself. Hence for aviation applications the information about total lightning (IC and CG lightning) is of importance.

In the LISDAD (Lightning Imaging Sensor Data Demonstration) project total lightning information from NASA's (LDAR) is merged with CG lightning data from the NLDN and with WSR-88D radar data. The US National Weather Service Office at Melbourne (Florida) uses LISDAD for storm nowcasting and warning products for the Florida airports (Boldi et al., 1998).
5 USE OF LIGHTNING LOCATION DATA

Airport management can benefit from real time lightning data in decision finding on closing and re-opening the flight operations. Autones et al. (1999) presented an algorithm for support of the routing of air traffic in case of thunderstorms in the approach area which merges lightning and radar data in the surrounding of the Paris airport.

Nierow et al. (1999) investigated the benefit from the implementation of total lightning data for convective weather forecast. The Federal Aviation Administration uses lightning data for improved routing of airplanes (Nierow and Showalter, 2000). Due to the lack of lightning location data over the Oceans the experimental long range lightning detection network (Cramer and Cummins, 1999) was employed for this purpose. The (Aviation Weather Center) AWC is using these oceanic lightning data as input to their operational oceanic weather hazard alerts referred to as International SIGMETs (which depict significant meteorology).

5.6.2 Aerospace

Apollo-12 and Atlas/Centaur-67 were strucked by triggered lightning during launch (Christian et al., 1989). To avoid these incidents lightning forecasts and flight rules are given for scheduled missile and space shuttle launches (Garner and Oram, 2000). Primary inputs are cloud observations with radar and satellite as well as lightning observation from the NLDN and the NASA operated local high resolution LLS (LDAR, (Maier et al., 1996)).

The European Space Agency (ESA) operates a SAFIR LLS at the European Space Center CSG in Kourou, French Guyana.

5.6.3 Power Utilities

Lightning is a major cause of transmission and distribution faults and outages. Power utility operators use the real time lightning data for the network management to avoid electricity disruption and for dispatching the repair crews. Lightning data also aid in locating and identifying the cause of faults and damages of transmission lines (Fister et al., 1992; Kappenman et al., 2001). Another application is the estimation of outage statistics from lightning distribution data (Diendorfer, 2001).

5.6.4 Fire Weather Warning

Lightning is the main natural cause of forest fires and consequently, one of the first applications of LLS served the forest fire detection (Krider et al., 1980). LLS can help to identify lightning producing storms which might cause wildfires. Especially in large unhabitated areas the lightning location data can narrow the areas to be observed by aircraft.

Bothwell (2000) reported on the use of data from the NLDN in combination with computer models and remote automatic weather stations for the prediction lightning from dry thunderstorms, that create 50 percent of all wildfires in the U.S. The special role of positive lightning in fire ignition in Canada was examined by Kochtubajda et al. (2002).
5.6.5 Explosives

Substantial losses result from lightning caused ignition of fuels and explosives (e.g. Zoro et al., 1997). Well known is the Picatinny Arsenal incident in July 1926, which killed 14 people and cost 70 million Dollar. More recently in June 2001 at Buryatia, Russia 17 people were killed, 3000 people were evacuated when lightning hit a munition depot. The munitions losses exceeded 20 million rubles (Kithil, 2002). Lightning detection systems help to recognize the lightning hazard for warning and activation of protection measures.

5.6.6 Recreation and Public Event Management

Most lightning casualties happen outdoor and during recreation activities (Holle et al., 2001). Hence, lightning data can successfully be used for early warning at places with intensive recreation activity e.g. at lakes, mountains or golf courses. A prominent application was the use of NLDN data in combination with several other data for short-term forecast for the whole area of the 1996 centennial Olympic games in Atlanta (Johnson et al., 2000).

5.6.7 Insurance Companies

Lightning damages represent approximately 9% of all insurance claims amounting to several 100 million USD per year (Kithil, 1999, 2000). Insurance companies use lightning data for verification of the lightning damage claims. Insurances make use of lightning climatologies for lightning and storm damage risk assessment (Dinnes, 1999). There is an ongoing research in re-insurance companies in implications of global climate change. An increase in global lightning frequency is expected due to increase of the global temperature (Price and Rind, 1994). Mills et al. (2001) presented strong correlation between average temperature and lightning related insurance claims between 1990-95 in the United States.

5.7 Applications Summary

Lightning data are widely used in real time application for forecast and warning purposes. The intensive research on lightning data resulted in the development of many algorithms for identification and nowcasting of convective storms motion. Lightning data are a valuable addition to the other cloud observation tools like radar and satellite. Lightning is a useful proxy for other storm related hazards.

For certain applications (e.g. weather forecast at airports) a higher location accuracy than provided by the present operational systems is desirable. A higher spatial resolution and accuracy can be achieved with closer spacing of the receivers. Best suited for lightning location with accuracy in the order of 100 m are VHF systems, which are in use in few local LLS operated by research institutions for cloud and lightning research.

Many users of lightning data are interested in lightning impacts to the ground. This information is provided by the LF (GAI) networks with high accuracy and detection efficiency. For applications in weather forecast (nowcasting) and aviation, as well as for cloud research and atmospheric chemistry the information about total lightning which includes IC lightning is important. Among the commercially available systems only SAFIR provides total lightning data.
Global lightning data could be a useful information for atmospheric research, climate monitoring, and applications such as long range air traffic and communication services.

Satellite based lightning location detects uniformly CG and IC lightning over any region. The existing prototype sensors on low orbits have been used in many research applications. Due to the short observation times caused by the low orbits, their use for most of the real time applications is limited.

6 Summary and Conclusion

Lightning location by ground based networks is well established now. The detection and location principles are in use for more then 10 years and were continuously improved. The reliability and quality of the data (detection efficiency 90%, location accuracy 0.5 – 1 km) is close to the physical limit and is sufficient for the most user requirements.

The main difference in the existing systems is in the used detection frequency band (LF or VHF). One implication is the difference between total lightning detection (VHF, SAFIR) and return stroke detection (LF, GAI).

The concentration of the production of the LLS in one company now (Vaisala Group) should favour the convergence of the still existing differences of the systems as well as the exchange of knowledge and methodology.

The majority of the ground based LLS is owned by private companies. This may limit the access to data for the general public.

The existing ground based LLS operate in the industrialized countries. For large parts of the tropics (Africa, Asia) and other remote areas, as well as for the oceans no lightning data are provided. The necessary infrastructure for installation and operation (communication lines, technical support, trained operators) of the LLS is not available or affordable everywhere. The networks operating in the LF or VHF range do not reach presently far into the oceanic areas.

The existing satellite based lightning detection sensors give reliable data. Much experience have been gathered in processing, validation and application of the data. The value of optical location principle from space has been proven. The instruments detect both IC and CG lightning, the detection efficiency for CG lightning is comparable to ground based LLS. The location accuracy is in the order of 10 km and is limited by scattering in the clouds. Advantageous is the spatial homogeneity and the possibility of global observation from satellite. The low orbit of the presently used platforms has limiting implications such as short observation time and low repetition rate for a fixed point on earth. To achieve a permanent lightning detection over the American continent a geostationary platform is prepared by NASA.

The lightning data, where available, are used for warning of lightning hazard and the prevention of lightning induced damages. The requirements of the most applications with respect to data availability and quality can be met by the existing ground based LLS taking into account the improvements of these systems.

Weather forecast and nowcasting of thunderstorms use lightning data successfully but could get additional benefit from information about the intracloud lightning. This concerns particularly air traffic applications and nowcasting. Global lightning studies e.g. on NOx production or climate monitoring depend on global lightning information, which is currently not continuously available.
7 Acknowledgements

We acknowledge gracefully the provision of information and helpfully discussion which were given in interviews and email communication by S. Senesi (Meteo-France), H. Christian (NASA), S. Thern (Siemens AG, BLIDS), P. Richard (Vaisala), P. Laroche (ONERA), G. Diendorfer (ALDIS), F. Montariol (Meteo-France), T. Kratzsch (DWD).
References


REFERENCE


REFERENCES


Kithil, R. (2000). Results of investigations into annual USA lightning costs and losses. Technical report, Lightning Safety Institute, Louisville Colorado USA.


REFERENCES


REFERENCES


REFERENCES


## Appendices

### A Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALDF</td>
<td>Advanced Lightning Direction Finder</td>
</tr>
<tr>
<td>ALDIS</td>
<td>Austrian Lightning Detection and Information System</td>
</tr>
<tr>
<td>ATD</td>
<td>Arrival Time Difference</td>
</tr>
<tr>
<td>DE</td>
<td>Detection Efficiency</td>
</tr>
<tr>
<td>ELF</td>
<td>Extremely Low Frequency (30 Hz – 300 Hz)</td>
</tr>
<tr>
<td>EUCLID</td>
<td>European cooperation on Lightning Detection</td>
</tr>
<tr>
<td>FORTE</td>
<td>Fast On-orbit Recording of Transient Events</td>
</tr>
<tr>
<td>GAI</td>
<td>Global Atmospherics Inc. (now Vaisala-GAI)</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>IMPACT</td>
<td>IMProved Accuracy from Combined Technology</td>
</tr>
<tr>
<td>LANL</td>
<td>Los Alamos National Laboratory</td>
</tr>
<tr>
<td>LF</td>
<td>Low Frequency (30 kHz – 300 kHz)</td>
</tr>
<tr>
<td>LIS</td>
<td>Lightning Imaging Sensor</td>
</tr>
<tr>
<td>LLP</td>
<td>Lightning Location and Protection</td>
</tr>
<tr>
<td>LLS</td>
<td>Lightning Location System</td>
</tr>
<tr>
<td>LPATS</td>
<td>Lightning Positioning and Tracking System</td>
</tr>
<tr>
<td>MSG</td>
<td>Meteosat Second Generation</td>
</tr>
<tr>
<td>NALDN</td>
<td>North American Lightning Detection Network</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautic and Space Administration</td>
</tr>
<tr>
<td>NLDN</td>
<td>National Lightning Detection Network (USA)</td>
</tr>
<tr>
<td>ONERA</td>
<td>Office National d’Etudes et de Recherches Aéronautique</td>
</tr>
<tr>
<td>OTD</td>
<td>Optical Transient Detector</td>
</tr>
<tr>
<td>OLS</td>
<td>Optical Lightning Sensor (on FORTE)</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SAA</td>
<td>Southern Atlantic Anomaly</td>
</tr>
<tr>
<td>SAFIR</td>
<td>Surveillance et Alerte Foudre par Interférométrie Radioélectrique</td>
</tr>
<tr>
<td>TOA</td>
<td>Time of Arrival</td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency (30 MHz – 300 MHz)</td>
</tr>
<tr>
<td>VLF</td>
<td>Very Low Frequency (3 kHz – 30 kHz)</td>
</tr>
</tbody>
</table>
## Related Internet Links

- [http://www.lightningsafety.com](http://www.lightningsafety.com) National Lightning Safety Institute