On the relevance of Lightning Imagery from Geostationary Satellite Observation for Operational Meteorological Applications

by

Serge CHAUZY, Sylvain COQUILLAT, and Serge SOULA
Laboratoire d’Aérologie, UMR UPS/CNRS n° 5560

Ref EUMETSAT: EUM/COL/LET/02/1562
Request for Quotation N° 02/642

Introduction and objectives:

Lightning activity represents a major production of convective cloud systems development. As a consequence of the mechanisms at the origin of cloud electrification and of discharge initiation, lightning is closely related to all other characteristics of convective systems: covered areas, cloud tops, precipitation, ice content, updraught velocity... Lightning detection has been developed for tens of years. Ground based networks presently cover large continental surfaces. Space lightning detection has been operational since 1995. It covers the whole Earth surface within the considered latitudinal area (roughly 65° North, 65° South). The operational sensors are based on optical detection and carried by orbiting satellites. Next step of space based lightning detectors to be considered relates to geostationary satellites. The present proposal submitted to EUMETSAT plans a twofold work. The first part will review the present systems (basic concepts, interests and lacks) and the scientific and operational usefulness of the provided data. The second part will evaluate the expected interest of a lightning detection system installed on a geostationary platform, the possible connection with all other ground based and space based lightning detection systems, and the possibility of such future system to meet the users requirements for both operational and scientific purposes.
PART I: Review of existing concepts

I. 1 What does “Lightning detection” mean? 5
   I. 1. 1 The mechanism of a lightning flash 5
   I. 1. 2 Geometrical extension of a lightning flash 6
   I. 1. 3 Time scale and spatial detection 8
   I. 1. 4 Lightning climatology 8

I. 2 Relationship of lightning activity with other meteorological characteristics 10
   I. 2. 1 With precipitation of convective systems 10
   I. 2. 2 With cloud ice content 12
   I. 2. 3 With dynamics and microphysics of convective systems 13
   I. 2. 4 With hail production and severe weather 16
   I. 2. 5 With climate change 17
   I. 2. 6 Operational meteorological application of lightning detection 20

I. 3 Ground based detection 22
   I. 3. 1 The various principles of operational systems 22
   I. 3. 2 Perspectives – “The systems of the future” 25
   I. 3. 3 Comparing performances and limitations in terms of requirement users 26
   I. 3. 4 The operational applications (over continents) 27

I. 4 Detection from space 29
   I. 4. 1 The various principles of present systems 29
      I. 4. 1. 1 Optical detection 29
      I. 4. 1. 2 Electromagnetic detection 33
   I. 4. 2 Perspectives – The projects 35
      I. 4. 2. 1 ORAGES Project 35
      I. 4. 2. 2 Lightning Mapper Sensor mission 39
   I. 4. 3 Comparing performances and limitations 47
      I. 4. 3. 1 Accuracy 48
      I. 4. 3. 2 Horizontal resolution 48
      I. 4. 3. 3 Time sampling 49
      I. 4. 3. 4 Lightning flash type discrimination ability 49
      I. 4. 3. 5 Ocean/land detection 50
      I. 4. 3. 6 Comparison to user requirements 50

I. 5 Conclusion – The operational applications 52
PART II: Feasibility

Introduction 54

II. 1. Value added of a detection from Geostationary platform 55

II. 1. 1 Detection over oceanic and land masses 55
II. 1. 2 Large global area homogeneously covered 55
II. 1. 3 Theoretical possibility of following a given thunderstorm event from space 56

II. 2 Various possible systems 57

II. 2. 1 Optical detection 57
   II. 2. 1. 1 Advantages 57
   II. 2. 1. 2 Disadvantages and uncertainties 57
   II. 2. 1. 3 Possibility to meet users requirements 58
II. 2. 2 Electromagnetic detection 58
   II. 2. 2. 1 Advantages 58
   II. 2. 2. 2 Disadvantages and uncertainties 59
   II. 2. 2. 3 Possibility to meet users requirements 59

II. 3 Limiting factors of the platform 61

II. 4 Possible synergies based on geostationary lightning detection 62

II. 4. 1 Association with other spatial lightning detection systems 62
II. 4. 2 Association with ground lightning detection systems 62
II. 4. 3 Association with other meteorological observations 65

II. 5 Conclusion 67

References 68
PART I

Review of existing concepts
I. 1 What does “Lightning detection” mean?

All lightning flash detection systems aim at determining the instant \( t \) and the coordinates \( (x, y \) and sometimes \( z) \) of a cloud discharge produced by a thunderstorm. Some of the existing operational systems detect only cloud-to-ground discharges, whereas others detect all types of flashes and usually discriminate between intracloud and cloud-to-ground lightning activity. An estimate of the electric current intensity produced by return strokes is also performed by some of the existing networks. In order to better identify the required performances of a detection system, the characteristics of such an event necessary for the detection procedure must be correctly defined.

I. 1. 1 The mechanism of a lightning flash

A lightning flash is the result of an electrostatic stress within the cloudy medium. This stress is established through various mechanisms of electric charge separation that involve the microphysics and the dynamics of the thundercloud. When a given threshold (determined by the local electric field intensity and microphysical conditions) is reached, a propagating discharge is initiated. Between 70 and 80% of these discharges stay within the cloud: they are called intracloud (IC) discharges. From 20 to 30% of them connect to ground. Although most cloud-to-ground (CG) discharges lower negative charge to the earth surface, some of them bring positive charge.

Except for some CG flashes that initiate from ground elevated structures (towers, high building, mountain tops...), both types (IC and CG) start with a bi-leader process. Emerging from the region of the cloud where the initiating conditions are gathered, a positive leader propagates towards and within a negatively charged cloud zone whereas a negative leader propagates towards and within a positively charged cloud zone. Each leader extremity propagates horizontally within oppositely charged regions (Fig. I.1.1).

In the case of an intracloud flash, when both regions of opposite polarity are connected through the bi-leader discharge, a “recoil streamer” process takes place. This stage of the IC flash corresponds to high current intensities propagating back through the channel already formed. It produces the highest temperature, luminosity, and thunder.

In the case of a cloud-to-ground flash, one of the target zones is the surface and thus a ground impact occurs. The leader phase is thus followed by the return stroke, a strong discharge propagating up from the ground to the cloud. The return stroke produces an intense electric current (up to several hundreds of kA) and a strong luminosity, propagates at high velocities.
(up to $2.7 \times 10^8\, \text{m s}^{-1}$), and undergoes strong temperature elevations (up to 30 000 K) that produces thunder.

A given flash, regardless of the type, can be composed of several strokes. That is to say successive strokes can occur after the first return stroke following the channel already formed. Up to several tens of such subsequent strokes have been recorded for CG flashes. This multiplicity produces the flickering aspect of some long lasting flashes (up to 2 seconds).

### I. 1. 2 Geometrical extension of a lightning flash

Depending on the technique utilized, lightning mapping is based on the detection of leader phase (all kinds of flashes), return stroke phase (CG flashes) or recoil streamer phase (IC flashes). Operational ground systems detect the electromagnetic radiation generated by the channel. Most operational space systems rely on optical detection, i.e. is triggered by the most energetic phase, return stroke or recoil streamer.

It is thus necessary to characterize the possible extent of a given flash in order to adapt the resolution requirements to the observed phenomenon.

The vertical extension is a characteristic rather easy to establish. Thunderclouds usually extend vertically beyond the tropopause, up to 16 or even 20 km in tropical latitudes. Measurements performed from acoustic and electromagnetic detection show that channel segments can reach 15 km of altitude (Fig. I.1.2). This feature is relevant only for 3D detection procedures. Most operational mapping systems (ground as well as space) carry out 2D detection and do not consider the vertical dimension.

Of more importance, as far as flash detection is concerned, is the horizontal extension of the lightning discharge. The variety of channel geometry is such that some CG flashes are predominately vertical (Proctor et al., 1988). However the development of sophisticated mapping systems such as the 3-dimensional Lightning Mapping System of New Mexico Tech (Krehbiel et al., 1999) revealed that some flashes may reach considerable horizontal extensions. Distances over 100 km are observed in Mesoscale Convective Systems (MCS’s), or in Squall Lines.

Moreover, recent measurements show examples of mostly intracloud discharges developing over horizontal extensions of some 200 km and eventually connecting several times to ground on locations separated several kilometers from each other or even several tens of kilometers. Such events give an idea on the difficulty to characterize a lightning flash as a localized event.
Figure I.1.3 displays a VHF radiation pattern generated during a period of 52 s during which a sequence of seven flashes (IC’s and CG’s) were produced by a South African thunderstorm (Proctor, 1983). The horizontal extension exceeds 20 km.

Still more striking appears the event presented on figure I.1.4 (Krehbiel et al., 1999) that shows similar results obtained by detecting the VHF radiation from a single extensive hybrid IC-CG discharge lasting about 1.5 s during a thunderstorm in central Oklahoma (June 1998). The horizontal extension exceeds 60 km, and the discharge connected twice to ground during the 1.5 s-event.

These recent results show that flash detection is not a trivial task. If a mapping system is meant to indicate the horizontal location of a flash event, one must consider the kind of flash and its overall characteristics. As a matter of fact, only a CG flash impact on the ground can be clearly determined if the system is accurate enough. The whole development of the
discharge within the cloud may reach such a volume of the thundercloud that its horizontal extension sometimes considerably exceeds the resolution of the detection system. Therefore, the horizontal resolution required for the future sensor should take this characteristics into account.

I. 1. 3 Time scale and spatial detection

Lightning detection from satellite requires a specific procedure very different from all other observations. Most parameters observed from space evolve with rather long time constants. Temperature, humidity, pollution, do not vary much during periods of the order of a few minutes. Vegetation undergoes still slower evolution processes. On the contrary, a lightning flash lasts from a few milliseconds up to about 2 seconds. The task of a ground detection network consists in detecting, identifying, and recording all flash events that occur over a given territory. The network achieves this goal by constantly observing the whole area under investigation.

Lightning detection from space proceeds differently. The instruments carried by orbiting satellites sweep the Earth surface and therefore at a given instant observe only the rather small area corresponding to the field of view. Such a system has a limited ability to follow and monitor the activity of a given thunderstorm that can last several hours, and up to a few days for squall lines and hurricanes. As a matter of fact, it samples the lightning activity. A geostationary platform allows a constant observation of a large portion of the globe. The picture restitution usually takes a few minutes, which does not affect the majority of the observed parameters. However, if this procedure is extended to the lightning detection system, it keeps this system from observing all the simultaneous lightning events. Again it achieves a sampling of the related activity, but with a higher rate than the orbiting system. Under such conditions it will still not be possible to constantly monitor a thunderstorm event. However it will be able to follow the evolution of a thunderstorm whose lifetime stays much longer than the time sampling. Depending on the various possibilities examined in this report, the issues of the detection system will achieve different goals.

I. 1. 4 Lightning climatology

The detection of the lightning flashes allows to evaluate the climatology of this specific activity of storms, at various scales of space and time, depending on the available detection system. Thus satellites equipped with sensors sensitive to the whole lightning activity provide a global distribution in time and space estimated from fragmentary observations corresponding to the satellite passages (Christian et al., 1999). These observations emphasize several characteristics of the lightning activity at the Earth scale, as indicated in Fig. I.1.5 : (i) the lightning activity is much higher over continents than over oceans (with a ratio of about 11). (ii) the lightning activity is dominant in the tropical areas. (iii) the lightning activity is weaker at higher latitudes. (iv) the lightning activity is higher in summer than in winter for both north and south temperate zones. The ground networks, with continuous observations, provide facilities for determining the climatology of the Cloud-to-Ground lightning flashes at a country scale. Various works provide some aspects of these climatologies, Orville (1994) for the contiguous United States from 1989 to 1991, Zajac and Rutledge (2001) for the contiguous United States from 1995 to 1999, Orville et al. (2002) for the North American
detection network, Rivas et al. (2001) for the Iberian Peninsula, Finke and Hauf (1996) for the Southern Germany.

Fig. I.1.5 : Distribution of lightning activity estimated from the sensor OTD for December, January, and February 1999 (upper graph) and for June, July, and August 1999 (lower graph). (http://thunder.nsstc.nasa.gov/data/OTDsummaries/)

Fig. I.1.5 : Distribution of lightning activity estimated from the sensor OTD for December, January, and February 1999 (upper graph) and for June, July, and August 1999 (lower graph). (http://thunder.nsstc.nasa.gov/data/OTDsummaries/)
I. 2 Relationship of lightning activity with other meteorological characteristics

The lightning activity of a thunderstorm is the result of the complex physical mechanisms undergone by the corresponding cloud convective system. Cloud electrification processes, on the one hand, and discharge initiation processes, on the other hand, are the complementary key mechanisms leading to this activity. Electrification processes (i.e., electric charge separation mechanisms) are closely related to the microphysical and dynamical properties of the cloudy medium through the main motor of in-cloud precipitation. Two basic phenomena are nowadays considered to play the major part in electrification: inductive processes (those mechanisms requiring preexisting intense electric field), and non-inductive processes (those that separate electric charge independently from the presence of such a field). Both phenomena occur during collisions between hydrometeors, therefore necessitate the presence of precipitation within the cloud. The non-inductive mechanism, actually considered as the most efficient electrification process, occurs when ice particles collide in a given region of the cloud (Takahashi and Miyawaki, 2002). Concentration of super-cooled liquid water and ambient temperature are the key parameters that govern the amount and the polarity of the electric charge separated during collisions. The initiation of a propagating discharge eventually producing a lightning flash occurs when the relevant electrical conditions are gathered within a given region of the cloud. Recent investigations consider that such conditions require high electric field and presence of large liquid hydrometeors that locally enhance the field (Coquillat and Chauzy, 1994; Blyth et al., 1998).

Considering that both phenomena at the origin of lightning activity, electrification and discharge initiation, depend on microphysics and dynamics of thunderclouds, we can expect a strong correlation to appear between lightning activity and basic meteorological characteristics related to cloud systems, such as those considered in the following subsections. Lightning activity can thus play the part of a simple parameter that integrates various atmospheric conditions and brings information on these conditions.

I. 2. 1 With precipitation of convective systems

A relationship in terms of rainfall yield per flash between Cloud-to-Ground lightning activity and ground rainfall has been noted firstly by Battan (1965) by using very basic observation means. The lightning flashes were counted by human observers and the rainfall was measured by a rain gauge network. Even with such an approximate method, he determined a rainfall yield per flash that will not be contradicted in the following studies. Thus, from 52 storms in Arizona, he found an average value of $30 \times 10^3$ m$^3$ and a yield range from 3 to $300 \times 10^3$ m$^3$. A few years later, with more elaborated flash detection techniques, these values were roughly confirmed in most of cases (Kinzer, 1974; Lopez et al., 1991; Holle et al., 1994; Soula and Chauzy, 2001). Table I.2.1 shows some examples of values found by different authors in various conditions and locations around the world. The yield is observed to decrease as the number of CG flashes produced by the thunderstorm increases (Kinzer, 1974; Lopez et al., 1991; Maier et al., 1978; Williams et al., 1992; Buechler et al., 1990). Furthermore, it is generally higher in tropical storms (Williams et al., 1992) and in storms producing large proportions of positive CG (Soula and Chauzy, 2001). Few studies have been made to
determine a yield per flash with the total flash activity. However, Piepgrass et al. (1982) found values of 0.7 and 0.9×10³ m³ in two cases of storms. Furthermore, they observed that for a given storm, the maximum of flash activity occurred before that of rainfall at the ground. This last observation tends to present the flash activity as a possible criterion of nowcasting for the very large rainfall amounts producing flash floods.

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Cases</th>
<th>Yield (10⁶ kg per ground flash)</th>
<th>Average Yield (10⁶ kg per ground flash)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battan (1955)</td>
<td>Arizona</td>
<td>52</td>
<td>0.3–30</td>
<td>3</td>
</tr>
<tr>
<td>Kinzer (1974)</td>
<td>Oklahoma</td>
<td>1°</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Groth (1978)</td>
<td>Illinois</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Maier et al. (1978)</td>
<td>Florida</td>
<td>22</td>
<td>0.3–90</td>
<td>10°</td>
</tr>
<tr>
<td>Piepgrass et al. (1982)</td>
<td>Florida</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Buechler et al. (1990)</td>
<td>Tennessee Valley</td>
<td>21</td>
<td>0.9–20</td>
<td>4</td>
</tr>
<tr>
<td>Williams et al. (1992)</td>
<td>Darwin, Australia</td>
<td>45°</td>
<td>9–100</td>
<td>30°</td>
</tr>
<tr>
<td>Williams et al. (1992)</td>
<td>Darwin, Australia</td>
<td>6°</td>
<td>200–3000</td>
<td>800°</td>
</tr>
<tr>
<td>Holle et al. (1994)</td>
<td>central United States</td>
<td>4°</td>
<td>30–80</td>
<td>50</td>
</tr>
</tbody>
</table>

*From the selected portion of a squall line; °Continental storms (as opposed to monsoon storms); °Monsoon storms; °Mesoscale convective system; °A rough estimate from graphed data.

Table I.2.1: Rainfall yield per ground flash for individual storms or storm days. (From MacGorman and Rust, 1998)

In order to explain the wide variation of the rainfall yield per flash, authors evoked the duration of different stages of storm evolution. Rainfall rate generally decreases less rapidly than the lightning activity and even can continue several hours after the deep convection in the cases of squall lines (Holle et al., 1994; Rutledge and MacGorman, 1988). The estimation of the rainfall amount produced by a convective system highly depends on the duration taken into account. The other important factor for the variation is the climatological conditions in which the storms develop. For example, the CG flashes increase with the peak base-scan reflectivity (Reap and Mac Gorman, 1989). Several authors reported smaller rainfall yield when the CAPE is larger in different locations, in the Tennessee Valley for Buechler and Goodman (1991), in northern Australia for Williams et al. (1992). However, because of a large number of environmental conditions influencing the convection, it is difficult to determine a constant correlation between the yield and other parameters. The variability of the CG flash proportion can be also a cause of the yield variation (Buechler et al., 1990). Furthermore, some convective systems produce rainfall with very few lightning flashes, especially above sea in tropical regions (Zipser, 1994). A recent result showed a good correlation between the rainfall yield and the proportion of positive CG flashes produced by the thundercell in a study based on about 40 thundercells (Soula and Chauzy, 2001). Figure I.2.1 illustrates this correlation by displaying the rainfall yield versus the positive CG percentage. The rainfall yield increases with this percentage and the correlation coefficient is very high for this distribution (0.96). The limitation of the distribution is linked to the low number of cases with large positive CG percentage.
Figure I.2.1: Distribution of the water volume per CG flash versus the positive CG flash percentage. (From Soula and Chauzy, 2001)

For the understanding of a possible relationship, we can assume that both precipitation growth and charging processes need the presence of specific particle types and quantities. However, several mechanisms of charge separation are suspected to occur in the cloud according to several meteorological conditions like temperature, water content, condensation nuclei concentration. The variation of this relationship is then comprehensible. Furthermore, the lightning triggering could require other specific conditions of high electric field and microphysical contain (Coquillat and Chauzy, 1994).

I. 2. 2 With cloud ice content

The ice crystal concentrations in the anvils of thunderstorms are considered as a parameter of considerable climatological importance. As a matter of fact, the thunderstorm anvils are a significant source of ice particles in the upper atmosphere, and these particles exercise a large influence on the radiative balance of the atmosphere. By a model study, Baker et al. (1999) suggested a value of $10^6$ kg for the mass of non-precipitating ice associated with a lightning flash, independently from the flash type. By associating this result with satellite observations issued from OTD providing total lightning frequency, they estimated the global flux of ice crystals upwards into thunderstorm anvils as $4 \times 10^7$ kg/s. They estimated the total mass of ice crystal in the anvils as $4 \times 10^{11}$ kg. More satellite data and analysis should be necessary to confirm these large scale estimations.
Another work by Blyth et al. (2001) showed the possibility to associate the global lightning frequency with the precipitating and non-precipitating contents and fluxes of ice. In this work, they associated the observations made from the satellite-borne Lightning Imaging Sensor (LIS) and TRMM Microwave Imager (TMI). By choosing the microwave scattering signatures at 37 and 85 GHz, they exhibited a log-linear relationship between the number of optical lightning pulses produced by each storm considered and the corresponding microwave brightness temperatures (Fig 1.2.2). These relationships were found to be consistent in various conditions of climatology, environment and season. The conclusion of this work could be the possible existence of global relationships between lightning activity and cloud ice content. However, more calculations have to be led in order to refine the determination of the cloud ice content. An important phenomenon to take into account is the interaction between precipitating ice particles of different size for the electric charge separation. A relevant study on this issue would require more data on the charge/size relations.

Fig. 1.2.2: The observed relationships between LIS lightning activity and TMI brightness temperatures \( T_B \) at 85 GHz (left side) and at 37 GHz (right side). (From Blyth et al., 2001)

I. 2. 3 With dynamics and microphysics of convective systems

The lightning production is related to other characteristics of the thundercloud, as the height of cloud top, the base-scan reflectivity, the vigorous convective growth, the particles content, the stage of development of the storm.

Several studies showed that lightning activity began when the top of the radar echo of the storm grew at an altitude where the temperature was \( \leq -20 \) °C. However, this condition is not absolute because storms without any lightning were observed with temperatures between –25 °C and –40 °C (Jones, 1950). Tohsha and Ichimira (1961) found that there was a 90 % probability that storms whose radar-detected tops were –16 °C or colder were thunderstorms (with lightning). On the other hand, storms with maximum cloud heights of 8-9.5 km (-20 to –30 °C) and producing large electric field at the ground (10 kV m\(^{-1}\)) did not become thunderstorms as observed by Dye et al., 1989).

For the criterion of the electric field measured at the ground, some works have shown that its value is not really representative of the cloud charge (Soula and Chauzy, 1991). As a matter
of fact, because of the point discharge at the ground, the development of a screening charge layer can limit the field value measured below.

Holle and Maier (1982) studied a large number of storms in Florida and established the results given in Table I.2.2 about the probability of lightning with the altitude of cloud top. Logically, the probability increases with altitude but only reaches 100% in the very high altitude with little case for its estimation. It is important to note that this criterion, like many others, can change according to the climatology of the region, the season etc…

Another relation has been considered between the lightning presence probability and the base-scan reflectivity. The base-scan reflectivity is the maximum reflectivity observed in the cloud at the lowest elevation angle. Reap and MacGorman (1989) studied this relation for storms in Kansas and in Oklahoma on one hand, and for storms in the United States on the other hand.

As shown in Figure I.2.3, the probability of occurrence of thunderstorms increased with increasing reflectivity but did not reach 1. The VIP level corresponds to a reflectivity value (for example VIP 3 is 41 dBZ). The evolution of the probability is different for both regions.

The parameter that can be another relevant criterion is the dynamics of the cell, and especially the vertical velocity distribution and value. So, from several studies, a requirement for lightning production appears to be the presence of vigorous convective growth at temperatures colder than value estimated between \(-10 \, ^\circ C\) and \(-20 \, ^\circ C\). However, the timing of initial lightning activity does not correspond to that of strong convection, as indicated by Dye et al. (1989). As a matter of fact, the electrification sufficient to cause lightning seems to be reached during or at the end of the convective growth. Examples of values were given by Michimoto (1991) for Japanese thunderstorms at 7 m s\(^{-1}\) and by Zipser (1994) and Petersen et al. (1996) for tropical oceanic thunderstorms at 6-7 m s\(^{-1}\) at the \(-10 \, ^\circ C\) level. Apparently the strong velocities are needed in the mixed phase region, where the non inductive mechanism is effective.

<table>
<thead>
<tr>
<th>Altitude (km MSL)</th>
<th>Number of Storms</th>
<th>Storms with Ground Flashes(^a)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0–5.9</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6.0–6.9</td>
<td>11</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7.0–7.9</td>
<td>21</td>
<td>1</td>
<td>4.8</td>
</tr>
<tr>
<td>8.0–8.9</td>
<td>16</td>
<td>2</td>
<td>12.5</td>
</tr>
<tr>
<td>9.0–9.9</td>
<td>25</td>
<td>4</td>
<td>16.0</td>
</tr>
<tr>
<td>10.0–10.9</td>
<td>32</td>
<td>12</td>
<td>37.5</td>
</tr>
<tr>
<td>11.0–11.9</td>
<td>38</td>
<td>18</td>
<td>47.4</td>
</tr>
<tr>
<td>12.0–12.9</td>
<td>70</td>
<td>48</td>
<td>68.6</td>
</tr>
<tr>
<td>13.0–13.9</td>
<td>100</td>
<td>76</td>
<td>76.0</td>
</tr>
<tr>
<td>14.0–14.9</td>
<td>145</td>
<td>125</td>
<td>86.2</td>
</tr>
<tr>
<td>15.0–15.9</td>
<td>74</td>
<td>68</td>
<td>91.9</td>
</tr>
<tr>
<td>16.0–16.9</td>
<td>19</td>
<td>19</td>
<td>100</td>
</tr>
<tr>
<td>17.0–17.9</td>
<td>1</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>

\(^a\)Number of cases with ground flashes within ±5 min of the height determination by radar.

**Table I.2.2: Occurrence of ground flashes relative to radar-detected storm height.**

**Fig. I.2.3:** Fraction of storms with \(\geq 2\) ground flashes versus maximum base-scan radar reflectivity for storms in Oklahoma and Kansas (a) and from storms in the Western United States (b). (From Reap, 1986)
With strong convection the graupels are maintained more time in the cloud to have many collisions with ice crystals, according to the non inductive charging process. In the cases of oceanic storms where much less lightning flashes are observed (Rutledge et al., 1992; Williams et al., 1992; Zipser, 1994), the release of latent heat during formation of cloud ice particle could increase updraft speeds in the upper region of the cloud and in the mixed phase region the updrafts should be weaker. Observations made during the development of a given thunderstorm showed an increase of the lightning rate with an increasing updraft speed to values > 20 ms\(^{-1}\) at temperatures colder than –10 °C (Lhermitte and Krehbiel, 1979). Other observations showed the dependence of the flash rate on the convective vigor that is conditioned by convective indexes like CAPE. Large CAPE values generally correspond to high lightning production (Rutledge et al., 1992; Williams et al., 1992). However, weak flash rates have been observed in high conditional instability and therefore other parameters must play a role. One of these parameters could be a favorable precipitation vertical distribution within the cloud. Dye et al. (1986) reported the probable role of ice particles becoming larger and more numerous just before the electrification increasing and the first lightning flash observed in a thunderstorm. Recent observations made during the Mesoscale Alpine Program (MAP) Special Observation Period (SOP) clearly show the correspondence between graupels and lightning locations for several thundercells scanned with several Doppler radars and especially with a polarimetric radar providing the possibility to retrieve the dominant particle type in the cloud.

![Figure I.2.4: Probability to find the particle type dominant in a cylinder of 2-km radius around the lightning strike versus the particle type. Positive and negative CG flashes are separated and the black histogram displays the probability to find the particle type dominant in the whole cloud volume scanned by the radar. (From Seity et al., 2002)](image)

Figure I.2.4 shows such a result where the percentage is the probability to find the particle type in a cylinder of 2-km radius around the lightning strike for all the CG flashes (Seity et al., 2002). The mixture graupel-hail (GH) is the most probable type for both positive and negative CG flashes. Several thundercells are included in the study. It clearly indicated the role of the graupel in the electrification processes. Such observations confirm previous ones about the correlation between ground flash rates and cloud areas with large reflectivity values above a given altitude or temperature (Keighton et al., 1991; Lhermitte and Krehbiel, 1979).
By combining several parameters about the cloud characteristics, new conditions were proposed by several authors. Buechler and Goodman (1990) used a combination of storm height and reflectivity threshold. For 15 storms in the Southeastern United States, they found that lightning was imminent when the reflectivity of 40 dBZ began to be observed at a -10 °C isotherm and when the radar echo top exceeded 9 km. This kind of combination was proposed for improving warning time in operational applications (Hondl and Eilts, 1994). From multiparameter radar observations, Lopez and Aubagnac (1997) suggested that the growth of graupel was responsible for the overall level of electrification in the storm, but that the presence or descent of small hail appeared to enhance ground flash rates, possibly by providing positive charge below the main negative charge. Because the non inductive graupel-ice mechanism is important to lightning production, then at least one factor that affects electrification and, hence, flash rates, is the number of graupel-ice interactions that occur under conditions favorable for electrification. This depends on a sufficiently high concentrations of graupel, cloud ice, and supercooled cloud water particles simultaneously in the mixed phase region. It also depends on where the polarity of graupel charging is positive or negative, on the volume in which particle interactions occur, on the residence time of graupel in the mixed phase region, and on the subsequent trajectories of charged particles. All these properties are affected by the vertical and horizontal distribution of the updraft speed, particularly above the lower boundary of the mixed phase region, by the structure of the wind field advecting charged particles, by the existence and prior history of particles that are injected into a cell from preexisting convection, and by the environment of the convective system that can influences its microphysics. The relation between lightning activity and cloud parameters are therefore very complex.

I. 2. 4 With hail production and severe weather

Severe storms generally include tornadoes, strong winds, and hail. Many types of storms can produce such hazardous events, and especially supercells. From the development of lightning detection devices, several particularities have been observed for the severe storms. The strong wind at the surface is one of the hazardous parameters for various human activities and it can be associated with microbursts produced by thunderstorms. The microbursts are the result of strong downdrafts diverging at the ground. They occur in the lifetime of the storm roughly 10 minutes after peaks in total lightning activity (Williams et al., 1989). They are more coincident with the peak of ground flashes. They can also be accompanied by heavy or moderate rainfall, but sometimes only light rain and in this case the lightning activity is also relatively moderate (Williams et al., 1989). Few studies reported observations of lightning activity in thunderstorms producing hail and especially large hail (diameter above 1.9 cm). In the first results about this topic, the flash rates were observed higher in the thunderstorms producing hail in Montana, U.S.A. (Baughman and Fuquay, 1970). From a study of three hailstorms producing hail large enough to be considered as severe storm, Pakiam and Maybank (1975) observed two cases of multicellular storms where the hail sizes had a slight tendency to increase with increasing lightning rates and one case that appeared to be a supercell with hail > 5 cm and fairly low flash rates. Later, Rust et al. (1981) confirmed that low total flash rates could be a characteristic of the supercell from observations in the Great Plains of the U.S.A.. Reap and Mac Gorman (1989) found the probability that a storm in the Great Plains had produced severe weather increased as the number of negative ground flashes it produced increased at large values and then decreased with still high flash rates. The differentiation of flash types (IC, negative CG, and positive CG) showed particularities in hailstorms. Reap and MacGorman (1989) found that the probability of large hail increased
considerably as the number of positive ground flashes increased. Several subsequent studies found severe storms whose ground flash activity consisted predominantly of positive ground flashes, and often these thunderstorms produced large hail during the period when they were producing positive ground flashes. Usually, the positive CG lightning flashes can occur during the dissipating phase of the storm (Fuquay, 1982), or in the stratiform region of complex convective systems (Rutledge and MacGorman, 1988). In these cases their densities and rates are quite low. More recently, Carey and Rutledge (1998) studied a severe hailstorm thanks to multiparameter radar and electrical observations and they found an extremely high IC-to-CG ratio (up to 70) and predominantly positive CG lightning (over 74 %). Another study by Lang et al. (2001) showed a decrease of the negative CG flashes before the end of the storm activity while hail was present in the cloud. From the MAP experiment as previously indicated in this report, data obtained with the polarimetric value illustrate such a decrease of the negative CG and an increase of the positive CG. Figure I.2.5 displays the evolution of several parameters for a hailstorm, including the rates of both positive and negative CG flashes, the volume of cloud where the hail is the dominant particle type, and the vertical speed in the cloud. It clearly indicates the strong decrease of the negative CG flashes before the thunderstorm exhibits strong convection and large hail volumes, and the increase of the positive CG flashes at that moment. In this case, the cloud flashes were not available.

Fig. I.2.5 Evolution of some dynamical, microphysical, and electrical characteristics of a thundercell producing hail during the MAP campaign. V(HL) (black curve) represents the volume of the cloud where hail is the dominant particle type. W_{max}(green curve) is the maximum vertical speed retrieved from the Doppler radars and averaged over large volumes. The histograms represent the positive and negative CG rates. (From Seity et al., 2002)

I. 2. 5 With climate change

Basically, the lightning activity is associated with deep convection during which large particles are created. Collisions of ice particles and charge separation by differential particle
velocity produce the necessary cloud electrification meanwhile the large water drops favour the lightning initiation process. The convection is mainly driven by the vertical profiles of temperature and of water vapor through the convective available potential energy (CAPE). Both temperature and water vapor are closely connected to the climate evolution. As a matter of fact, the enhancement of the greenhouse effect leads to a global warming accompanied by an increase in surface temperature that has a twofold impact. On one hand, the induced higher instability of the air leads to stronger vertical updrafts in which the precipitating particles can reside, grow, and charge during a longer time. On the other hand the water vapor, which is the major greenhouse gas, can accumulate in the atmosphere by evaporation. Subsequently, the phase change (from vapor to water or ice) undergone by this accumulated water vapor during the updraft cooling associated with the convection is accompanied by a higher release of latent heat. This liberation of heat enhances in turn the convection necessary for lightning production. Climate change and lightning activity are therefore closely correlated.

This correlation has been analyzed by Williams (1992) for the tropical atmosphere (±23° of latitude), the contribution of which to the lightning activity is predominant as it can be seen in figure I.2.6 for one year of spatial observations by Orville and Henderson (1986). He showed that the fundamental mode of the ELF electromagnetic waves - excited by global lightning in the resonant cavity between the conductive earth and the ionosphere - exhibits a time evolution of the associated magnetic field amplitude that closely fits the time evolution of the tropical surface air temperature anomaly. Both time series are plotted in figure I.2.7 for more than five years. They are in very good agreement, in such a way that Williams proposed that this electromagnetic phenomenon called Schumann resonance (see MacGorman and Rust, 1998) would be a fairly sensitive global tropical thermometer and a means for monitoring global warming.

Several other investigations have been performed in the 90’s on the relationship between lightning and climate. Price and Rind (1994) numerically studied the possible implications of global climate change on global lightning activity by means of a general circulation model. For two kinds of scenario (warming and cooling), they showed that a ±1 °C variation of global surface temperature would result in a 5-6 % increase/decrease in lightning activity. The changes in lightning activity would be larger over continental surfaces, and cloud-to-ground...
flashes would be more sensitive than intra-cloud flashes to the climate change. Taking into account the limitations induced by the parameterization of cloud processes and convection schemes that lead to unavoidable uncertainties, their results show nonetheless that a climate warming is expected to be accompanied with a significant increase in lightning frequency. This has been confirmed by Reeve and Toumi (1999) who used data from the Optical Transient Detector (OTD) as an indicator of climate change. They found that a global change of about 40 % (56 % in the northern hemisphere) of lightning activity would result from a change of 1 °C of the average wet-bulb temperature. This result appears substantially higher than that of Price and Rind (1994) but Reeve and Toumi focused on the land lightning activity which is known to be significantly higher than that over the ocean (Goodman and Christian, 1993) and hence than the average global activity. They also used the wet-bulb temperatures rather than the dry-bulb because it is much more correlated to CAPE since it takes the water vapor into account. They pointed out that the correlation is better if the ratio land-area/ocean-area is high, i.e. in the northern hemisphere.

The recent developments in lightning space detection have permitted the observation of inter-annual changes in lightning activity. On this basis, Goodman et al. (2000) revealed a marked increase in lightning activity in the local array of the Gulf of Mexico basin during the 1997-1998 warm episode of the El Niño Southern Oscillation (ENSO). This episode resulted in a temperature increase of more than 3 °C of the Pacific Ocean in the coastal zone of South America near the equator, as shown in figure I.2.8. Goodman et al. observed an increase of 100-150 % in lightning days and about 200 % in lightning hours in the Gulf of Mexico during the winter of 1997-1998. They attributed this change in lightning activity to the enhanced synoptic-scale forcing associated with ENSO and the unusual strength of the upper level jet stream.

**EL NIÑO**

**Jan-Mar 1998**

*Figure I.2.8: Left: ocean temperatures (°C) and right: ocean temperature departures (°C) during the warm episode of El Niño in the 1998 winter. Adapted from the web site of the Climate Prediction Center (http://www.cpc.ncep.noaa.gov).*

If lightning is partly driven by climate change as seen above, it is not without any influence on the climate itself. As a matter of fact, lightning flashes are known to produce significant amounts of nitrogen oxides (Franzblau and Popp, 1989), about 10 % of the estimated global tropospheric NOx budget (51.9 TgN/yr) according to IPCC 2001 (http://www.ipcc.ch). However, last estimates of the NOx produced by lightning vary from 3 to 12 TgN/yr (Price et
These nitrogen oxides do not directly affect Earth’s radiative balance, but they contribute to the photochemical production of tropospheric ozone (Huntrieser et al., 1998), which is an important greenhouse gas that has a positive impact on climate change in the troposphere (IPCC 2001). Furthermore, as noted by Price and Rind (1994), changes in the ratio of intraccloud to cloud-to-ground or increases in the depth of penetrating convection in a warmer climate can result in change in the vertical distribution of NOx in the atmosphere, which could have major consequences on tropospheric chemistry.

Another link between lightning and climate could probably be pollution. One striking event has been observed by Lyons et al. (1998), and Murray et al. (2000). In May 1998, thunderstorms in the U. S. southern plains were polluted by smoke from fires from seasonal biomass burning in Central America. Lyons et al. (1998) reported a large amount of cloud-to-ground lightning with positive polarity and a high number of sprites, i.e. transient luminous glows initiated above thunderclouds. Murray et al. (2000) compared the cloud-to-ground lightning characteristics to those of May 1995-1997 and 1999. As it can be seen in figure I.2.9, May 1998 exhibits a marked increase in positive flashes percentage and in median peak current of positive flashes, more than 50 % and 20 kA respectively in Texas. Even the number of strokes by flash has been affected during this period, especially in negative polarity. The physical reasons are not yet analyzed and this pollution influence requires more investigations at present time. In this way, a global observation of lightning and aerosols would be of interest.

Fig. I.2.9: Deviation of May 1998 from the average of May 1995-1997 and 1999 after Murray et al. (2000). Left: percentage (%) of positive flashes, right: median peak current (kA) for positive flashes.

### I. 2. 6 Operational meteorological application of lightning detection

Several experiments of estimation of the rainfall from lightning activity have obtained relatively good results when comparing to more direct detection methods like radar detection (Tapia et al., 1997; Soula and Chauzy, 2001) or rain gauges data (Rivas et al., 2001). Figure I.2.9 shows an example from Soula and Chauzy (2001) for an area in the region of Ile-de-France (Paris) for one day of summer 1997. The cumulative rainfall is calculated from radar observation by using a classic Z-R law and from CG flashes detected by the ground network by affecting different water volumes per negative and positive CG flashes. The result is quite close in both estimations and the larger water heights correspond to large densities of positive CG flashes.
These data analyses show that the lightning activity can be a substitute for rainfall amount when the direct observation is not available. For example, in mountainous regions where heavy rainfall can produce flash flood, radar coverage is not always complete because of the terrain obstruction or existing because of the difficulty to install a radar in this kind of area. The application of the rainfall estimation by lightning can respond to goals at several time scales. For example, in a nowcasting context, it could prevent a risk of damages caused by strong rainfall if the activity is high and located in a sensitive area (steep terrain with human activity, proximity of a city with vulnerable buildings, proximity of a structure being built). A study of eight flash floods in Arizona by Holle and Bennett (1997) shows that many of them could have been previously detected by using criteria based on the duration of ground flash activity. Soula et al. (1998) studied a flash flood in Northern Spain and found a strong correlation between very high densities of CG flashes and large cumulative rainfall. Another aspect could be the climatology in terms of rainfall at several scales of time and surface (forecasting of the harvest in a given area, general climatology of the Earth or of more limited regions…).
I. 3 Ground based detection

I. 3. 1 The various principles of operational systems

The lightning flash rapidly modifies the electrostatic structure of the cloud by partly or totally neutralizing some charge accumulation regions, from the ground in the case of a CG flash and within the cloud in the case of an IC flash. This neutralization is in all cases composed of a series of physical processes which can be detectable by various observation devices. The knowledge of these physical processes can permit to identify the type of flash and some characteristics of the flash from adequate systems of observations.

One of the first systems of detection uses the electrostatic field variations produced by the lightning flash and measured at the ground by an adapted sensor like a field mill. Such a detection is possible because the electrostatic field changes very quickly during the lightning flash as compared to the other phases of the thunderstorm life. This kind of detection is possible in a radius of about 10 km around the neutralized charge. By using several detection sensors, it is possible to locate this charge under some conditions. The first condition is to recognize the type of flash (CG or IC) by analyzing the electric field variation corresponding to the lightning flash duration, and therefore a high resolution is necessary. Then, from several simultaneous electrostatic field changes measured by different field mills and by applying the equations appropriated to the flash type, it is possible to determine the parameters related to the position of the charges neutralized. Such a method has been used in the analysis of data retrieved from a field mill network working at Kennedy Space Center in Florida (Jacobson and Krider, 1976; Koshak and Krider, 1989). This method of localization of the neutralized cloud charge by lightning is difficult to extend to a large area because of the necessary number of sensors only a few kilometers apart. Furthermore, the method operates if the neutralized charge/s is/are effectively quasi punctual within the cloud. Finally, it can provide interesting results only for local studies but also for phenomenological studies.

Another technique consists in using the meteorological radar, usually devoted to rain detection. The ionized channel of the lightning flash backscatters the centimeter wavelength radar beam, just like raindrops do (fig. I.3.1). The location accuracy depends on the observational volume in the cloud and therefore on the antenna beamwidth and on the transmitted pulse duration. This method was used by Rust et al. (1981) but it is not conveniently adapted to lightning mapping in general.

For that, several microphones scattered at the ground can be associated and the time of detection of the sound by each one permits the determination of the source location of the acoustic sound. The time of propagation is calculated by comparison to the electromagnetic signal detected by a sensor like a slow antenna installed at the ground. Because of the difference of propagation velocity between acoustic and electromagnetic waves, the time of
detection by the antenna can be considered as the lightning flash production time. The number of microphones has to be numerous enough to determine the different location parameters of the source. This technique was used in the seventies (Mac Gorman, 1977; Few, 1970; Few and Teer, 1974).

Radio signal detection technique

Other techniques based on the detection of the electromagnetic radiation produced by the lightning have been developed these last years. The first technique was formulated by Oetzel and Pierce (1969) by using radio frequencies. The large radiation emission range permits to separately detect different phases of the lightning flash or different types of lightning flash. For example at high frequency in the VHF band (30-300 MHz), the radio signal is produced by the leader phase of the Cloud-to-Ground lightning flash and by the Intra-Cloud activity. At low frequency (around 100 kHz) the emission is produced by the return stroke of the CG flash. So, several techniques have been developed, according to the objective addressed. The different methods of detection differ by the sensor type adapted to the signal detected, the size of the antenna in the case of the radio detection and the method of determining locations. The detection is made by antenna arrays with variable baselines. A small baseline array (1-100 m) provides the direction of the source either by interferometry technique or by time of arrival difference. To have the complete location by triangulation, it is necessary to have either at least two such arrays or a large baseline array (about 10 km). Such systems can provide a three-dimension location of the radio sources.

Long base-line, time-of-arrival technique

An example of the first systems developed for the three-dimension location is that of Proctor (1971) that used a long base-line array and a time-of-arrival technique, and a detection frequency of about 355 MHz. The first problems encountered concerned the possible acquisition duration and the time for analyzing the data, but these problems were eventually solved. In an improved version of this first system, the error on horizontal coordinates reached about 25 m while it could be much higher for the vertical one, up to 1000 m. Another system of this type had been developed at the Kennedy Space Center, the Lightning Detection And Ranging system (LDAR) (Poehler and Lennon, 1979). It operated at a center frequency of 63 MHz with two synchronized networks of antennas. This system could either provide the real-time locations or store data for more detailed analysis. A new version of the LDAR system is now operating at the Kennedy Space Center (Maier et al., 1995). This new version can work either at 60-66 MHz or at 222-228 MHz. Another long base-line and time-of-arrival system was developed at the Kennedy Space Center by Thomson et al. (1994). The time-of-arrival in this case was calculated from the analysis of the dE/dt shape detected at each station located about 10 km apart.

Short base-line, time-of-arrival technique

A short base-line and time-of-arrival VHF system was developed by Taylor (1978). A station was equipped with five antennas separated by 13 m and locating radio sources in the 20-80 MHz. Two stations at a distance of 15-50 km provided the three-dimensional location but only for 20-30 % of the sources detected by an antenna station.

Short base-line, interferometric technique

Some examples of short-baseline and interferometric technique exist. They use the VHF frequency with a detection of the phase difference from several antennas constituting the station. Each station provides the direction of the radio source and several stations a few kilometers apart can permit the determination of its 3D location. The error in the
determination of the source direction is inversely proportional to the baseline length. There are several techniques for determining the phase difference in the interferometers. So, this technique, the number of antennas and their disposition in the station requires or not several stations for the complete location of the source.

For example, the SAFIR system (Richard, 1990) uses three stations with an array of three antennas and a frequency around 110 MHz. Such a system (Fig. I.3.2) can determine the location of the source in the horizontal plane. In a SAFIR version designed to three-dimensional mapping of electromagnetic sources, a station consists of two independent arrays of antennas, 8 horizontally separated and 16 vertically separated. The station used in the SAFIR system can also use a sensor at low frequency to detect the return stroke of the Cloud-to-Ground flashes in order to discriminate both types of lightning. In summary, each technique can bring something specific but none is complete in the analysis of the lightning process. For example, the technique based on the analysis of the electric field change can estimate the charge neutralized but cannot describe the lightning flash propagation. On the contrary, the radio sources location techniques provide a good description of the lightning development in the cloud without information about the charge neutralized.

**The Cloud-to-Ground lightning location systems**

Specific systems of location of the Cloud-to-Ground flashes have been adopted and generalized in many countries. All the sensors used in these systems perform the detection of the signal produced by the return stroke phase when it is maximum and corresponding to a point of the channel just above the strike location at the ground (Krider et al., 1976). The analysis of the wave form is therefore made in order to determine the exact moment of this emission. The same analysis performed from several sensors provides the location of the strike point in the horizontal plane. Two techniques and a combination of both exist for determining this strike point.
The first one is the Direction-Finder system initially adopted by the Lightning Location Protection Inc. and known from that moment as the LLP technique. Such a station is composed of two vertical loops mounted perpendicular to each other for the detection of the magnetic field of the wave produced by the vertical channel above the strike point (fig. I.3.3). One station providing the direction of the strike point, several stations are necessary to locate exactly this point by triangulation. Since the energy emitted by the return stroke in the low frequencies (typically 100 kHz for this detection system), the distance between two stations can be large enough, on the order of two or three hundreds of kilometers. So, a whole territory like the USA can be covered with about 100 stations. The French territory is covered with 17 stations.

The other technique is based on the time-of-arrival determination and is called Lightning Position And Tracking System (LPATS). The signal analyzed is also that emitted by the return stroke phase in a vertical channel and detected by several stations. The time of arrival determined at each station permits to build different ensembles of points, generally hyperbola for stations in a flat plane, and their intersection provides the strike point. The accuracy of this system is given to be lower than 1 km. However, some lightning signals can be misinterpreted. As shown by Théry (2001), a large proportion of intra-cloud discharges (up to 25 %) can be interpreted as negative cloud-to-ground strokes, and positive CGs are often overestimated. The combination of both techniques has been firstly realized in certain stations of the network of the USA. This hybrid technique is called the IMPACT technology and has been adopted in several countries including France. The performances are improved since now the US network, with 40 % of the stations of the hybrid type, provide an efficiency of about 80-90 % and an accuracy of about 500 m (Cummins et al., 1995).

The British Meteorological Office developed a system (ATD) based on the detection of the Cloud-to-Ground flashes in the very low frequency (VLF) band (Lee, 1986). This system uses the direction-finder technique with possibilities of detection at large distances, typically over ranges of thousands of kilometers, thanks to the strong signals radiated in the VLF band and their large distances of propagation. The frequency of detection is 2-23 kHz. The objective of the system is to detect only part of the flash activity to locate the thunderstorm area. It consists of seven stations (five in the United Kingdom, one in Gibraltar and one in Cyprus). The initial number of detection possible was about 400 flashes per hour but now with a new computer for controlling over the network of the seven ATD outstations, the capability has increased to a rate of 8,000 per hour. The maximum rate achieved to date is greater than 4,500 fixes in one hour. The long-range capability of the ATD system has become even more apparent with this higher fixing rate, as lightning is now detected regularly as far away as South America. The accuracy is <2 km for the best over the United Kingdom, <5 km over most of western Europe and about 15 km for the worse at a distance of about 2400 km west of the United Kingdom.

I. 3. 2 Perspectives – “The systems of the future”

Several countries are equipped with networks for the detection of Cloud-to-Ground flashes. Large areas are not covered with such networks, like the oceans, the large and underdeveloped countries where the storm activity is intense (African continent). Furthermore these large areas are often devoid of any other observation means for the severe weather (radars for example). The use of existent networks to fill the holes in the observations is considered. This possibility is demonstrated since data from the U.S. network are used by the U.S. National Weather Service Aviation Weather Center from several years for lightning observations over the ocean (Cramer and Cummins, 1999). In these uses the long-range
lightning information are obtained from electromagnetic waves reflected by the ionosphere and received by the ground sensors. In the case of the United States, by using the existent network (NLDN), lightning flashes are detected over both Atlantic and Pacific oceans within 2000-4000 km of the coast. The location technique is a combination of time-of-arrival and direction finding and it is adapted for signals issued from reflection on the ionosphere. The accuracy in the range concerned by this detection is 16-32 km and the detection efficiency is low because of the distance of propagation and the reflection conditions that can change from night to day. Studies are made to determine the possible improvements in this long-distance detection by adding some sensors along the coastal areas in the US territory (Cramer and Cummins, 1999).

The whole U.S. NLDN network is rebuilt by Global Atmospherics (now VAISALA) with new sensors. The existing sensors will be replaced by latest generation of intra-cloud and cloud-to-ground lightning detection sensors, the IMPACT ESP (Enhanced Sensitivity and Performance) (Fig. I.3.4). The new IMPACT ESP sensors should both anchor and extend the network's proven performance and workhorse reliability. Seven locations will be added to the existing 107 ground-based lightning detection sensor sites. In addition, several sensors will be relocated. Adding and relocating sensors optimises network geometry, improving the detection efficiency and location accuracy, improving the network performances. The accuracy should be 500 m or better.

When the upgrade is completed, the NLDN will consist of 114 IMPACT ESP sensors. Each strike will be reported by an average of more than five sensors, ensuring high levels of accuracy and built-in system redundancy.

During 2001 the British ATD system will be pushed gradually to much higher fixing rates. Further development is required to enhance system operation with an improved propagation model that will increase fixing accuracy and the addition of extra features such as the determination of the flash strength, polarity, type (cloud to ground strike, or cloud to cloud) and multiplicity (number of strokes per flash).

### I. 3. 3 Comparing performances and limitations

The performances and limitations of ground detection systems depend not only on the technique used but also on the coverage of the corresponding network. Thus, if the system is designed for long distance lightning detection, the performances are reduced. Those given in the following table for the main operational systems correspond to the best configurations of each system.
### Table I. 3. 1

<table>
<thead>
<tr>
<th>Systems Parameters</th>
<th>IMPACT (TOA-DF)</th>
<th>IMPACT ESP (TOA-DF)</th>
<th>LDAR (TOA)</th>
<th>ATD (TOA-DF)</th>
<th>SAFIR (Interferometry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection efficiency</td>
<td>80-90%</td>
<td>&gt; 90%</td>
<td>&lt; 50%</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>0.5 – 1 km</td>
<td>&lt; 0.5 km</td>
<td>1 km</td>
<td>2 km - 100 km</td>
<td>1 km</td>
</tr>
<tr>
<td>Time sampling level 1</td>
<td>1 ms</td>
<td>&lt; 1 ms</td>
<td>0.1 ms</td>
<td>0.45 s</td>
<td>0.1 ms</td>
</tr>
<tr>
<td>Detected events</td>
<td>CG</td>
<td>CG and IC</td>
<td>VHF Sources</td>
<td>CG</td>
<td>VHF Sources</td>
</tr>
<tr>
<td>Ocean detection</td>
<td>Possible</td>
<td>Possible</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

#### I. 3. 4 The operational applications (over continents)

The applications of the lightning flash detection can be considered of two types: the research and the operational applications, specially the alarm for the activities sensitive to the phenomenon. For the first type mentioned, some aspects about the phenomenology of the lightning or of the whole thunderstorm system in relation with the other parameters of the thundercloud are discussed in section I. 2. It is important to note also the importance of the lightning detection in the study of the lightning phenomenology. Thus, the systems adapted to the description of the propagation of the lightning flash during its different phases will be specially useful. As a matter of fact, the location of the VHF sources by the 3-D interferometer within the cloud and during the development of the thunderstorm permitted to characterize various types of flash propagation (Krehbiel et al., 1999). We can also distinguish the expertise to estimate the eventual influence of the lightning in case of accident. The most important application is the warning role of the detection. The domains of activity where it is useful are numerous. There is for example the public works when blow up techniques are used, and generally for people working outside on building sites. In the domain of electric power, it can also be useful to follow the displacement of thundercells active in terms of lightning for anticipating the risk of line cut off and prepare solutions of power supply. For the electricity power the statistical study and the expertise of lightning strikes can be a tool for the management of the protection equipment. In the case of forest fires often caused by lightning, the information about the location of the lightning activity permits to organize the supervision and a more rapid intervention. Since the heavy rain is correlated with a strong lightning activity, the information given by the lightning location can be an indicator of the risk of flood. In the industry, many activities need to estimate the risk or the probability of lightning strike close, for stopping certain devices or for starting processes of safe keeping. The industries concerned are various and can range from electronics to steel industry. In meteorology science and services the data of lightning location are used in real time for nowcasting or in past time for climatology and specific situations studies. They can be integrated in the products distributed by the meteorological services for public or professional applications, for the monitoring of special meteorological events like severe weather. A domain is particularly sensitive to the lightning producing weather, that is the aeronautics.
Several products specific for the air traffic have been designed, either with total lightning activity as it is provided by VAISALA-DIMENSIONS (Richard, 1990) or with CG lightning flashes issued from ground networks. For public activities in general, an access to such an information is also a good indicator of the risk.
I. 4 Detection from space

I. 4. 1 The various principles of present systems

Lightning detection from space started more than thirty years ago on a research basis. First observations from low orbiting satellite were performed in the mid sixties (Herman et al., 1965), using radio frequency sensors. Optical devices were designed to do the job as early as in the late sixties (Vorpahl et al., 1970). The National Aeronautics and Space Administration (NASA) started study programs on lightning detection from space in several ways. The Space Shuttle has been used as a platform for lightning studies from the beginning of the shuttle program. Several experiments were carried out, including the use of a simple sensor carried by hand by astronauts (Vonnegut et al., 1983). The first pictures and films of Transient Luminous Events (TLE’s), i.e. Sprites and Jets, were performed from the Space Shuttle. Maps of global lighting activity were derived from the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) sensor.

All these pioneer instruments provided useful and qualitative information, but their spatial resolution and localization accuracy remained very low, on the order of 100 km for the first experiments. No real systematic procedure could be undertaken until more operational systems were designed, based on two different principles, and launched. Some of them use optical sensors, some others electromagnetic detection.

I. 4. 1. 1 Optical detection - The first operational sensor designed for systematic and total (IC and CG) lightning detection was the Optical Transient Detector (OTD) launched as a secondary payload aboard the MicroLab-1 satellite, on a Pegasus vehicle on April 3, 1995, into an Earth orbit of about 740 kilometers altitude, with an inclination of 70 degrees with respect to the equator. This sensor is considered as being the engineering prototype of the more recent Lightning Imaging Sensor (LIS) instrument that will be described later. The OTD Mission ended March 23, 2000.

The main features of the OTD instrument are described as follows by the Global Hydrology and Climate Center (GHCC) Lightning Team of the NASA on the web site:  

http://thunder.nsstc.nasa.gov/otd/

The satellite orbits the Earth once every 100 minutes at an altitude of 740 km, and at any given instant views a 1300 km × 1300 km region of the Earth at 128 × 128 pixels. The instrument has a spatial resolution of 10 km and a temporal resolution of 2 ms.

"Flashes" are determined by comparing the luminance of adjoining frames of OTD optical data. If the difference is more than a specified threshold value, an "event" is recorded. One or more adjacent events in the same 2 ms time frame is recorded as a "group". One or more groups within a sufficiently small time period are classified as a "flash". These are grouped into "areas" if there are one or more sufficiently separated from existing areas.

The OTD detects lightning flashes during both daytime and nighttime conditions with a detection efficiency ranging from 40% to 65%, depending upon external conditions such as glint and radiation.

Because the OTD never observes a given location for more than a few minutes each day its data may be unsuitable for studying localized weather. What it is suitable for is studying global lightning patterns and how they change with time. It can also prove a valuable comparison item if the OTD happens to be in the right spot at the right time to gather data on a given storm. In these cases, the data can be compared against data from other sources to get an estimate of the total flash rate of the storm.
OTD Browse Data is available to provide a quick, graphical overview of the OTD data. Each day of OTD data has been totaled into a single image. Using these images, it is easy to tell from a glance on which days there was a particularly high or low amount of lightning activity over a given area. At the end of each month, OTD Browse Data is quality checked and archived. The most current OTD browse data is kept in a Non-Quality Controlled area for those who need the data as soon as possible. This data may contain inaccuracies.

A QuickTime movie of example OTD data is also available. This movie consists of a series of browse images played as a sequence to give a feel of the lightning dispersion over the Earth.

OTD data consist in the number of “flashes”, of “groups”, of “events” reconstructed from the signals detected by each pixel of the sensor during the period considered. However, these numbers represent only a sampling of the real activity over each area. The trajectory period of the satellite (about 100 minutes) is such that the sensor pictures every year some 400 separate 3-minute observations of each location on the earth.

Various OTD images are thus reconstructed and made available on the web site, each of them corresponding to a given period: 1 day, 1 month, 1 year… As an example, Figure I.4.1 shows the distribution of the total flash detected by the sensor over the globe during the year 1999. In fact such a valuable product brings very useful information on lightning climatology. Thus, it can be observed on Figure I.4.1 that most of the lightning activity develop over the continents and there are many more lightning flashes over the land masses than over the oceans. On the other hand, the InterTropical Convergence Zone (ITCZ) receives most of the lightning activity. This fact most probably results from the stronger convective motions in continental clouds than in oceanic clouds. Other hypotheses are formulated amongst the scientific community, namely a possible influence of the aerosol content.

Fig. I.4.1: The global distribution of total lightning flashes detected by OTD during 1999
In order to infer from these data a more comprehensive and really global information, the numbers on Figure I.4.1 must be converted into lightning flash densities (flashes per square kilometer per year). These densities appear on Figure I.4.2 that displays the global distribution of the total flash activity. They are calculated statistically using OTD data and sampling rate.

Thus from the fact that between September 1, 1995 and August 31, 1996, the OTD observed nearly 1 million lightning flashes worldwide, it is now estimated that over 1.2 billion lightning flashes (intracloud plus cloud-to-ground) occur around the world every year. A controversial result arises from this result. The global flash rate deduced from this estimation reaches approximately 40 flashes per second, less than half of the widely accepted estimates dating back to 1925.

The Lightning Imaging Sensor (LIS) was the successor instrument of OTD considered as its prototype. Based on the very same optical principle, it was launched on 28 November 1997 from the Tanegashima Space Center in Japan aboard the TRMM Observatory. The orbit of the platform has an inclination of 35 degrees with respect to the equator, and an altitude of about 350 km. As a result, the LIS instrument, can observe lightning activity only in the tropical regions of the globe where it occurs the most, between 35 degrees South latitude and 35 degrees North latitude.

Some improvements were brought to the sensor designed and used to detect the distribution and variability of total lightning (cloud-to-cloud, intra-cloud, and cloud-to-ground lightning). The staring imager is optimized to detect and locate lightning flashes with storm-scale resolution (4 to 7 km) over a region of the Earth's surface slightly smaller (600 km × 600 km) than OTD. The TRMM satellite travels a distance of 7 kilometers every second as it orbits the Earth, thus allowing the LIS to observe a point on the Earth or a cloud for more than 80 seconds as it passes overhead. Despite the brief duration of an observation, it is long enough to estimate the flashing rate of most storms, the minimum being on the order of 1-2 per minute. The instrument records the time of occurrence, measures the radiant energy above a given threshold, and determines the location of lightning events within its field-of-view.
A summary of the performance criteria released by NASA is displayed in table I.4.1.

<table>
<thead>
<tr>
<th><strong>LIS PERFORMANCE CRITERIA</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel IFOV</td>
<td>5 km</td>
</tr>
<tr>
<td>Total FOV</td>
<td>$80^\circ \times 80^\circ$</td>
</tr>
<tr>
<td>Wavelength</td>
<td>774.4 nm</td>
</tr>
<tr>
<td>Radiant energy threshold</td>
<td>$4.7 , \mu J , m^{-2} , sr^{-1}$</td>
</tr>
<tr>
<td>SNR</td>
<td>6</td>
</tr>
<tr>
<td>Array size</td>
<td>$128 \times 128$ pixels</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$&gt; 100$</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>$&gt; 90 %$ of all events</td>
</tr>
<tr>
<td>False alarm rate</td>
<td>$&lt; 10 %$ of total events</td>
</tr>
<tr>
<td>Measurement accuracy</td>
<td>Location: 1 pixel  &lt;br&gt; Intensity: 10 %  &lt;br&gt; Time: tag at frame rate</td>
</tr>
<tr>
<td>Command interface</td>
<td>Adjust threshold  &lt;br&gt; Record/image  &lt;br&gt; Power on/off  &lt;br&gt; Self test  &lt;br&gt; Safe mode (close/open aperture cover)</td>
</tr>
<tr>
<td>Weight</td>
<td>20 kg</td>
</tr>
<tr>
<td>Power</td>
<td>25 W</td>
</tr>
<tr>
<td>Telemetry</td>
<td>Data rate: 6 kb/s  &lt;br&gt; Format PCM  &lt;br&gt; Sample size: 12 bits</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-25°C to +40 °C</td>
</tr>
</tbody>
</table>

Table 1.4.1

This calibrated lightning sensor uses a wide field-of-view expanded optics lens with a narrow-band filter around 777.4 nm wavelength corresponding to the atomic line optical emission of neutral oxygen in the discharge channel heated up to a temperature exceeding 20,000 K. The sensor itself is a high speed 128 $\times$ 128 charge-coupled device (CCD) detection array, identical to OTD’s. A Real Time Event Processor (RTEP), inside the electronics unit, is used to determine the occurrence of a lightning flash, even in the presence of bright sunlit clouds. This system allows a nearly uniform 90 \% flash detection efficiency within the field of view (FOV) of the sensor. The time resolution reaches 2 ms, and the detectable radiant energy threshold is $4.7 \, \mu J \, m^{-2} \, sr^{-1}$.

Both instruments, OTD and LIS, have been validated through several experiments, some of them being prior to launch, some others during normal use. Lightning space detection has been cross-compared to ground-truth measurements as they are provided by the existing networks, like the National Lightning Detection Network (NLDN) over the contiguous United States.

The advantages and limitations of this type of optical lightning detection will be developed and compared to other types of measurement in section I. 4. 3.
**I. 4. 1. 2 Electromagnetic detection** – The intense and pulsed electric current that flows through the channel during the various phases of a lightning flash produces a broadband spectrum of electromagnetic radio frequency (RF) energy.

The synthetic curve displayed on Fig. I.4.3 and established by Oetzel and Pierce (1969), gathers normalized electromagnetic field amplitudes received from lightning sources at a distance of 10 km within a 1 kHz bandwidth. This spectrum reveals the very large frequency domain covered by the signal generated from a lightning channel. Each phase of the flash radiates in a specific frequency band. Leader phases correspond mostly to VHF-UHF frequency bands, whereas return strokes radiate more power around 100 kHz. The space detection systems based on radio frequency reception must pick a frequency free of ionospheric disturbance.

The only RF system known to be presently in function is one of the instruments carried by the FORTE Project payload (Fast On-orbit Recording of Transient Events) managed by Los Alamos National Laboratory and Sandia National Laboratories (USA). It is associated with optical detection. The following information is available on the web site of FORTE project:


FORTE accomplishes a threefold mission: nuclear detection, study of ionosphere disturbances, and lightning properties investigations. The satellite carries three different instruments:

1. The VHF instrumentation, built by Los Alamos consists of two broadband receivers that can each be independently configured to cover a 22-MHz sub-band in the 30 - 300 MHz frequency range. For this study, one receiver was chosen to span the 26 - 48 MHz range and the other spanned the 118 - 140 MHz range. The instruments are configured
to collect 40960 samples in a 800 ms record length resulting in a time resolution of 20 ns (sample rate of 50 Megasamples/s). The trigger point in each record allowed for 500 ms of pre-trigger information and 300 ms of post-trigger information. The record length and pre/post trigger intervals were chosen to optimize the detection and identification of the VHF lightning emissions. Data collection is triggered off the lower (26 - 48 MHz) band receiver when the amplitude of its detected signal exceeds a preset noise-riding amplitude threshold in at least five of eight 1-MHz wide sub-bands distributed throughout the 22-MHz bandwidth (Jacobson et al., 1998). This triggering technique allows the instrument to trigger on and detect weak lightning signatures in the presence of strong interfering manmade carriers. Retriggering can occur after only a few microsecond delay allowing the instrument to record extended multi-record signals with essentially zero dead-time. The "field-of-view" of the VHF receivers is determined by the antenna pattern; the 3-dB attenuation contour of the antenna response approximates a circle of about 1200 km diameter and was chosen to roughly correspond to the 80° field-of-view of the PDD. (1) a multi-band-coincidence trigger with perpetual recording of power background in all 16 trigger subbands (each 1 MHz wide), (2) a wideband (300 Megasamples/sec) RF receiver operating in any of three positions within the VHF, and (3) a pair of medium-bandwidth (50 Megasamples/sec) simultaneous RF receivers also operating anywhere in the VHF. The RF payload derives its signals from either of two active monopoles, or alternatively from two mutually orthogonal, multi-element, passive, moderate-gain log-periodic antennas on a nadir-directed deployed boom (see figure).

2. A fast-time-response photodiode detector (PDD) sampling an 80-degree field-of-view throughout the visible and near-IR (0.4 à 1.1 µm band) and sampled every 15 microseconds. The corresponding footprint reaches about 1200-km diameter.

3. A 128 × 128 pixel CCD array imager (LLS) whose square image is inscribed in the PDD field-of-view, and whose input is the bright narrow-band-filtered line emission at 0.77 µm wavelength. Both optical instruments are built by Sandia.

The trigger times of both the VHF and PDD records are GPS-time-stamped to a 1 ms precision. Both the RF and optical payloads are configurable for signal-triggered or for time-triggered digitization. There are also options for cross-triggering of PDD and LLS and for cross-triggering of PDD and the RF payload. There is ample memory on board (the RF memory is by far the largest, at 160 Megabytes) for thousands of events to be stored and then downloaded. The downloading is done up to several times per day, at both Sandia and University of Alaska.

FORTE satellite was launched on Friday, 29 August, 1997. It is in a circular, 800-km-altitude orbit inclined 70 degrees from the Earth's equator sweeping about the same area as OTD satellite within a period of about 100 minutes.

Amongst the different kinds of signals detected by the electromagnetic instrument of FORTE, the system discriminates those produced by lightning flashes. To do so, coincidence of FORTE RF signal with both optical detection devices onboard the FORTE payload are performed. The processing of all three different kinds of signals received should allow soon a discrimination of the various types of lightning flashes: intra-cloud, cloud-to-ground (negative and positive). Basically, the optical CCD array imager provides the localization of the discharges and the VHF instrumentation analyses its structure and characteristics. Numerous scientific reports and publications (for example Jacobson et al., 1999) on the results obtained are available on the web site of FORTE project.
One of the major results obtained by the group working on this project is the identification of the so-called trans-ionospheric pulse pairs (TIPPs). TIPPs were first observed in 1993 with a VHF receiver, called Blackbeard, onboard the ALEXIS satellite (Holden et al., 1995). TIPPs are distinguished from other naturally occurring radio emissions by several features. TIPPs consist of exactly two broadband (25-100 MHz) pulses that have been dispersed by the ionosphere. The duration of each pulse is a few microseconds and the time separation of the pulses is typically tens of microseconds (figure I.4.4). The signal processing of such TIPPs detected by FORTE leads to consider that the second pulse of the signal results from the reflection on the ground of the electromagnetic emission from the regular cloud discharge, rather than from the electromagnetic signature of a high altitude discharge triggered by the cloud discharge.

**I. 4. 2 Perspectives – The projects**

Several projects of lightning detection from space are being planned. The two main programs considered here relate to electromagnetic detection from orbiting satellite (ORAGES) and optical detection from geostationary platform (Lightning Mapper System - LMS - mission).

**I. 4. 2. 1 ORAGES Project**

ORAGES, standing for “Observation Radioélectrique et Analyse Goniométrique des Eclairs par Satellite”, was selected in 1998 by the French space agency (CNES) for a preliminary phase to validate the design concept of the instrument. The principal investigator is the Office National d’Etudes et de Recherches Aérospatiales (ONERA), and the co-investigator the Laboratoire d’Aérologie, UPS/CNRS. This program aims at detecting and locating the VHF radiation of lightning flashes using an interferometric antenna network aboard an orbiting microsatellite of the French space agency (CNES). ORAGES is planned to provide a continuous observation of the lightning activity produced by tropical thunderstorms. The localization of the VHF sources of the channel discharges through interferometry will provide the spatial distribution of lightning discharges over the considered regions. Onboard numerical processing will release important information like discrimination between
intracloud and cloud-to-ground flashes, evaluation of the total channel length, determination of the type of emission…

With a low inclination with respect to the equator (20-25°), ORAGES will be devoted to the observation of the intertropical zone (≈ 25°S – 25°N) where about 60% of thunderstorms on Earth occur. Measurements are intended to be made at a relatively high repetition rate. The altitude of the orbit will be high enough (750-850 km) in order to obtain a good compromise between a wide field of view and a reasonable horizontal resolution (<15 km). ORAGES is an experimental mission without plan for immediate operational follow-up. In order to study phenomena ranging from individual convective events to interannual variability, the duration of the mission should be at least 2 years.

It is highly desirable that ORAGES be coordinated with meteorological satellites devoted to the observation of precipitating systems and their environments in the tropics. In particular, the French-Indian MEGHA-TROPIQUES planned for a launch in 2006 is an interesting opportunity.

**Scientific background** - The development of a database concerning lightning activity in the intertropical zone, in relation with data from meteorological satellites, will allow to investigate the following themes:

- Classification of electrical activity as a function of cloud type (continental or oceanic, convective or stratiform, mesoscale organization, evolution, duration, …);
- Relationships between electrical activity and rainfall intensity (deduced from direct – raingauges – or indirect – radars, radiometers, … – measurements).
- Characteristics of lightning activity associated with perturbations of the tropical atmosphere (cyclogenesis, tropical and equatorial waves, intra-seasonal oscillation, monsoons, …).
- Relation between lightning activity and surface temperature (e.g. in relation with interannual perturbations over the tropical oceans such as ENSO, …).
- Production of NOX by lightning, role of the intracloud vs. cloud-to-ground flashes.
- Correlation between TIPPs and VHF emissions.

ORAGES’ orbit at about 800 km altitude and 20-25° inclination with respect to the equator enables the satellite to pass several times a day over the same regions and to gain some insight on the evolution of the convective systems. ORAGES intends to bring new scientific data to investigate the perturbations of the tropical atmosphere and will complement the MEGHA-TROPIQUES mission. This program from CNES and ISRO (French-Indian cooperation) is planned for a launch in 2006, and is designed to obtain reliable statistics on the water and energy budget of the tropical atmosphere and to describe the evolution of convective systems at appropriate time scales, using a microwave imager, a microwave sounder and an infrared radiometer. If the two missions were to fly together, precise observations on humidity, cloud and precipitation, as well as radiative budget elements, obtained by MEGHA-TROPIQUES should certainly help in the interpretation of the ORAGES products. Reciprocally, information on the presence or the absence of electrical activity could help to more correctly analyze the microwave brightness temperatures observed by MEGHA-TROPIQUES.

During the scientific preparation phase of ORAGES, the relationships between rainfall and electrical activity have been investigated following two directions. The first one consists in analyzing available data from radar, satellite and lightning detection systems. To that purpose, observations from the operational networks in France (ARAMIS for radars, METEORAGE for cloud-to-ground flashes and SAFIR for total lightning activity) and from field campaigns (MAP in the Alps in 1999) have been analyzed and compared (Seity et al., 2001). Further studies will be devoted to radar and lightning data collected in the tropical environment of
The second item relates to the development of a specific module in the French non-hydrostatic model for atmospheric simulation MésoNH (Lafore et al., 1998), in order to simulate the electrification of the thundercloud and the development of lightning when the electric field inside the cloud reaches critical values. The “electrified” version of Méso-NH model has been tested for the ideal case of a supercellular storm (Molinié et al., 2002) and will be applied to tropical continental and oceanic storms.

Technical background - The ORAGES project is a continuation of the international studies presented above (OTD, LIS, FORTE). The main difference between OTD, LIS and ORAGES relates to the method used for lightning detection. OTD and LIS detect and locate the optical emission from lightning flashes at a wavelength of 777.65 nm, whereas ORAGES – like FORTE – will use the VHF radiation emission. Unlike the geolocation of each event deduced from an imaging CCD array aboard FORTE system, ORAGES technique uses interferometry for discharges localization. This proposed solution should improve the detection efficiency (>90%), independently from day/night or ocean/continent background. It is planned to allow a large field of view (> 1000 km × 1000 km) with a possibility of detection up to the limb, and to permit the extraction of additional information on the lightning sources.

Geophysical parameters to be retrieved - The data provided by ORAGES will be:

- Detection, localization and time sampling of the VHF lightning emission, within a field of view of 1000 km × 1000 km, with a horizontal resolution of 15 km × 15 km;
- Outside this region, the most intense emissions will be located up to the limb (3200 km horizontally from the nadir) with a horizontal resolution less than 150 km × 150 km;
- From spatial and temporal criteria, lightning channels will be reconstructed from the series of detected lightning sources;
- Evaluation of the total lightning length;
- Discrimination between intracloud and cloud-to-ground flashes;
- Determination of the type of emission (lightning leader development, recoil streamers, TIPPs, … ).

Principle of the instrument - Two different techniques are used to detect and localize the radiating elements of a lightning channel. The first one is based on a measurement of range difference, which implies to use a minimum of 4 stations separated by several tenths of kilometers. This method could only be applied if a constellation of satellites were to fly in Earth’s orbit. The second method is based on a bearing measurement. The direction where the lightning radiation comes from is determined by an interferometric network of antennae. This principle enables the design of an instrument compatible with the constraints of a microsatellite platform.

For example, when two antennae are considered, the phase difference \( \phi \) between the two signals received is given by the following expression (Fig. I.4.5):

\[
\phi = 2\pi \frac{D}{\lambda} \sin \theta \sin \phi
\]

where \( D \) is the distance between the antennae and \( \lambda \) the wavelength of the signal. When more than two antennae and several baselines are considered, an unambiguous localization can be obtained. An example of lightning observations using such a method and obtained through the interferometer of ONERA is presented in Fig. I.4.6.
A prototype of ORAGES has been designed and built in 2001. It is composed of:
- a circular network of 5 antennae;
- An analog receiver;
- A numerical unit for real-time signal analysis.

Some technical characteristics of ORAGES are given in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Volume</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-antenna network</td>
<td>&lt;6.5kg</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Analog receiver</td>
<td>2.5 kg</td>
<td>6.25 l dm³</td>
<td>15 W</td>
</tr>
<tr>
<td>Numerical unit</td>
<td>4 kg</td>
<td>4.2 l dm³</td>
<td>28 W</td>
</tr>
</tbody>
</table>

*Characteristics of the ORAGES prototype.*

In October 2001, the prototype has been installed inside a balloon nacelle (Fig. I.4.7).
I. 4. 2. 2 Lightning Mapper Sensor mission

The optical detection from geostationary platform of all types of lightning flashes has been planed in the United States as early as 1980 (Wolfe and Nagler, 1980). An optical lightning imaging sensor was presented by NASA within a project of deployment in geostationary orbit on a GOES satellite (Christian et al., 1989) before it was eventually installed on orbiting satellites (OTD and LIS).

More recently, the experience acquired from the use of OTD and LIS data lead to a new project of Lightning Mapper Sensor mission. The program is fully described by H. J. Christian (1998) in a draft available on the NASA web site: [http://thunder.msfc.nasa.gov/](http://thunder.msfc.nasa.gov/). This draft is as follows.

1. Overview

   The Lightning Mapper Sensor (LMS) mission consists of fabricating a small, dual telescope, optical lightning sensor; flying it on a GOES spacecraft in CY2003; and measuring total lightning activity on a continuous basis over the continental United States, Central and South America and portions of the adjoining oceans.

   The deliverables will consist of:
   1. space qualified optical lightning sensors;
   2. sufficient lightning data to thoroughly evaluate proxy relationships and contributions to the Earth Science enterprise; and
   3. detailed evaluations of real time total lightning measurements for storm warning and nowcasting activities.

2. Mission Objectives

   2.1. Objective 1: Measure total lightning activity over large areas of the Americas and nearby oceans on a continuous basis.

   2.2. Objective 2: Develop an extensive lightning climatology to be used for global change research.
2.3. Objective 3: Demonstrate ability to deliver, on a real-time basis, lightning measurements that are of sufficient quality and quantity for operational storm monitoring and severe weather warnings.

3. Mission Success Criteria
3.1. General: Demonstrate measurement of lightning from space using a staring optical imager that meet future research and operational mission requirements.
3.2. Specific:
   3.2.1. Produce and validate lightning measurements during daytime and nighttime, demonstrating high detection efficiencies with low false event rates.
   3.2.2. Produce a set of raw instrument data with which advanced ground-based signal processing techniques can be developed for real-time, quality controlled data dissemination.
   3.2.3. Demonstrate all technology issues that are critical to follow-on operational missions:
      3.2.3.1. maintenance of instrument performance over the mission lifetime.
      3.2.3.2. accounting for all sources of error associated with pointing control authority, pointing control accuracy, and pointing knowledge.
      3.2.3.3. successful real-time data dissemination using both ground based and space based processing.

4. Mission Requirements
Tables I.4.2 and I.4.3 provide the baseline set of science based requirements for the LMS mission. These requirements define the minimum performance needed to satisfy both the scientific and the operational elements of the mission.

4.1 Mission Science Requirements Matrix
Note: This table represents the P.I.'s best and current estimates of the requirements that would result in a successful mission. It is anticipated that there will be a need to undergo multiple iterations with special attention to the following issues: thermal management, pointing control and knowledge, data processing techniques, and data volumes/downlink rates.
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Large Area Coverage</strong></td>
<td>Monitor lightning in the tropics, extra tropics to 50° latitude over both land and water</td>
<td>Provide data sets from as many areas of the globe that will assure unbiased performance statistics; assure operations over calibration/validation sites.</td>
</tr>
<tr>
<td><strong>High Detection Efficiency</strong></td>
<td>Estimate the total lightning activity of each storm.</td>
<td>Used for inferring convective activity, mixed phase precipitation, etc.</td>
</tr>
<tr>
<td><strong>Low False Event Rates</strong></td>
<td>Accurately detect only lightning events.</td>
<td>Less than 5% of total events Minimize ground based processing</td>
</tr>
<tr>
<td><strong>Measurement Sensitivity</strong></td>
<td>(3.8 \times 10^{-6} \text{ J m}^{-2} \text{um}^{-1} \text{sr}^{-1}) (preferred) (4.7 \times 10^{-6} \text{ J m}^{-2} \text{um}^{-1} \text{sr}^{-1}) (acceptable).</td>
<td>The sensitivity numbers include 6 dB of SNR margin.</td>
</tr>
<tr>
<td><strong>Dynamic Range</strong></td>
<td>&gt; 2 orders of magnitude.</td>
<td>After background subtraction, the system must maintain greater than 2 orders of magnitude dynamic range for lightning detection.</td>
</tr>
<tr>
<td><strong>Spatial Resolution</strong></td>
<td>Identify individual convective cell</td>
<td>8 km at nadir</td>
</tr>
<tr>
<td><strong>Contiguous Observations</strong></td>
<td>Continuous observation of the monitored area.</td>
<td></td>
</tr>
<tr>
<td><strong>Single Wavelength Operation</strong></td>
<td>Daytime lightning detection.                                      (7774 \text{ Å})</td>
<td></td>
</tr>
<tr>
<td><strong>Radiometric Measurement</strong></td>
<td>Determine lightning intensity</td>
<td>Measure to 10% accuracy</td>
</tr>
<tr>
<td><strong>Continuing current</strong></td>
<td>Detect and quantize continuing current</td>
<td>Do not update background during active pixel periods</td>
</tr>
<tr>
<td><strong>Data compression</strong></td>
<td>High event rate throughput</td>
<td>Multiple dimension, adjacent pixel compression</td>
</tr>
<tr>
<td><strong>Platform Attitude</strong></td>
<td>Earth viewing</td>
<td></td>
</tr>
<tr>
<td><strong>Command and Control</strong></td>
<td>Must be able to select subarray(s) adjust threshold select image area</td>
<td>Map 20 subregions to 16 RTEPs preferred RTEP readout.</td>
</tr>
<tr>
<td><strong>Pointing Accuracy</strong></td>
<td>Locate lightning to specific cell</td>
<td>110 microradians</td>
</tr>
<tr>
<td><strong>Pointing Knowledge</strong></td>
<td>Locate lightning to specific cell</td>
<td>40 microradians</td>
</tr>
</tbody>
</table>

Table I.4.2
4.2. Observational Requirements
The Lightning Mapper Sensor must operate on a continuous basis under both day and nighttime conditions. The data must be transmitted to MSFC in near real time, where it will be processed for quality assurance and redistributed with a maximum latency of 20 seconds. As the real-time processing algorithms mature and become operational, it might prove desirable to upload some of the software so that some of the processing, such as sun glint event filtering could be performed on orbit. This capability could be very valuable when the sensor is transition to operational status.

5. Calibration Requirements
Of highest priority for the LMS is the calibration (or validation of calibration) of the instrument and confirmation of the performance claims. Determinations of detection efficiency, location accuracy and false event rates must be made via laboratory calibrations prior to launch and ground base validation studies after launch. A detailed calibration plan for the LMS instrument will be developed. It will be similar in concept to the OTD and LIS plans.

5.1. Pre-launch
Pre-launch component, subsystem, and system end-to-end test and calibration shall include:
   5.1.1. DC radiometric calibration
   5.1.2. AC response calibration
   5.1.3. Field of view measurement
   5.1.4. Spectral response
   5.1.5. Lightning simulator test
   5.1.6. Pointing knowledge measurement

5.2. During Flight
The actual on-orbit performance will depend on the instrument performance and its calibration, the background scene stability, radiation effects, and source characteristics.
   5.2.1. Ground Truth
   Permanent ground validation sites will be established prior to launch. These sites will be used to validate instrument performance. Sites will likely include existing TRMM sites that are within the instrument field of view.
   5.2.2. Field Campaigns
   Intensive field campaigns will take place on a periodic basis to perform LMS validation and to investigate relationships between lightning and other convective parameters.
   5.2.3 Navigation
   Navigation will be verified using landmarks identified from LMS images. Algorithms will be developed to compensate for identified pointing errors that occur as a function of the diurnal and seasonal cycles.

6. Data Requirements

6.1. Data Processing
Data will be processed and archived at the GHCC operations facility.

6.2. Data Downlink
A continuous data downlink operating at 80 Kbps is required throughout the life of the program.

7. Operations Requirements
This data will be processed and quality controlled on the ground in order to insure data reliability and integrity. Only quality controlled data will be disseminated to either scientific users or to real time operational users.

A. Appendices

A.1. Lightning Instrument

A.1.1 LMS Measurement Approach

The LMS images a scene much like a television camera. However, because of the transient nature of lightning, its spectral characteristics, and the difficulty of daytime detection of lightning against brightly lit cloud backgrounds, actual data handling and processing is much different from that required by a simple imager. In order to achieve the performance goals required to meet the scientific objectives, the LMS combines many off-the-shelf and custom components in a unique configuration. A wide field of view telescope, combined with a large, narrow-band interference filter is focused on a high speed mosaic array focal plane. The signal is read out from the focal plane into real-time event processors (RTEP) for event detection and data compression. The resulting "lightning data only" signal is formatted, queued, and transmitted via the satellite to ground.

The specific characteristics of the sensor design result from the requirement to detect weak lightning signals during the day. During the day, the background illumination produced by sunlight reflecting from the tops of clouds is much brighter than the illumination produced by lightning. Consequently, the daytime lightning signals tend to be buried in the background noise, and the only way to detect lightning during daytime is to implement techniques that increase or maximize the lightning signal relative to this bright background. These techniques take advantage of the significant differences in the temporal, spatial, and spectral characteristics between the lightning signal and the background noise. A combination of four methods will be employed by the LMS for this purpose. First, spatial filtering is used which matches the instantaneous field of view (IFOV) of each detector element in the LMS focal plane array to the typical cloud-top area illuminated by a lightning stroke (i.e., ~10 km). This results in an optimal sampling of the lightning scene relative to the background illumination. Second, spectral filtering is obtained by using a narrow-band interference filter centered on a strong optical emission line (e.g., OI(1) at 777.4 nm) in the lightning spectrum. This method further maximizes the lightning signal relative to the reflected daylight background. Third, the LMS employs temporal filtering which takes advantage of the difference in lightning pulse duration which is on the order of 400 microseconds versus the background illumination which tends to be constant on the time scale of seconds. In an integrating sensor, such as the LMS, the integration time specifies how long a particular pixel accumulates charge between readouts. The lightning signal-to-noise ratio improves as the integration period approaches the pulse duration. If, however, the integration period becomes too short, the lightning signal tends to be split between successive frames which actually decreases the signal-to-noise ratio. Since the median optical lightning pulse width when viewed from above is 400 microseconds, an integration time of 1 ms is most appropriate to minimize pulse splitting and maximize lightning detectability. Present technological limitations require that a 2 millisecond integration time be used in the LMS instrument design. As demonstrated by the OTD and the LIS, this compromise does not seriously degrade the sensor's performance.
Even with the three "filtering" approaches discussed above, the ratio of the background illumination to the lightning signal will often still exceed 100 to 1 at the focal plane. Therefore, a fourth technique, a modified frame-to-frame background subtraction, is implemented to remove the slowly varying background signal from the raw data coming off the LMS focal plane. A detailed discussion on the measurement approach proposed for the LMS is given in a later section of this document. Each real-time event processor generates an estimate of the background scene imaged at each pixel of its section of the focal plane array. This background scene is updated during each frame readout sequence and, at the same time, the background signal is compared with the off-the-focal-plane signal on a pixel-by-pixel basis. When the difference between these signals exceeds a selected threshold, the signal is identified as a lightning event and an event processing sequence is initiated. The implementation of this RTEP results in a $10^6$ reduction in data rate requirements, while maintaining high detection efficiency for lightning events.

A.1.2 Instrument discription

The LMS will consist of a staring imager optimized to detect and locate lightning. An imaging system, a focal plane assembly, real-time event processors, a formatter, power supply, and interface electronics are the six major subsystems of the sensor. The imaging system is a fast f/1.2 telescope with a 12 cm aperture, and an 10 nm interference filter. The $50 \times 50$ LMS field of view must be restricted in order to minimize wavelength shifts through the interference filter. The focal plane assembly, (including a 700 × 560 pixel array, preamplifiers, multiplexers, and clock and drive electronics) provides an analog data stream of an appropriate amplitude to subsequent circuits. As noted earlier if, after background removal, the difference signal for a given pixel exceeds a threshold, that pixel is considered to contain an event. Subsequently, the event is time tagged, location tagged, background bin tagged, and passed to the satellite for transmission to the ground.

A.1.3 Imaging System

The imaging system includes an f/1.2, 11 cm diameter telescope and a 1 nm bandwidth interference filter. A broad-band blocking filter is placed on the front surface of the filter substrate in order to maximize the effectiveness of the narrow-band filter. Because the bandpass of interference filters shifts to shorter wavelengths for non-normal incidence, it is necessary to restrict the field of view of the optics and use two telescopes to cover the required FOV. That is, if the wavelength of interest is incident upon the filter at an angle that shifts it beyond the filter bandpass, the signal will not be passed. This problem is minimized by choosing a filter which passes the high wavelength end of its bandpass at normal incidence. As the angle of incidence increases to a maximum, the wavelength shifts down through the entire band pass to the low wavelength end, allowing the full filter bandwidth to compensate for the wavelength shift.
## Table I.4.3 – LMS Performance Criteria

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pixel IFOV</td>
<td>8 km (at nadir)</td>
</tr>
<tr>
<td>FOV</td>
<td>8 degree × 5 degree FOV</td>
</tr>
<tr>
<td>Wavelength</td>
<td>777.4 nm</td>
</tr>
<tr>
<td>Threshold</td>
<td>&lt; 4.0 J m² sr⁻¹</td>
</tr>
<tr>
<td>SNR</td>
<td>6</td>
</tr>
<tr>
<td>array size</td>
<td>700 × 560 pixels</td>
</tr>
<tr>
<td>dynamic range</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>&gt; 90% of all events</td>
</tr>
<tr>
<td>false alarm rate</td>
<td>&lt; 5% of total events</td>
</tr>
<tr>
<td>measurement accuracy</td>
<td></td>
</tr>
<tr>
<td>location</td>
<td>1 pixel</td>
</tr>
<tr>
<td>intensity</td>
<td>10%</td>
</tr>
<tr>
<td>time</td>
<td>tag at frame rate</td>
</tr>
<tr>
<td>command interface</td>
<td>adjust threshold (threshold 63 = events disabled)</td>
</tr>
<tr>
<td></td>
<td>record/image</td>
</tr>
<tr>
<td></td>
<td>power on/off</td>
</tr>
<tr>
<td></td>
<td>self test</td>
</tr>
<tr>
<td></td>
<td>subregion selection</td>
</tr>
<tr>
<td></td>
<td>active RTEP selection</td>
</tr>
<tr>
<td></td>
<td>continuing current enable</td>
</tr>
<tr>
<td></td>
<td>on board event processing enable</td>
</tr>
<tr>
<td></td>
<td>safe mode</td>
</tr>
<tr>
<td>weight</td>
<td>35 kg</td>
</tr>
<tr>
<td>power</td>
<td>100 watts</td>
</tr>
<tr>
<td>telemetry</td>
<td></td>
</tr>
<tr>
<td>data rate</td>
<td>80 kb/s</td>
</tr>
<tr>
<td>format</td>
<td>PCM</td>
</tr>
<tr>
<td>sample size</td>
<td>12 bits</td>
</tr>
<tr>
<td>operating temperature</td>
<td>-10 to +40 °C</td>
</tr>
</tbody>
</table>

The filter temperature is controlled with an active thermal heating system in order to insure minimal filter wavelength shift as a function of temperature. Furthermore, the temperature control point can be adjusted on orbit.

### A.1.4 Real-Time Event Processor

The data rate coming off the LMS focal plane will be on the order of $4 \times 10^8$ pixels per second. It must be processed with at least 12 bits of resolution, yielding a data rate of $5 \times 10^9$ bits per second. This far exceeds transmittable rates, thus the need for off-the-focal plane signal processing (i.e. the RTEP). Both the OTD and LIS use an RTEP. The concept has been successfully tested and demonstrated both in the laboratory and on-orbit. In addition, numerical analyses, evaluations, and trade-off options have been performed.

As noted previously, the RTEP detects weak lightning flashes from an intense, but slowly evolving background. The daytime background varies with sun angle, clouds, ground albedo, etc., and can reach in excess of 900,000 photo-electrons as compared to lightning produced signal electrons which may be as small as 6000 electrons. Typically lightning stroke will occur during a single integration frame producing a signal that is superimposed on top of the essentially constant background. The RTEP continuously averages the output from the focal plane over a number frames on a
pixel-by-pixel basis in order to generate a background estimate. It then subtracts the average background estimate of each pixel from the current signal of the corresponding pixel.

The subtracted signal consists of shot noise fluctuating about zero with occasional peaks due to lightning events. When a peak exceeds the level of a variable threshold, it triggers comparator circuits and is processed by the rest of the electronics as a lightning event. The threshold must be set sufficiently high that false triggers are kept to a small percent of the total lightning rate. Clearly, the threshold must be higher during daytime when shot noise is dominated by the solar background.

The components of the real-time event processor include a background signal estimator, a background remover, a lightning event thresholder, an event selector, and a signal identifier. Analog/digital hybrid processing is used in an unique way that takes advantage of the strengths of each technology in order to provide high processing rates while consuming minimal power. Much of the signal processing is performed in a pipeline fashion that maximizes throughput.

The background estimator (averager) and remover (subtraction) circuits combine to perform the functions of a time domain low pass filter. The signal coming off the focal plane is fed through a buffer and clipping stage in order to ensure that a strong lightning signal does not contaminate the background estimate. The signal is then multiplied by a fractional gain (B) and added to (1-B) times the previous background estimate for the same pixel. The inverse of the fractional gain is equivalent to the number of frames used in generating the background estimate and is analogous to setting the cutoff frequency in conventional frequency domain filters. Too high a fractional gain might permit lightning events to contaminate low background estimates and would increase the processing noise. Too low a fractional gain would not allow the background estimator to respond rapidly enough to changes in background intensity.

The proper operation of the background estimator requires that the background data are clocked through the estimator synchronously with the data being clock off the focal plane and that the number of discrete storage elements in the background memory is exactly the same as the number of pixels in the focal plane array. When data are properly synchronized, the signal appearing on the output of the delay line during a given clock cycle corresponds spatially to the signal being clocked off the focal plane. That is, it contains a history of what that specific pixel has measured over the last 1/B frames. These two signals are then subtracted using a difference amplifier in order to generate a difference signal. Since the original signal contains either background plus lightning or just background, the subtracted signal will be either a lightning signal, near zero or a false event.

The difference signal is then compared with the threshold level (which will be adaptive). If the signal exceeds the threshold level, a comparator triggers, which enables a switch and passes the lightning signal for further processing. In addition, the comparator output is encoded using a digital multiplexer in order to generate a row address which identifies the specific pixel that detected the lighting event. The digital outputs from the data processor represent the intensity of the lighting event and the location where the lightning occurred. These signals are then forwarded to encoding electronics in which the data are formatted into a digital bit stream and sent to the spacecraft. Experience from OTD and LIS have demonstrated that it is not necessary to remove all the false events with the RTEP. We have found that it is relatively straightforward to filter out the bad events via ground-based processing since the true lightning events have much different characteristics. The main function
of the on-board processing is to capture all the lightning events and to reduce the number of false events to a manageable number that can be handled by the telemetry system.

The mapping of 20 subregions to 16 RTEPs should allow for the uninterrupted observations of the continental United States under the conditions of spacecraft yaw flips and one RTEP failure. This may be best accomplished by allowing each RTEP to be mapped to one of two subregions.

A.1.5 Instrument Configuration

After gaining on-orbit experience with the LMS, it may prove desirable to implement additional on-board signal processing. A forty percent reserve of processor resources must be preserved to support this requirement. The driver for this requirement would be improved real time data dissemination in support of operations. This level of signal processing would be implemented in software utilizing the LMS microprocessors. In addition, data record configuration options should allow for inclusion of event count and event amplitude summaries. A capability for selecting certain subregions for preferred event detection is also required. This allows full event rates in the preferred subregions at the expense of possibly missing event in other subregions.

A.1.6 Interface Requirements

The LMS requires power and data resources from the satellite bus. The packaging of the instrument will be driven by its location on the spacecraft, its field of view requirements, its need for passive thermal control and by the specific services provided by the bus. These issues require a detailed accommodation study to resolve. However since LMS is a small, lightweight sensor, it should be relatively easy to accommodate on the spacecraft with the main issue being heat dissipation and maintenance of pointing stability and knowledge.

A.2. Project Science Team

The LMS program will fund a project science team under the guidance of the P.I. that will be responsible for processing raw instrument data into lightning data, for validating the lightning data, for coordinating ground-based validation activities, for making mission data available to other researchers, and for providing an interface to the general science community. Additionally, other scientific work will be sought from other programs (e.g. Earth Science Enterprise).

1.4.3 Comparing performances and limitations

As it appears from the previous review, most ground lightning mapping systems are based on electromagnetic detection, and most space lightning mapping systems are based on optical detection.

As far as future spatial lightning detection systems are concerned, both options are open and performances and limitations of presently functioning systems or network must be compared and evaluated. Part II of this report will examine the implications of the geostationary option on the various systems performances. The differences between systems are indicated in terms of user requirements. Basically, accuracy, horizontal resolution, time sampling are to be considered, as well as lightning flash type discrimination ability and land/ocean behavior.
I. 4. 3. 1 Accuracy
The detection efficiency, or hit rate (HR), represents the percentage of the real flashes actually detected by the system. It is usually determined by comparing the number of events detected by the system to a “ground truth”. This reference is obtained from ground and reliable networks. For all systems, the detection efficiency depends on the location of the events in relation to the sensors and especially on the distance. As it is indicated in the specific sections, most operational ground networks claim to reach or exceed HR of about 90 % for isolated discharges occurring within a given area.

Considering the spatial systems based on optical methods, the HR depends on the threshold of detectable radiant energy density. A study by NASA (Christian and Goodman, 1987) shows that 90 % of a given flash sample produce peak energy densities of $4.7 \mu J m^{-2} sr^{-1}$ or greater. On the other hand, the influence of daytime/nighttime conditions plays also an important part in this optical counting. Thus OTD detection efficiency ranges from 40 % to 65 %. The more recent LIS instrument and the associated signal processing considerably improve this performance up to over 90 % for all events. The FORTE project associates optical and RF detection. The optical sensor being the same as LIS, the same kind of detection efficiency is expected. Since the RF sensor does not cover the same area as the optical device, it does not detect as many events. The percentage of discharges detected by the RF sensor among those identified by the optical sensor ranges between 11.4 % and 21.8 %.

The ORAGES project plans a detection efficiency of the same order of magnitude as that reached by the ground systems based on the same principle of VHF interferometry (for example SAFIR), i.e. over 90 %. The Lightning Mapper Sensor performances should reach better limits than those of the previous optical sensor LIS. The HR is planned to be higher than 90 %.

The False Alarm Rate (FAR) represents the percentage of non-flash events counted as flashes. Most detection networks and spatial sensors indicate a FAR lower than 10 %. Progress in signal processing procedures should lead to decrease this rate. The Lightning Mapper Sensor plans a lower value reaching down to 5 %.

I. 4. 3. 2 Horizontal resolution
This parameter is difficult to define. The precise localization of a lightning flash depends on the type of event. If we consider a cloud-to-ground discharge, the impact on the surface is perfectly defined. A very short resolution is meaningful and corresponds to a physical reality. Now all flashes (CGs as well as ICs) travel within the cloud over distances that can exceed tens of kilometers. In particular an intracloud discharge has no precise location beyond its channel length around the small region where the bi-directional discharge is initiated. As a matter of fact, a lightning flash is not a pin point event. The best way to characterize its occurrence would be to reconstruct its channel geometry, which is usually performed using research instruments like VHF interferometers. To do this the electromagnetic sources have to be precisely localized, and preferably in a 3-dimensional way. No optical detection can do the job because of the cloud diffusion of light. On the other hand no global detection system does it up to now. Only limited areas, like airports, benefit by operational 3-D detection.

Considering the optical detection from space, the diffusion by the whole cloud volume of the light produced by all types of flashes (IC and CG) keeps the sensor from determining a small volume around the flash, even in the case of the short channel of a vertical CG discharge. As a matter of fact, NASA reports (namely Christian et al., 2000) indicate that “the diameter of the cloud top illumination associated with a single storm cell will typically be on the order of 10 km. Observations of large storms systems from the shuttle have shown that illuminated regions can exceed 60 km (Goodman and Christian, 1993).” As a consequence, the horizontal resolution of such an optical sensor does not need to be much better than 10 km. This 10 km
value is indicated for OTD. It corresponds to the size of the pixel. For LIS the pixel size corresponds to about 5 km. The horizontal discrimination is claimed to be on the order of 3 to 6 km (at nadir and limb respectively). Finally, the announced value of this parameter for the LMS future optical sensor is 8 km at nadir. The nature of the observed phenomenon limits this value.

Considering the electromagnetic detection from space, the resolution limitation does not come from the diffusion phenomenon. The cloud does not scatter the RF energy as it does optical. The limit depends on the location accuracy of the antenna network and on the associated electronic circuits. The ORAGES project proposes a resolution reaching 15 km from an orbit about 800 km from the Earth surface.

Most operational ground networks detect only CG flashes through the electromagnetic field signature of the channel base. In this case, the localization of the discharge impact can be determined with the whole accuracy permitted by the technical limits. Common values released in the literature range between 1 and 0.5 km.

I. 4. 3. 3 Time sampling

There are two levels of time sampling: (i) the first one corresponds to the inhibition period during which the sensor detects and processes a flash signature and cannot record a new event occurring during this period within its detection area; (ii) the second one relates to space detection from orbiting or spinning satellites and corresponds to the period of time between two passages of the sensor field-of-view over a given region.

(i) Time sampling level 1: Most systems take between 1 and 2 ms to process a lightning flash signal. It has been demonstrated by NASA (Christian, 1998) that an increase of this integration time up to 2 ms “does not seriously degrade the sensor’s performance.” Therefore, this parameter is not critical as long as it remains below this value. The Lightning Mapper Sensor is designed to equip a GOES geostationary platform without spin up. The optical sensor itself will thus constantly observe the scene and therefore act like a ground detection system. The only time sampling to consider is the 2 ms time resolution of the imager.

(ii) Time sampling level 2: This parameter applies only to spatial detection (the field of view of ground networks remains constant). For orbiting satellites like those carrying OTD, LIS, and FORTE instruments, the thunderstorm lightning flash activity is not permanently observed. The sensor realizes a sampling of this activity. The sampling period is governed by the orbit characteristics. The satellite carrying OTD instrument orbits the Earth once every 100 minutes at an altitude of 740 km, and at any given instant views a 1300 km × 1300 km region of the Earth. As a result most regions on Earth are “visited” by OTD once or twice a day, twice being the maximum. Highest latitudes are more frequently explored than lowest latitudes. As an average, each region is observed 400 times a year during about 3 minutes each time. LIS time sampling data are close to OTD’s. As an average, a given region is observed about once a day during almost 90 seconds each time. FORTE satellite characteristics are quite similar to the previous ones and ORAGES project will also display the same kind of lightning activity sampling. In conclusion, the instruments carried by orbiting satellites are not designed to detect and observe the lightning activity of a given thunderstorm event during its whole lifetime. However, they are clearly adapted to realize an overall lightning climatology.

I. 4. 3. 4 Lightning flash type discrimination ability

Atmospheric discharges can be divided into two general types - cloud-to ground (CGs) and intra-cloud (ICs) flashes – and two categories of cloud-to-ground flashes must be
distinguished: negative (the most frequent) and positive. As already mentioned, each type of discharge reflects specific characteristics of the thundercloud. For obvious reasons the ability of a given detection system to discriminate those categories represents an advantage.

As indicated in section I. 3, some lightning detection networks based on the ground detect only CG flashes (LPATS, LLP…). They discriminate negative and positive strokes, and often provide the peak current intensity. Some others (SAFIR, LDAR) detect and discriminate all types of flashes.

Let us consider now the spatial instruments:

(i) Those based on optical detection determine the total lightning rate of thunderstorm, which is quite appreciable for all sorts of studies, as opposed to those that “see” only CGs. However they do not distinguish between cloud-to-ground and intracloud discharges. The main reason is related to light scattering process from cloud. As it is stated by Christian (1998), “the scattering process dominates the characteristics of the optical signature, the optical pulses from both intracloud and cloud-to-ground flashes are very similar.” This lack of discrimination can be overcome by associating the optical detection from space to ground detection of CG flashes. Both types can thus be determined by subtraction. Nevertheless, this procedure can only be performed over land surfaces where CG flash detection is available.

(ii) Unlike optical emission, the electromagnetic emission of all types of flashes is not disturbed by cloud scattering. Radio frequency detection from space is thus able to provide the discrimination of flash categories. Besides it can also characterize each phase of the flash from the structure of the electromagnetic emission.

I. 4. 3. 5 Ocean/land detection

Global space detection clearly shows that a large majority of lightning activity is produced over continental masses. However, oceanic lightning production is not negligible and many human activities over the oceans undergo thunderstorm threat and need to be protected against it.

All ground networks are installed over land surfaces and most of them are not designed to detect lightning activity over the oceans. When they do it, the performances over ocean are quite different than over continent. On the other hand, these ground systems are based on various principles and their results may differ from each other. Thus only spatial surveillance can provide a unified and global coverage of all regions of the Earth surface.

I. 4. 3. 6 Comparison to user requirements

The performances and limitations of the lightning detection systems presently functioning or already planned are summarized on table I.4.4. They must be compared to the user requirements presented in the EUMETSAT Statement of Work. Table I.4.5 displays these requirements.

The comparison shows that the ground detection systems presently in function mostly meet these requirements, except that they do not inform on the oceanic (and therefore on the global) thunderstorm activity.

Now if we consider the spatial detection systems, two remarks can be raised:

(i) The required horizontal resolutions are not met by any of the existing and planned systems. The relevance of such required resolutions should be discussed keeping in mind the geometrical extension of a lightning flash (discussed in I. 1. 2) and the optical scattering by the cloud of the flash light (discussed in I. 4. 3. 2).

(ii) The time sampling as required by the user requirements (15 minutes) is not met by the instruments on orbiting satellites but should be met by the geostationary systems.
<table>
<thead>
<tr>
<th>System</th>
<th>Parameters</th>
<th>C-G ground detection</th>
<th>Total lightning ground detection</th>
<th>OTD</th>
<th>LIS</th>
<th>FORTE</th>
<th>ORAGES</th>
<th>LMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection efficiency</td>
<td>&gt; 90 %</td>
<td>&gt; 90 %</td>
<td>40 % to 65 %</td>
<td>&gt; 90 %</td>
<td>&gt; 90 %</td>
<td>&gt; 90 %</td>
<td>&gt; 90 %</td>
<td></td>
</tr>
<tr>
<td>False alarm rate</td>
<td>10 %</td>
<td>10 %</td>
<td>5 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>0.5 km to 1 km</td>
<td>10 km</td>
<td>3 km to 6 km</td>
<td>10 km</td>
<td>15 km</td>
<td>8 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time sampling level 1</td>
<td>1 ms</td>
<td>0.1 ms</td>
<td>2 ms</td>
<td>2 ms</td>
<td>RF:</td>
<td>1.3 ms Opt.:</td>
<td>2 ms</td>
<td></td>
</tr>
<tr>
<td>Time sampling level 2 (average)</td>
<td>Not relevant</td>
<td>Not relevant</td>
<td>24 h</td>
<td>24 h</td>
<td>24 h</td>
<td>24 h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detected events</td>
<td>CG</td>
<td>CG / IC</td>
<td>CG / IC</td>
<td>CG / IC</td>
<td>CG / IC</td>
<td>CG / IC</td>
<td>CG / IC</td>
<td></td>
</tr>
<tr>
<td>CG / IC discrimination</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>Ocean detection</td>
<td>Limited</td>
<td>Limited</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td></td>
</tr>
</tbody>
</table>

**Table I.4.4**

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>Horizontal Resolution</th>
<th>Time Sampling</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ELECTRICAL DISCHARGES FOR FUEL / EXPLOSIVE HANDLING (CLOUD TO GROUND LIGHTNING)</td>
<td></td>
<td>Very High</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
<td>Break through level</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
<td>Break through level</td>
</tr>
<tr>
<td></td>
<td>CONVECTION MONITORING INDICATOR OF INTENSITY AND HAIL (INCLUDES CLOUD TO CLOUD LIGHTNING)</td>
<td></td>
<td>Very High</td>
</tr>
<tr>
<td></td>
<td>CHEMISTRY: LOCATION OF LIGHTNING FOR NATURAL NO₂ FORMATION (INCLUDES CLOUD TO CLOUD LIGHTNING)</td>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
<td>Break through level</td>
</tr>
</tbody>
</table>

HR: Hit Rate, FAR: False Alarm Rate.
Unit: km unless specified.
Unit: minutes unless specified.

**Table I.4.5: Users requirements from EUMETSAT**

51
I. 5 Conclusion – The operational applications

The three basic operational applications considered in the “User requirements for lightning detection” can presently be only partly developed based on the existing systems.

(i) Electrical discharges for fuel/explosive handling: Such activities are very sensitive to cloud-to-ground discharges but also to surface electrostatic field conditions. Locally initiated “static discharges”, occurring under high surface field intensities, can also cause serious damages. Concerning the danger from CGs production, most ground detection systems are useful and efficient as warning systems. However, the total lightning detection is preferable to only CG detection since in most thunderstorms, the intracloud activity precedes the production of CGs (the delay ranging from a few seconds to some tens of minutes) and therefore provides better warning criteria. On the other hand, ground detection systems do not cover the whole Earth surface. Only developed countries benefit from a total coverage, and ocean are poorly covered. The presently functioning spatial detection systems undergo the problem of time sampling. It may help in this respect only if the satellite happens to visualize at the right time the region to protect. Therefore a global lightning detection from geostationary platform appears to be the best way to achieve such a warning task. Finally it must be pointed out that a local electrostatic field measurement is in all cases necessary in order to prevent the danger of local discharge formation. Such a risk appears when the local field exceeds a given threshold.

(ii) Convection monitoring indicator of intensity and hail: The tight correlation existing between severe meteorological events and lightning activity (see section I. 2) allows the use of the latter activity as an aid to nowcasting. Beyond the usefulness of total lightning detection it is important to achieve the lightning flash discrimination (ICs, positive and negative CGs). The distribution of the different types of flash activity brings fruitful information on the lifetime and characteristics of the convective system that generates this activity. The continuous monitoring of flash activity is another necessity to achieve an indication of convection and hail intensity. As for the previous item, some operational ground networks (those detecting and differentiating all types of flashes) have the capability to accomplish the task. Considering spatial detection, again only a sensor on a geostationary platform will be able to follow each event activity.

(iii) Chemistry (NOx formation) and climate change: Climatological studies do not require a continuous monitoring of each convective system. The estimation of the global temperature evolution can be managed through the operating spatial instruments. On a global scale, the estimation of NOx production by thunderstorms may probably be achieved on a statistical basis, i.e. referring to the same global lightning activity as that established for global change studies. Again the present spatial detection from orbiting satellites is able to bring an answer. Now if we want to evaluate the amount of NOx formed within specific convective systems, it is necessary to get an estimate of the channels length (Laroche et al., 1999). In this case, only a 3D lightning mapper can get this kind of information. Up to now, only VHF interferometric ground detection systems are able to do so. No operational and global detection of channel length is planned for the moment. The solution would probably be to carry out a series of field experiments using such interferometers in order to characterize the NOx production of the different types of convective systems in order to parameterize global models. Such field experiments have already be performed, for example STERAO (Dye et al., 1999) in Colorado.
PART II

Feasibility
**Introduction**

Lightning detection from a geostationary platform can be performed through different modes. Up to now most spatial instruments functioning on an operational basis and installed on orbiting satellites has used the optical transient energy produced by lightning flashes. On the other hand, electromagnetic detection remains widely used in ground networks and tends to develop in spatial projects. Therefore, both possibilities must be examined in planning the systems of the future.

Concerning the satellite, there are two kinds of geostationary platforms: those whose scene exploration is performed through satellite spin up (present METEOSAT platforms) and those without spin up (GOES platforms). The first kind would imply a scanning of the scene (as long as the sensor undergoes the same rotating motion as the whole platform) whereas the second kind allows a staring imager to constantly aiming at the same region. The choice between these two possibilities is probably the most important issue concerning lightning detection.

Scanning a still picture like the global cloud coverage is a perfectly relevant procedure that is widely used. Now the lightning flash activity is composed of a large number of very brief events scattered over the whole scene. The lightning activity of a given storm system is estimated through the determination of the flash rate (the flash number per minute). In order to do so it is necessary for the lightning sensor to aim at the same area during at least a few minutes. Thus the scanning procedure appears to be totally unable to faithfully provide this activity. A quantitative estimation of such scanning procedure is performed in II. 1. 3.
II. 1 Value added of a detection from geostationary platform

The advantages of a lightning detection system installed on a geostationary platform must be examined against the possibilities offered by both ground and orbiting satellite systems, and considering the priorities of operational issues.

II. 1. 1 Detection over oceanic and land masses

The ground detection systems presently functioning perform a permanent survey over most developed country territories. Their detection ability partly overlaps the oceanic regions (coastal regions) with a deterioration of their efficiency that increases with the off-shore distance. Furthermore, most oceanic areas are surface detection free. Although the ATD system detects flashes almost world-wide, its low detection efficiency at distance (5-10 %) does not allow it to provide a confident flash rate.

On the other hand, national ground detection networks often differ from a country to another. Sometimes their characteristics are very different (especially their detection efficiency) and they do not provide the same kind of information, making it difficult to reach an homogeneous coverage of a given region. Fortunately, there is a net tendency to overcome this lack of homogeneity by cross-calibration procedures, and to interconnect the various networks of a given continent in order to cover as much as possible the contiguous territory of this continent. For example, data of the national networks of Canada and United States have been gathered and provide a wide coverage of North America (Orville et al., 2002).

Nevertheless a large fraction of the developing countries do not benefit by such ground detection. This is especially the case of Africa whose lightning activity is very high (the highest in the world according to OTD and LIS data) and therefore crucial not only for the country itself, but also for a reasonable global estimation of lightning activity. Thus the overall coverage of the continental masses is basically not complete. If we consider that oceanic detection is not correctly performed by surface networks, we can only conclude that spatial detection if highly necessary.

Finally, difference in detection efficiency over land and over ocean must be studied for both kinds of possible spatial detection, from orbiting satellites as well as from geostationary platforms. This difference is probably not the same for optical and electromagnetic detection. A preliminary study should thus be conducted in this respect.

II. 1. 2 Large global area homogeneously covered

An important value added of the geostationary platform relates to the large area constantly covered by the sensor in this configuration as compared to the orbiting satellite. The field of view nearly covers the whole Earth disc. Now, the benefit of such a large coverage depends on the scene exploration procedure. Consequently, it depends on the detection technique, i.e. optical or electromagnetic.

An electromagnetic detection system cannot select a limited part of the field of view. Therefore such a system, if it is suitable in terms of sensitivity and resolution, achieves a simultaneous detection of the whole lightning activity produced within the totality of the earth disc. The optical detection, as it is planned within the LMS program, can also observe simultaneously a large portion of the Earth disc, but also can select a particular area under surveillance and perform a specific exploration of a given target. In this respect, both systems installed on a geostationary platform provide the most useful information about the lightning risk evaluation.
II. 1. 3 Theoretical possibility of following a given thunderstorm event from space – Image scanning/Lightning activity sampling

When compared with orbiting satellite observations, probably the most important advantage provided by the observation of lightning activity from a geostationary platform resides in the theoretical possibility of monitoring a given thunderstorm. This is crucial for the warning task.

At the present time, a given area can be observed from space during no more than 3 minutes once or twice a day from an orbiting system (see I. 4. 3. 3), meanwhile it should be observed on a continuous basis from a geostationary platform. The continuous observation should require minimum time characteristics described in the following.

The sampling duration, i.e. the time during which a continuous observation of a given area is performed, must exceed 90 s for ensuring the lightning flash rate measurement of most storms (visit http://thunder.nsstc.nasa.gov/lis/). The sampling period – the time between two successive observations of the same area – cannot exceed 250 s if the minimum horizontal resolutions of 5 km is required. As a matter of fact, it corresponds to the time taken by a thundercell to cover this distance with an advection velocity that can exceed 20 m/s. This leads to a total sampling time per day for a given area that rises up to about 8 hours and 40 minutes.

These time characteristics are achieved by LMS (see I. 4. 2. 2) and would be achieved by a system like ORAGES on a still geostationary platform. On the contrary, a spin-stabilised platform like MSG (Meteosat Second Generation) appears to be unsuitable for such requirements. First, an electromagnetic sensor using several antennas (5 in the case of an interferometer) and acting as an interferometer can not function undergoing this rotation. Second, optical detection also needs a still platform. As indicated in the following, the classical picture scanning cannot apply to lightning detection.

As a matter of fact, a line scan (9 km wide) performed from East to West by the satellite spin motion at 100 rpm lasts about 30 ms. Therefore, a given area at nadir (9 km × 9 km) is observed during only 21 µs during this line scan since the field of view is about 12800 km wide (Equator diameter). This sampling duration is far from the requirement indicated above in terms of lightning flash rate measurement.

Furthermore, the sampling period of 15 minutes (MSG) permits a new observation of the same line/area only 15 minutes later. In this time lapse, the corresponding motion of a thundercell (advection speed of 20 m/s) could cover distances up to 18 km, which does not correctly fulfil the warning purpose in view. On the other hand, the upgraded sampling period of 5 minutes (Table 1. 4. 5) would reduce this distance down to 6 km, distance that stays around the realistic horizontal resolution indicated in part I. 4. 3. 2 for an optical sensor.

Nevertheless, the total sampling time per day for a given area reaches only 6 ms/day for a spin-stabilized platform (MSG) with the 5-minute sampling period. This duration seems dramatically too short for a satellite which aims at constantly monitoring lightning activity. As a comparison OTD and LIS reach a minimum of 180 s/day and 90 s/day, respectively, although they were designed for lightning climatology.

In conclusion, the scanning procedure is not adapted to lightning detection. If the general spin up of the platform is necessary for stabilization and other optical sensing procedures, the device dedicated to lightning detection should remain still.
II.2 Various possible systems

The raw data obtained from optical as well as electromagnetic detection systems consist in individual sources that need to be grouped in order to provide individual flashes. As indicated in section I.1, the task is not so trivial. Several algorithms have been established to do the job. Christian et al. (2000) designed a special algorithm for the Lightning Imaging Sensor, and many others are applied to ground networks based on electromagnetic detection (for example Thomas et al., 2003). The same task will have to be performed in the case of lightning detection from space, whatever the system may be.

II.2.1 Optical detection

At the present time, the optical detection of lightning from space has been successfully performed by systems like OTD and LIS on orbiting satellites (cf. I.4.1). The detection efficiency has reached 90% with upgraded signal processing. This technology has well demonstrated its operational ability in such a way that the LMS projects (see I.4.2.2) plans to carry out the optical detection from a geostationary platform. We describe below the advantages and drawbacks of this kind of detection realized from a geostationary satellite.

II.2.1.1 Advantages - As far as scientific data are concerned, the optical detection provides only the basic lightning mapping information: counting and geographical location of lightning flashes at the thundercloud scale. The following important advantages can be pointed out.

1. **Tested and reliable technology for operational task.** It profits by the fruitful operational observations of OTD and LIS and from the recent progress in the LMS program.

2. **Simplicity and compactness.** Contrary to the electromagnetic detection, the optical detection does not need the deployment of large antennas and therefore remains of rather small dimension. Furthermore, the technology is simple, even if it requires real-time event processors (RTEP) for event detection and data compression.

3. **Flash luminous intensity.** The intensity of the light produced by each flash is an useful parameter that somehow can be related to current and/or exchanged electric charge, taking into account cloud attenuation.

II.2.1.2 Disadvantages and uncertainties - There are mainly two disadvantages in the optical detection of lightning from space. They result from the strong scattering of the light by the thunderclouds:

1. **Lightning location uncertainty.** As indicated in section I.4.3.2, the minimum diameter of the cloud top illuminated by a lightning flash is typically of the order of 10 km. Therefore, the optical detection does not permit to localize a lightning event with a better horizontal resolution. Even if the LMS program announces a 8 km horizontal discrimination at nadir, this location uncertainty could probably not be further reduced with this kind of detection.

2. **Lightning characteristics not provided.** First of all, the optical detection does not discriminate between Intra-Cloud and Cloud-to-Ground lightning flashes. This problem could be overcome by associating the optical detection from space to ground detection of Cloud-to-
Ground flashes but only over land surfaces where CG flash detection is available (see I. 4. 3. 4). The distinction between positive and negative Cloud-to-Ground lightning flashes and the measurement of the peak current intensity are logically impossible too. Furthermore, a precise estimate of the channels length cannot be provided by optical detection though it is of importance to evaluate the NOx production (see I. 2. 5).

II. 2. 1. 3 Possibility to meet users requirements - According to the Statement of Work, they are three kinds of users requirements (see Table I. 4. 5). Let us detail below if the optical detection can meet them or not:

1. **Accuracy.** The detection efficiency (or HR) reached by the staring sensor of the LMS program is expected to be higher than 90% for all events (see Table I. 4. 3). In this way, the users requirements are fully achieved since this percentage corresponds to the maximum accuracy desired. As far as the False Alarm Rate (FAR) is concerned, the characteristics given by the LMS program (lower than 5% of total events) are even better than the users requirements (10%).

2. **Horizontal resolution.** Due to light scattering from clouds, the best horizontal resolution that can be achieved by an optical sensor is about 8 km (LMS). Therefore the users requirements cannot be met with this kind of lightning detection. However, it is questionable whether such low resolutions (between 1 and 5 km) could have a physical signification given that a lightning channel cannot be considered as a pin point event (see I. 4. 3. 2).

3. **Time sampling.** For a staring optical detector, the signal processing is very short and permits a new acquisition 2 ms later. This is largely beyond the users requirements indicated in Table I. 4. 3, which have been chosen for a spin-stabilized platform that is not adapted for the lightning monitoring (see II. 1. 3).

II. 2. 2 Electromagnetic detection

Most electromagnetic basic principles used in ground based systems can be adapted to space based systems. A recent project from the Los Alamos National Laboratory plans to develop a satellite-based VHF Global Lightning and Severe Storm monitor using an already funded constellation of VHF receivers to be flown on the upcoming Block IIF Global Positioning System (GPS) satellite constellation (Suszinsky et al., 2000). This planned system would work on a DTOA basis (Difference of Time Of Arrival), and would detect only the strongest thunderstorm events.

In the present case of a unique geostationary platform, the VHF interferometry (among other VHF systems) seems to be the most appropriate system to achieve the geolocation of electromagnetic lightning sources. The advantages and disadvantages of such a device must be examined.

II. 2. 2. 1 Advantages – According to the review of various lightning detection procedures reported in Part I, we can expect the following advantages from the electromagnetic detection from space:

1. **Cloud transparency to VHF signatures.** The theoretical horizontal resolution could be better than the 10-km value imposed by optical diffusion from cloud hydrometeors. On the other hand, there is no significant alteration of electromagnetic signals, which allows them to keep their basic characteristics.
2. **Possibility to discriminate flash types.** This fact is the consequence of the previous issue. Under such conditions, we can expect that it should be possible, based on temporal characteristics differences, to discriminate Cloud-to-Ground from Intra-Cloud activity, and even to detect the polarity of each CG flash. Now, since the distribution of flash categories is tightly connected to the type of convective or stormy activity (see I. 2), such a discrimination would bring fruitful extra information.

3. **Possible determination of lightning channel lengths.** This ability benefits the estimation of NO\textsubscript{x} production by lightning activity. It must be reminded that this estimation is based on the amount of NO\textsubscript{x} produced by unit length of discharge channel.

4. **Constant and uniform detection efficiency.** Since there is no influence of background light on the electromagnetic signals we can expect this system to offer the same detection efficiency during day time as during night time. Furthermore, there should not be major differences between land and ocean detection.

II. 2. 2. 2 Disadvantages and uncertainties – A few drawbacks are expected as compared to optical detection. Some characteristics cannot be definitely determined without a quantitative and precise study.

1. **Received power.** The signal power received by an orbiting satellite based system from lightning sources has already been validated (see I. 4. 2. 1). A quantitative study must be realized in order to perform the same validation at geostationary distance. The power received by the sensor must be high enough in order for the system to detect as many flashes as possible and not to restrict the data gathering to the most powerful lightning flashes. This parameter has thus a strong influence on the detection efficiency. Nevertheless, the increase of the distance between source and receiver can be partially compensated by increasing the antennas gain. The lower angle of view of the Earth from the geostationary platform should allow the system to meet this goal.

2. **Necessity of antennas deployment.** The system itself is neither as simple nor as compact as the optical sensors already in function. The dimensions of the complete device depends on the frequency range and on the antenna gain required. On the other hand, a great accuracy of the antennas position is needed to meet the users requirements.

3. **Possible influence of the background noise.** The man-made electromagnetic noise will probably have a stronger impact on a geostationary based receiver than on a system based on the ground or in an orbiting satellite. The number of sources is higher in the case of the geostationary satellite and therefore requires a careful preliminary study. Such studies have already been performed by the FORTE group of Los Alamos (see I. 4. 1. 2) and within the ORAGES group (see I. 4. 2. 1) in the case of orbiting satellites. The choice of the receiver frequency range is strongly dependent on the distribution of the man-made electromagnetic background noise. Efficient signal processing and pattern recognition are necessary to extract the useful signal from the background.

II. 2. 2. 3 Possibility to meet users requirements – Three groups of requirements are considered that need quantitative studies.
1. **Accuracy.** The Hit Rates (HR or detection efficiencies) of operational ground systems based on the same principle already reach the mentioned values. 90% is required for isolated events. As long as the received signal power exceeds the detectable threshold (section II. 2. 1. 2), we can reasonably expect the same kind of figure. The same conclusion should be raised for the False Alarm Rate (FAR). Most ground based systems provide values smaller than 10%. Both requirements should receive successful answers if the pattern recognition procedure is powerful enough. This condition must be kept in mind.

2. **Horizontal resolution.** As already mentioned, the figures that appear in the Statement of Work (from 5 to 1 km) look very difficult and may be not so useful to achieve, taking into account the horizontal structure of a lightning flash. Only elaborated and dense ground based networks reach this kind of resolution. Again, the horizontal dimensions of a given lightning flash most often exceed 5 km, especially in the case of intra-cloud flashes, the most frequent among the flashes produced by a thunderstorm. On the other hand, given the limited baseline of the interferometer (distance between antennas), it would be very difficult to achieve a horizontal resolution as low as 1 km. The recent improvements in phase detection accuracy lead to expect a resolution on the order of 10 km. But a more elaborated study might improve the figure. Furthermore, the final resolution of the system depends on the angular accuracy of the platform orientation. This problem is discussed in section II. 3.

3. **Time sampling.** The required time sampling of 15 (resp. 5) minutes relates to the picture line scanning procedure. It has been shown (II. 1. 3) that this procedure is not adapted to lightning flash detection, whatever system (optical or electromagnetic) is chosen. Therefore, if the choice of a staring sensor is decided, the time sampling to be considered is that indicated “level 1” in section I. 4. 3. 3. It is on the order of 2 ms, which allows the sensor to constantly observe the scene and record the overall lightning activity.
II. 3 Limiting factors of the platform

The most critical point relates to the platform orientation accuracy. The stabilization accuracy must ensure the required horizontal resolution of lightning flash geolocation, from 1 to 5 km corresponding to the users requirements. There is a direct and simple relationship between the required resolution and the positioning accuracy. The table below indicates this correspondence.

<table>
<thead>
<tr>
<th>Horizontal resolution required</th>
<th>1 km</th>
<th>5 km</th>
<th>10 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Necessary positioning accuracy</td>
<td>30 µrd</td>
<td>140 µrd</td>
<td>300 µrd</td>
</tr>
</tbody>
</table>

The same kind of positioning accuracy will probably be necessary for most atmospheric parameters detected from the platform. In the case of electromagnetic detection, the possibility of using existing transmitters on the ground (for example the numerous aeronautical coordinate systems like VOR) as position references would represent a help in the geolocation of the lightning sources.
II. 4 Possible synergies based on geostationary lightning detection

II. 4.1 Association with other spatial lightning detection systems

Lightning observations from satellites have been performed during the last decades thanks to low orbit platforms. The sensors used were most of the time optical devices, like the OSO2 (Vorhpal et al., 1970) or OSO5 (Sparrow and Ney, 1971). More recently, the Defence Meteorological Satellite Program (DMSP) used also this kind of sensor (Orville and Henderson, 1986).

The last long-time missions using optical sensors are Optical Transient Detector (OTD) that worked from 1995 to 2000 (and Lightning Imaging Sensor (LIS) from 1997. These instruments provide geolocation, time and light intensity of each lightning flash of any type. They have not been able to provide detailed information on the lightning characteristics. These satellite observations were achieved from low Earth orbit and consequently, the detector take snapshots of storm events whose lightning rate can be estimated. With such limitations, most studies performed from the corresponding data have addressed questions of global lightning activity distribution. A lightning sensor on a geostationary orbit would provide new data adapted for monitoring or studying specific storms or systems.

The lightning detection systems from space presently operational are LIS on the TRMM platform and FORTE. FORTE mission is devoted to three objectives, nuclear detection, study of ionosphere disturbances, and lightning properties investigations. For the lightning detection, FORTE uses a VHF instrumentation and two optical instruments. The combination of the signals detected by the electromagnetic instrument with those detected by the optical detection devices enables to discriminate the lightning flashes from the background noise on one hand, and to characterize the different types of lightning flash (intra-cloud, negative and positive cloud-to-ground) on the other hand.

If the total activity of a given convective system or that of a given area is permanently observed from space thanks to a geostationary orbit, the ratio cloud-to-ground flash number/intra-cloud flash number can be studied versus various parameters like the latitude at large scales, the vertical development of the thundercloud, the stage of development of the thundercloud, the moment of the day, the type of ground surface, the type of meteorology conditions (Mackerras and Darveniza, 1994). Such observations can lead to improve the knowledge of the charge and discharge processes of the convective systems, especially over ocean surfaces (Boccippio, et al., 1999). As a matter of fact, the oceanic lightning activity is difficult to detect from ground networks and the development conditions are different from over land (Zipser, 1994). Some works show the possible associations of several spatial observations about lightning activity by different techniques when there is correspondence between the fields of observation of both satellite equipment (Boeck et al., 2003). Of course, if one of the satellite is a geostationary platform, the time of correspondence will be longer.

II. 4.2 Association with ground lightning detection systems

The existing ground detection systems are permanently working over a given area as opposed to those installed on orbiting satellite. They cover at least some continental areas, like North America or Western Europe. Since most ground networks provide the cloud-to-ground flash activity, the space observation of the total activity (intra-cloud and cloud-to-ground) is a good complement for the concerned areas.

Thus, the discrimination between intra-cloud and cloud-to-ground flashes can be realized even if the spatial equipment does not perform it. If this discrimination is made from the
geostationary satellite equipment, the ground data can also be a way to check the detection efficiency of the spatial device for the cloud-to-ground flashes (ground truth). As a matter of fact, because of the cloud scattering effect signals, we can suppose that the efficiency of cloud-to-ground flash optical detection can be altered. The estimation of this efficiency can also be performed for the intra-cloud activity when the convective system is observed from ground with a system like SAFIR. Several SAFIR systems are installed around the world, especially in Europe or in Japan, but they generally cover limited areas as compared to most cloud-to-ground detection networks.

The spatial system detection can be evaluated with respect to the cloud scattering effect if the system is based on optical detection. Of course, the efficiency and the accuracy of the detection can be permanently evaluated for any detection technique by comparing with the ground areas covered with operational systems.

A recent work shows how observations of lightning by ground-based and satellite-borne location and mapping systems can produce inferences for lightning physics (Beasley et al., 2003). Another work by Thomas et al. (1999) used ground-based 3-dimensional lightning mapping observations and satellite-based LIS observations in the Oklahoma area. This study showed that the LIS optical device can miss some cloud-to-ground discharges confined to mid- and lower-altitudes in the cloud. Figure 1 displays an example of result of this comparison. Another study showed this kind of comparison between LIS observations from space and SAFIR observations from ground (Kawasaki and Yoshihashi, 1999). Figure 2 shows the correspondence of both observations for a time sequence of 105 seconds by reporting the activity rates.
Figure 1: An expanded view of four seconds of observations, illustrating how the satellite-detected luminosity is associated primarily with intracloud lightning discharges that develop into the upper part of the storm and much less or not at all with cloud-to-ground discharges. The interior rectangular contour in panel e is twice the intensity of the outer contour and is centered above a classic bipleve IC discharge. Panels c and f show vertical projections as viewed from the south and west, respectively; these panels also show the horizontal scale in km. Detected LIS events are denoted by + symbols above the top of the lightning activity. Shown along the abscissa are the locations and times of negative (∆) and positive (∗) strokes to ground located by the National Lightning Detection Network (NLDN). Panel d shows a histogram of the radiation source heights and the total number of located points. Panel a shows the integrated light intensity observed by LIS. (From Thomas et al., 1999).
II. 4. 3 Association with other meteorological observations

One can distinguish a threefold type of possible synergies. The first one relates to other ground based observations, the second to airborne observation systems, and the third one to space observation systems:

1. **Synergies with ground based observations.** Several ground based systems could provide fruitful information for an operational warning of lightning flashes. When available (essentially over continents), Meteorological radars can provide a fine description of the characteristics and of the evolution of the thunderstorms that could enhance the warning criteria. Basically, all ground measurements that are closely connected to thunderstorm events are of interest if gathered with space detection in a single structure, which role would be to analyse the data and to diffuse the adequate warning information in the shortest time possible.

2. **Synergies with airborne observation systems.** It has been shown (cf. I.2.5) that lightning flashes are probably an important source of ozone via the production of NO$_x$. In order to evaluate this source, one could link the lightning activity detection from space with airborne measurements of ozone performed in the MOZAIC program (Measurement of Ozone and Water Vapor by Airbus In-Service Aircraft, web site: http://www.aero.obs-mip.fr/mozaic/). This program aims at automatically and regularly measure ozone and water vapour through five long range passenger airliners flying all over the world (Thouret et al., 1998).

3. **Synergies with other space observation systems.** For an operational purpose, this kind of synergy is probably the most practical to set provided the corresponding sensors exist. Several programs have already gathered multiple detectors for environmental measurements (MSG, www.eumetsat.de/; ENVISAT, http://auc.dfd.dlr.de/; UARS, http://daac.gsfc.nasa.gov/), and precipitation and lightning detection (TRMM, http://trmm.gsfc.nasa.gov/).
In order to reduce the False Alarm Rate, one could compare the lightning data with the measurement of various parameters that are known to be related to lightning (see I. 2). For example, the temperature and height of cloud tops is highly needed to check if the detected lightning flashes closely match the most vertically developed clouds of a given area. This can be made with infrared images (MSG), or radar (Ushio et al., 2002).

Most convective systems can be detected before their first lightning flash with a good accuracy as long as the sampling period of infrared images is short enough (Koffi et al., 2001). On the meteorologist point of view, various other measurements could enhance the forecast of thunderstorms evolution for nowcasting purpose: precipitation could be detected by radar (TRMM), ground temperature and water vapour (see I. 2. 5) by radiometer, discrimination between ice and water clouds by radiometer (SEVIRI on MSG), and cloud updraft velocity (cf. I. 2. 3) by Doppler radar (we are not aware if this kind of detector could work on a geostationary platform).

Furthermore the NOx or ozone detection could be of great interest for global climate change if coupled to lightning detection since it would allow to quantify their production by lightning in an operational way, at the best frequency and horizontal scale ever done until now. At last, the detection of aerosols could help to analyse the impact of pollution on lightning activity (cf. I.2.5). For example, SCIAMACHY on ENVISAT (http://auc.dfb.dlr.de) is designed to detect concentration of many gases (H2O, O3, CH4, CO, N2O, NO, NO2, CO2,...) and aerosols. Such sensor allows retrieval of vertical profiles of these species with the limb mode and provides information about only total trace gas concentrations with the nadir scanning mode. The limb mode is however not adapted at geostationary distance. On the contrary, sensors like MOPPIT (Measurement of Pollution in the Atmosphere) that used gas correlation spectroscopy can provide information at nadir at different levels in the atmosphere. The measurements performed in this program were CO and CH4. Maybe this technology should be adapted for the detection of other chemical species.
II. 5. Conclusion

The operational applications

Lightning detection from geostationary satellite appears to be highly relevant in comparison with and in addition to other ground networks and orbiting satellites sensors. The geostationary observation brings specific information that other systems do not. Detection on a global basis, real time observation of the total lightning flash activity (CG and IC flashes), possibility to follow a given thunderstorm during its complete lifetime represent valuable improvements for all operational applications.

Therefore, the three basic operational applications considered in the “User requirements for lightning detection” would be better developed based on a geostationary detection system.

(iv) Electrical discharges for fuel/explosive handling: Such activities are very sensitive to cloud-to-ground discharges but, as it is indicated in section I. 5, the total lightning detection, as it should be performed from geostationary platform, is highly preferable to only CG detection. The expected advantage of electromagnetic detection is flash type discrimination, which brings more information about the type of thunderstorm and thus achieves a better warning procedure.

(v) Convection monitoring indicator of intensity and hail: Given the tight correlation existing between severe meteorological events and lightning activity (see section I. 2) the possibility of discriminating the flash categories represents an improvement of the nowcasting procedure.

(vi) Chemistry (NOx formation) and climate change: Climatological studies do not require a constant monitoring of each thunderstorm. The choice of the detection system does not appear to be as critical as for the other tasks. The knowledge of flash channel extension is an extra information useful for the estimation of NOx production by thunderstorms. If the electromagnetic detection is supposed to offer an indication in that respect it only relates to the horizontal extension of the channel. The useful vertical dimension remains out of reach.

Recommendations

1. Lightning detection from geostationary satellite needs to be integrated into a still platform. A rotating sensor would not be able to accomplish the task.

2. Users requirements should be modified accordingly. The required horizontal resolution (from 1 to 5 km) will be hardly achieved and does not really correspond to the actual size of the phenomenon detected, the lightning flash. The required time sampling should be reduced in order for the system to be more efficient in terms of nowcasting. Anyway, if recommendation 1. is taken into account, the time sampling will be drastically reduced.

3. The choice of the sensor due to equip a geostationary platform should be decided based on the services offered by each system. The electromagnetic detection seems to provide more useful and diverse information than the optical detection. However, the optical sensor has proven its operational efficiency based on simplicity and compactness. The advantage of the electromagnetic detector depends on a precise evaluation of the energy transmitted to the receiver and on the horizontal resolution it is capable of from the geostationary orbit.
References


