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THUNDERSTORM MONITORING AND LIGHTNING WARNING, OPERATIONAL APPLICATIONS OF THE SAFIR SYSTEM

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A INTRODUCTION

During the past years a new range of investigation has been opened by the application of electromagnetic localization techniques to the field of thunderstorm remote sensing. VHF localization techniques were used in particular for the analysis of lightning discharges and gave for the first time access to time resolved 3D images of lightning discharges within thunderclouds.

The French national agency for aerospace research (ONERA) has been active for more than ten years in this domain. It developped systems based on the principle of VHF interferometry for research in lightning physics and thunderstorm phenomenology. Today these techniques are used for operational applications. The DIMENSIONS company, a spin-off of ONERA, develops thunderstorms monitoring and lightning warning systems for use in fields such as aerospace, industry, military activities and meteorology.

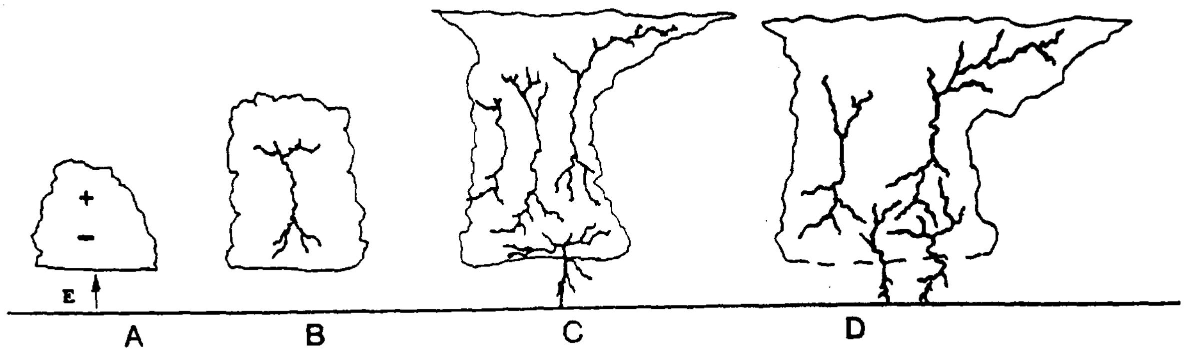


Fig 1: Typical phases in the development of a thunderstorm

B PRINCIPLES

TYPICAL DEVELOPMENT OF A THUNDERSTORM CELL

Thunderstorms are convective clouds created by the thermal instability of a humid air mass. They are made of convective cells. These cells develop very rapidly, they last a few tens of minutes, grow up to altitudes of 10 to 15 km and have a diameter of about 10 km. Thunderstorms are frequently multicellular, they can extend over tens or hundreds of kilometers and last several hours.

During its development a thunderstorm cell presents very strong updrafts (up to 50 m/s) carrying up precipitation particles such as ice crystals, supercooled droplets and graupels.

The main electrification process of the thundercloud during its development is due to the charging of graupels and ice crystals by collisions and to their separation by differential vertical motions within the cloud. These processes result in a tripole electrical structure with a main negative charge around 6 km at the -15°C level, a positive charge in the upper part of the cloud from 8 to 12 kilometers and a small positive charge at the cloud base (Krehbiel,1986). Winter thunderstorms have a similar structure, somewhat tilted, but over a smaller vertical extent .

The electrification of the thundercloud creates a strong electric field (*Figure 1* (A)). It can exceed 10 kilovolts per meter on the ground in the vicinity of the thunderstorm, and reaches several hundred kilovolts per meter within the cloud. This initial electrification phase can last less than 10 mn. The active phase starts with the first intra-cloud discharges (*figure 1* (B)) which occur when and where the conditions within the cloud (strong electric field and presence of hydrometeors) are sufficient for the production of lightning discharges. During the first part of the active stage, the vertical development of the thundercloud goes on. The activity is made of intra-cloud discharges occuring between the main negative and the upper positive charge regions. They have been observed to be well correlated with the upward development of the thundercloud and are most invigorated in the presence of updrafts carrying precipitation particles. Their rate increases until the cell reaches its maximum vertical development (*Figure 1* (C)).

Intra-cloud lightnings are thus the principal electrical manifestation of these charged and convective zones. They radiate electromagnetic waves over a very wide frequency spectrum and can be detected and located at long range.

In multicellular thunderstorms, intra-cloud lightnings can extend over very large distances (several tens of kilometers) between cells, within the anvil or in the dissipating part of the thundercloud. Intra-cloud lightnings are much more frequent than cloud to ground lightnings, they

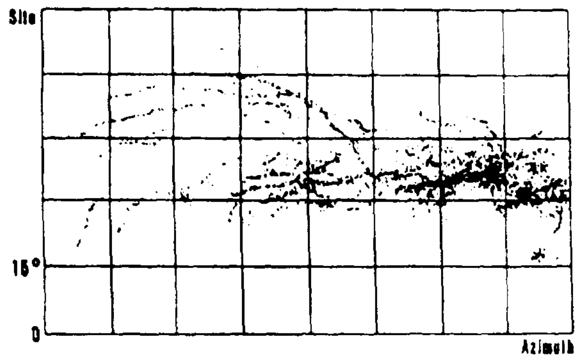
typically represent 70 to 90% of the total lightning activity of a thunderstorm.
First cloud to ground lightnings are usually observed 5 to 30 minutes after the first intra-cloud lightnings, during or after the thundercloud maximum development. They are due to the subsequent descent of precipitation particles below the main negative charge layer. At this moment the intra-cloud activity rate begins to decrease and the cloud to ground rate increases (*Figure 1 [D]*). Cloud to ground lightning activity culminates during the decay of the thunderstorm cell, it is accompanied in severe thunderstorms by strong downdrafts and intense precipitations at ground level; these severe phenomena have been observed to follow the peak intra-cloud activity with a delay of 5 to 10 minutes (Williams et al, 1988).

ELECTROMAGNETIC RADIATION FROM LIGHTNING

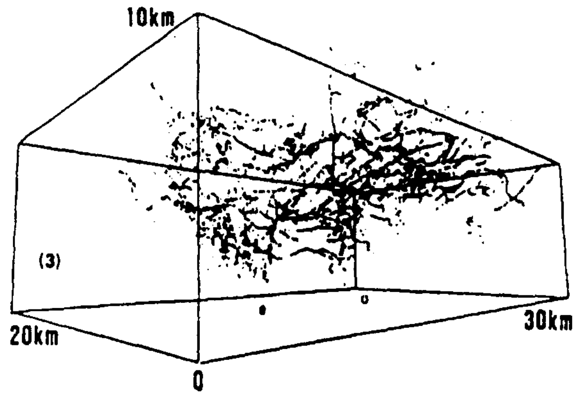
Lightning discharges produce electromagnetic radiation over a very large frequency spectrum. The overall spectrum of lightning peaks at a few hundred kHz and extends up to the Ghz with a 1/f dependance. The electromagnetic emissions are due to the occurence of intense and rapidly varying currents within the lightning channels.

The most powerfull radiation is the pulse produced by the return stroke wave during cloud to ground flashes. This wave typically occurs when a pre-ionized leader channel, progressing downward from the thundercloud, reaches the ground. At this moment an intense current propagates upward within the lightning channel at about 1/3 the velocity of light. The current waveform has a typical risetime of a few μs and a peak value of several tens of kA. This phenomena radiates at low frequency, mainly below 1 MHz. This radiation is used principaly for the measurement of the characteristics of the cloud to ground return stroke current (peak value, polarity, energy...) and for the long range localization of lightning strokes to ground.

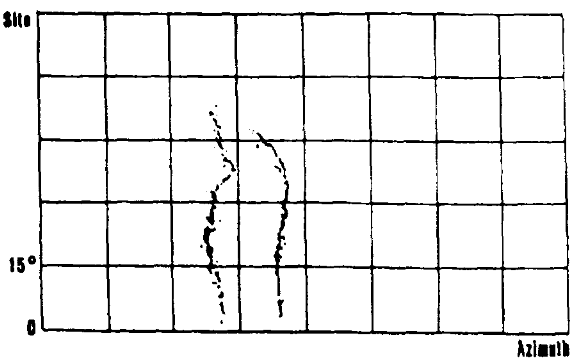
But lightning discharges radiate much more frequently at higher frequencies. The radiation is made of very short pulses of a few ns risetime, they cover the whole HF-VHF-UHF spectrum. These radiation pulses come from all along the lightning channels during their formation, or during the rapid propagation of a current wave within an existing pre-ionized channel . They are mainly due to fast transitions occuring between low and high conductivity phases of the lightning channel plasma in negative polarity breakdowns. They are observed in all types of lightning flashes (intra-cloud and cloud to ground), and in most phases of a discharge (preliminary breakdowns, stopped leader, dart leader, recoil streamer and return stroke). These pulses usually occur in bursts lasting from a few hundred μs to several ms; the pulse rate can range from a pulse every 50 μs up to several tens per μs.



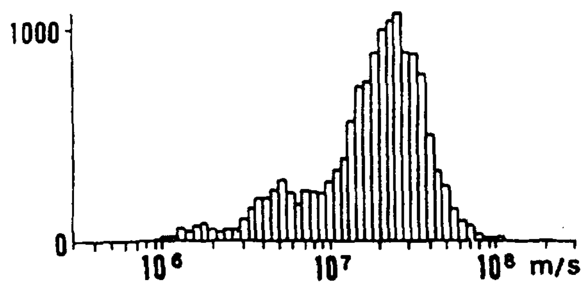
Intra-cloud flash (2-D)



3-D imaging of propagating discharges during 20 minutes of storm activity



Cloud to ground return strokes (2-D)



Histogram of discharge propagation velocities

Fig 2: Examples of results obtained with 3D VHF interferometry

VHF detection and location techniques have been of great interest for the analysis of lightning discharges properties, in particular within the thundercloud, where previous optical techniques were ineffectives, and which contain the large majority of lightning discharges phenomena. Figure 2 presents some of the results obtained at ONERA with a 3D interferometer, it illustrates some of the main characteristics of lightning discharges.

THE INTERFEROMETRIC TECHNIQUE

Measurement principles - Interferometry is based on the measurement of phase differences between signals received on different antennas of an antenna array. These phase differences are directly related to the direction of arrival of the signal and are used to calculate the angular position of the source in azimuth and elevation. 2D or 3D spatial location can then be obtained by the combination, through triangulation, of angular data given by at least two different interferometric stations.

Characteristics and advantages

The main advantage of this type of measurement is that it is independent of the signal wave form since measurement is only made on the electromagnetic wave phase. This is to be opposed to other modes of radio localization using amplitude measurements and wave form identification. Interferometric localization is thus not tributary to the identification of a typical wave form and can be made on any type of radiation from lightning phenomena. In addition the use of the VHF frequency range allows the localization of a large variety of atmospheric discharges phenomena in this band and the fine reconstruction of the spatial structure of lightning discharges in its different phases of development.

C APPLICATIONS TO THUNDERSTORM MONITORING AND LIGHTNING WARNING

Detection and localization techniques developped at ONERA during lightning research programs have been applied to the design of the SAFIR system. This development had for main objective the design of an operational system capable to assess and warn in real-time for lightning hazards and potential thunderstorm hazards.

The basic principle is that all along the development of a thunderstorm cell, the electrical activity (production of lightning discharges and generation of an electrostatic field) is closely related to the different stages of evolution of the cell and to the thunderstorm severity. The electrical activity of a thunderstorm can in consequence be used for achieving thunderstorm early detection and lightning hazard early warning, and for evaluation of potential thunderstorm hazards.

The SAFIR system main detection technique is the long range interferometric localization of thunderstorm electromagnetic activity; the system performs the localization of intra-cloud and cloud to ground lightning discharges and the analysis of the characteristics of the activity.

Applications and capabilities of the SAFIR technique in the field of thunderstorm monitoring and lightning warning can be summarized as follow:

High efficiency detection and monitoring capabilities - SAFIR can locate VHF sources present in all types of lightning discharges (intra-cloud and cloud-to-ground), and can therefore locate and monitor the total lightning activity of a thundercloud. The additional detection of intra-cloud activity usually represents a three-fold to ten-fold improvement in monitoring efficiency, it has been observed to reach a hundred fold in some cases of severe thunderstorm.

early lightning warning capability - Detectable at long range, intracloud discharges are the first signs of the electrical development of a thunderstorm.
By localizing these discharges SAFIR can provide early warning of thunderstorm developments and lightning hazards before the first cloud to ground discharges. Warning delays between first IC and first CG range from 5 to 30 minutes.

mapping and monitoring of electrically active hazard areas - Lightning discharges can extend over distances of several tens of kilometers, the localization and monitoring of these discharges enables the system to delimit the real extension of electrically active areas and to estimate the potential lightning hazard levels on the ground and in the air. In conjonction with previous capabilities the system is able to precisely analyse the stage of development of the thunderstorm and can project at short term its evolutions in space and time to give a previsionnal mapping of lightning hazard areas.

potential for the assesment of severe thunderstorm hazards - A close correlation exists between the convective state and severity of the thunderstorm and the characteristics of its lightning activity. Maximum vertical development of the thundercloud coincides with the maximum in total flash rate. The severe phenomena occuring at ground level during the thunderstorm decay such as maximum cloud to ground flash rate, intense precipitations, strong downbursts, have been observed to occur 5 to 10 minutes after the peak in IC flash rate (Williams et. al., 1988). Real-time localization and monitoring of total thunderstorm activity is thus a potential tool for the assessment of weather hazards produced by thunderstorms.

SAFIR SYSTEM ARCHITECTURE

A SAFIR system basic configuration is made of 3 detection stations and a central processing station (*figure 3*). Each detection station performs the interferometric angular localization of lightning discharges. Data are transmitted to the central station where the spatial locations of discharges are calculated by triangulation technique.

The central station performs the real-time monitoring and analysis of the activity and displays the hazard maps and warning informations. These informations can then be transmitted automatically or on request to remote display terminals.

Fig 3: SAFIR system typical configuration

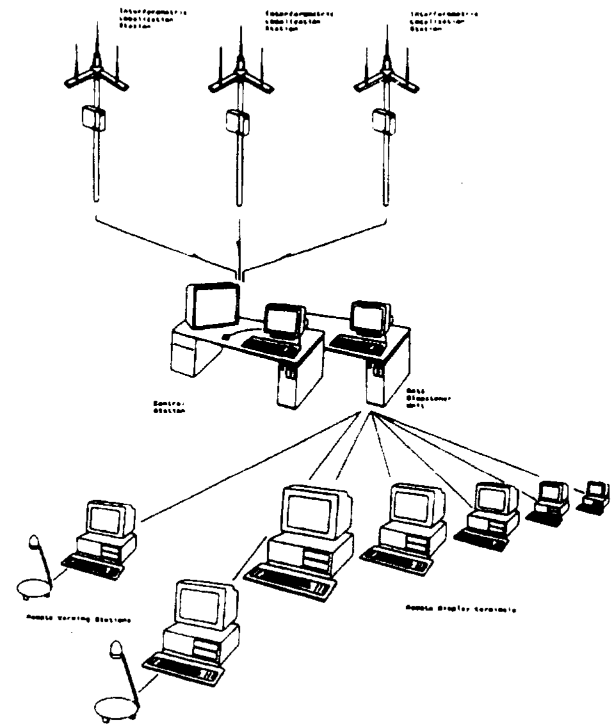
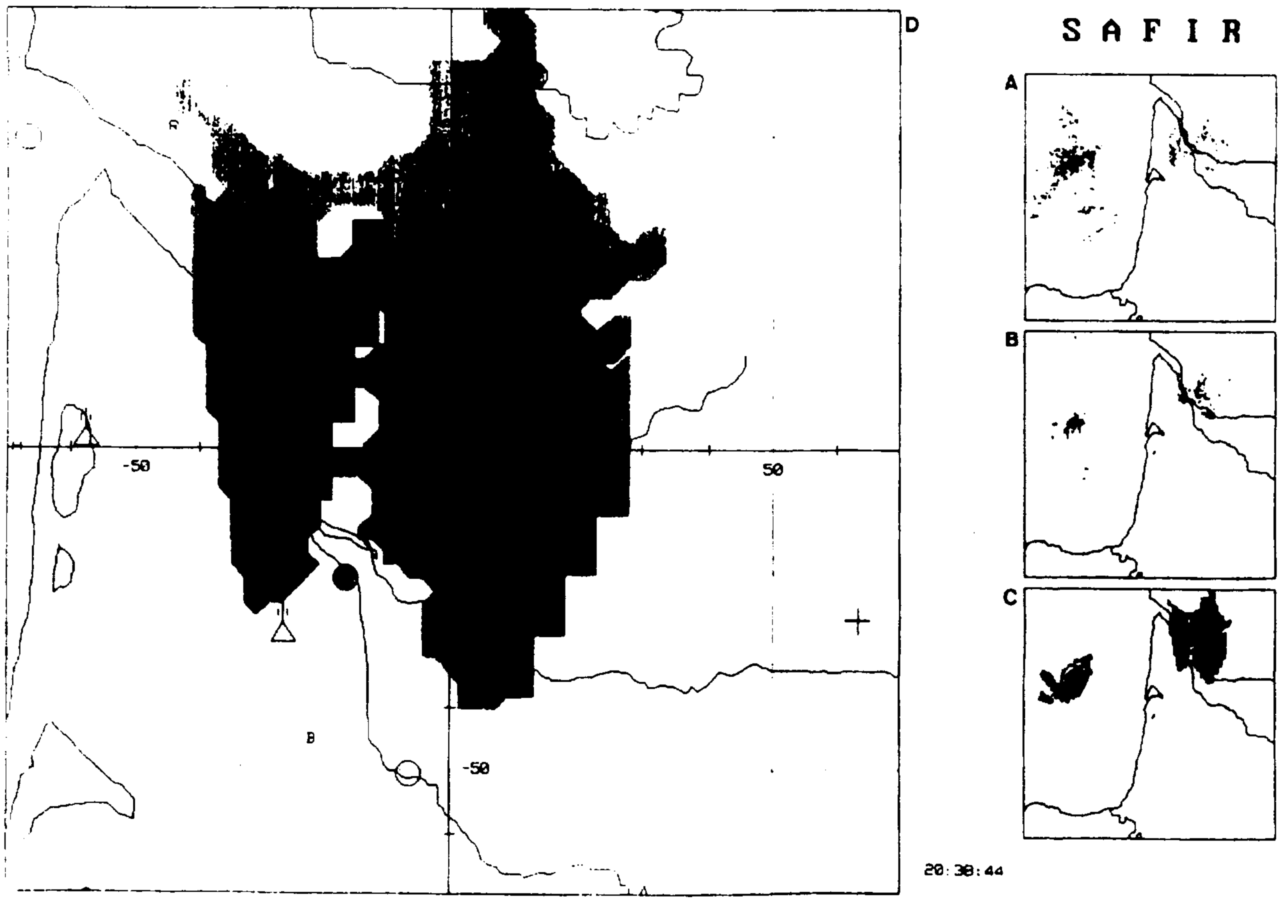


Fig 4: Real time Display

Real time functions are displayed in full scale in the 3 secondary windows

A: location of lightning flashes
B: present mapping of electrically active hazard areas
C: previsional mapping of hazard areas

Each function can be displayed in the main window (D) here is an enlargement of the previsional mapping of hazard areas; present contours of cells are displayed as well as short term previsional positions. Present and previsional activity levels are color coded for each cell



Typically, the coverage of the system is 300 by 300 km, the distances between stations can range from 20 to 100 km according to applications, and the locating accuracy is between a few hundred meters and five kilometers depending on the system configuration and the lightning location.

OPERATIONAL FUNCTIONS

The main real time operational functions of the SAFIR system are presented on a graphic display (fig 4); they include:

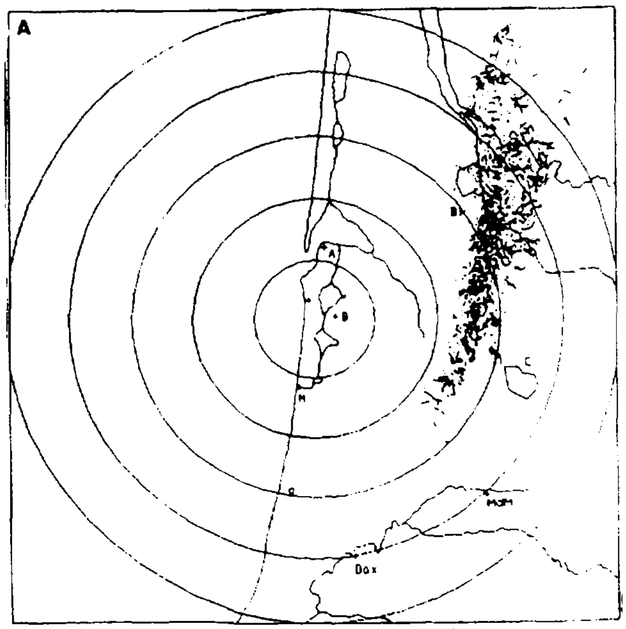
- **localization of lightning discharges;** discharges are displayed on background maps with color coding of their characteristics and time of occurence
- **mapping of electrically active hazard areas;** the activity level is color-coded within pixels of 2x2 km, evaluation is based on the real time analysis of the spatial and temporal characteristics of lightning activity.
- **previsional mapping of electrically active hazard areas and automatic warning ;** the real time processing function detects and tracks electrically active cells, the activity is analysed within each cell and a mapping of short term projections of thunderstorm position and intensity is provided (typically up to 30 min). For sensitive sites, the system calculates warning informations and can warn automatically the user of an approaching danger.

All data are stored for analysis. Post processing enables the user to perform statistical analysis on the electrical activity in order to characterize lightning hazards on a site or over a whole region.

EXAMPLES OF THUNDERSTORM SITUATIONS.

These examples illustrate the functions and performances of the system.
The first situation (*figure* 5) is a thunderstorm which occured in the SW of France in july 1989.
The local meteorological situation is characterized by a strong convective activity and a violent advection to the North/North-East high altitude. On the wind profile we can note very high wind velocities above 3000m up to 85 knots at 7000m.
This thunderstorm propagates over a distance of 140 km at an average speed of 100km/hour. It produces a total number of 867 ligtning flashes among which 13 are cloud-to-ground strokes. The time delay between the first intra-cloud lightning and the first cloud-to-ground lightning is 28 minutes.

This particular example illustrates two of the principal features of the SAFIR system :
The early lightning warning function before cloud-to-ground activity, and the monitoring capability mainly based on the location of intra-cloud activity.
An additional application is the assessment of severe weather hazards associated to a thunderstorm. This particular thunderstorm, though giving only a small number of cloud to ground discharges, produced heavy precipitations and caused important destructions on the ground. The plot of its lightning flash rate is presented in *figure 5B* together with its maximum radar reflectivity and its total radar reflectivity. Peaks in maximum radar reflectivity occur,5 to 10 minutes after the peaks in the flash rate, and the total precipitation reaches its maximum 35 minutes after the time of maximum flash rate.



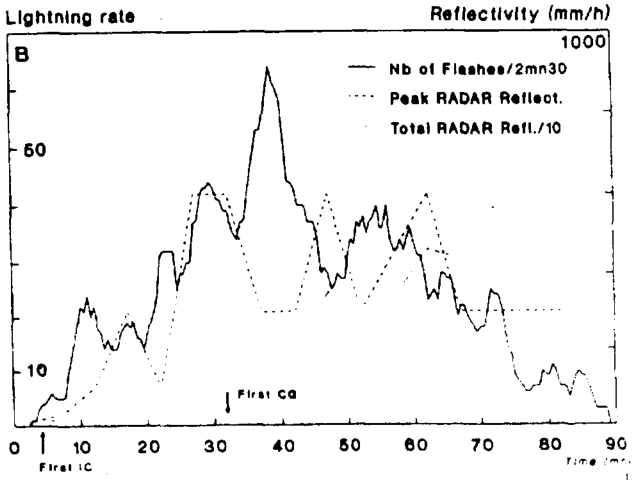


Fig 5:

A - Location of lightning discharges
B - Evolution versus time of the total flash rate, the peak radar relectivity and the total radar relectivity of the thunderstorm

The second situation was observed in april 1989 in the South-West of France.
The thunderstorm presented in *figure 6A* lasted for 1H30mn and moved slowly to the North over a distance of about 40 km. It produced 105 lightning flashes with 39 cloud to ground strokes.
Figure 6B presents separately the temporal evolutions of intra-cloud and cloud-to-ground flash rates. We can note that the warning delay is 27 mn between first IC and first CG; equaly remarkable is the 5 mn time delay between peaks in IC activity and peaks in CG activity which again appear in good agreement with the typical thunderstorm phenomenology. Both results confirm the IC activity as an effective solution for CG flashes warning.

Several thunderstorms were observed on the same day in the same meteorological situation. Time delays between first IC and first CG ranged between 8 minutes to 31 minutes.

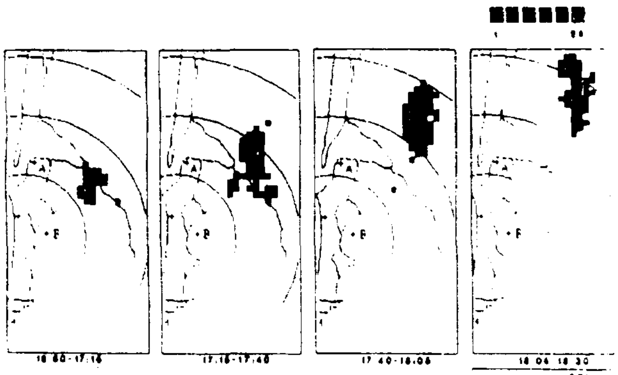

(spatial density)

fig 6A: Location of lightning discharges

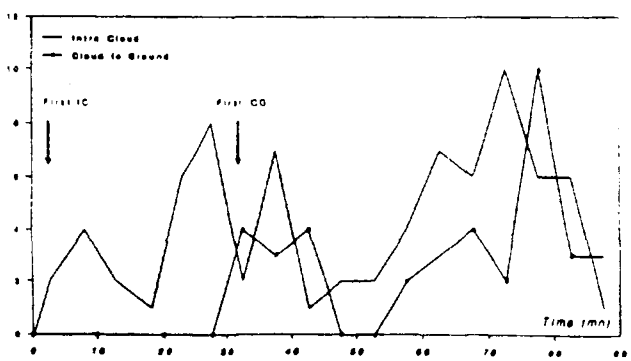


fig 6B: Evolution versus time of CG and IC flash rates

OPERATIONAL APPLICATIONS

Safir is already in operation at the European Space Center in Kourou, French Guiana. A second system is in use at the "Centre d'essais des Landes", a flight test center in the southwest of France.

Early lightning warning and thunderstorm monitoring functions have applications for the safety and efficiency of ground and airborne operations. Applications on the ground range from the management, protection and maintenance of telecommunication and power networks to decision making and active lightning protection for industrial and military sites.

For civil and military aerospace activities, the system in an important component in ensuring in-flight safety of launch vehicles and aircrafts; principal applications are for space centers, test ranges, and airports, where its lightning warning and thunderstorm monitoring capabilities aids in terms of air-traffic control and safety.

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