LIGHTNING EXPERIMENTATION IN BRAZIL
Single Rod & Early Streamer Emission (ESE) Lightning Conductor Field Tests

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Overview

Specifically designed to allow testing to be conducted on both naturally occurring and triggered lightning strikes, the Cachoeira Paulista facility was built in 1998 on the initiative of INDELEC, the University of Toulouse in France, Hydro-Quebec (IREQ) in Canada and the Brazilian universities of Campinas and San José Dos Campos in Sao Paulo state. The main on-going test involves comparing single rod and ESE lightning conductors, Hydro-Quebec being a neutral observer. An apparatus carrying the measuring instruments and lightning devices under test is subjected to strikes triggered at altitude, the final point of impact being determined by the discharge itself. The investigation techniques, together with the results of the 2000/2001 campaign are set out herein.

Introduction

The debate over the protection afforded by an ESE compared to single-rod lightning conductor rages on, meaning that, while laboratory tests continue to be a vital element in determining each model's technical performance characteristics, field test campaigns carried out in natural storm conditions represent an invaluable additional source of data, given the scale and the unpredictable nature of lightning.
The desire to realize a field test campaign is not new – the CEA in Grenoble, France, conducted a series of tests involving triggered lightning from 1993 through 1996.
Initial experiments involved uprating the traditional triggering technique, referred to as LRS-G and which used a copper wire connected to the ground, to the LRS-A technique, whereby insulator – usually between 100 and 400m in length – is first unraveled. The advantage of this technique is that it allows the altitude-triggered discharge to find its own way down to the final point of impact on the ground.
A series of identically calibrated sensors are placed on the ground within the likely impact zone.

The first significant results were obtained during the last campaign at Saint Privat d'Allier in 1996 [1]. In 1997, the CEA elected to wind up their diversification programs within the framework of an internal restructuring program, leading INDELEC to take full responsibility for the on-going campaign.
In 2000, the company decided to draw up a 5-year contract with Brazil, Canada & France, whereby the three countries would cooperate in the running of a natural & triggered lightning test facility.
The objectives were both scientific – studying the mechanics of lightning and measuring the physical parameters of the discharge, electromagnetic radiation, and so forth – as well as technological – comparative tests on the different types of lightning conductor, assessment of the effectiveness of meshing, inductions on test transmission lines, experimental laser triggering, atmospheric detection, forecasting and analyses, etc.
The lightning test facility was designed in a similar fashion to those already seen in France and the US and was completed in January 2000, thanks in no small part to the invaluable help provided by MAKER Brazil, to whom we would like to take this opportunity to express our gratitude.
Although the facility was designed and built by the aforementioned organizations, it is available to other bodies around the world, as long as intended experiments comply with those set out and implemented in the original agreement. So far, both TELEBRAS and FRANCE TELECOM have made use of the facility.

1. The site at Cachoeira Paulista

The triggering station is located half-way between Sao Paulo and Rio de Janeiro at the Brazilian National Space Research Institute (INPE), near the village of Cachoeira Paulista. Its location 22°41.2 S; 44°59.0 W and at an altitude of 625m provides for ideal tropical storm conditions. The site's prime geographical location was not the only criteria, however : the logistic, technical and monitoring support provided by the INPE, which also hosts the

Brazilian Meteorological Office (CPTEC) was also a determining factor.

1.1. Preliminary site analysis

A campaign to record the electrical field at ground level took place between December 1998 and May 1999 [2] at the INPE site 3 km from the test facility, with the aim of monitoring and analyzing the atmospheric disturbance which affected the site during the stormy season. Instrumentation consisted basically of an E2000-type storm warning device driven by proprietary software.

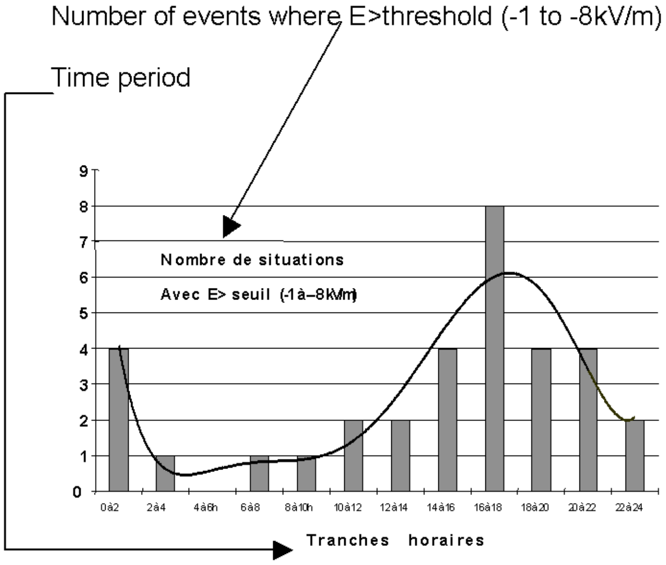


Fig.1. Daily storm breakdown.

Data was stored in real time on a PC and sent to France by the INPE lab at San Jose Dos Campos.

Despite the short test period, analysis of the data (fig. 1 above) revealed the following characteristics of the local storms :

- short, violent storms occurring late afternoon & early evening,
- high electrical fields (10 – 12kV/m) but only average activity,
- high-altitude cloud base,
- high proportion of flashes within & between clouds,
- situations with high field (10 – 12kV/m), without significant activity.

1.2. Naturally occurring strikes

At the same time, in December 1998, an experiment involving natural lightning strikes on the sensor systems was implemented, with the aim of comparing the performance of four different lightning conductors :

- a single tapered rod (r< 1mm),
- a single rounded rod (r = 15 mm)
- a standard type Early Streamer Emission lightning conductor (ESELC)*,
- a high-performance ESELC*.

**Note : both ESELC lightning conductors were standard models taken from the INDELEC range.*

The four lightning conductors were erected on metal masts at the four corners of a square frame, each side of which measured 15m. All the tips were placed 12m above ground level, with a single earthing rod connected to strapping at the base of each mast.

Despite a high Keraunic level prevalent in the area (100 – 110), the probability of a lightning strike is extremely low. As such, the testing needs to be conducted over a number of years.

An electromechanical lightning strike counter, mounted on each of the conductors' downleads, records the number of impacts to each device. To achieve this, a nylon sleeve is inserted in the mast to hold the strike counter. Kevlar stays are used to ensure the current flows through the counter. As of December 2000, none of the devices had been struck.

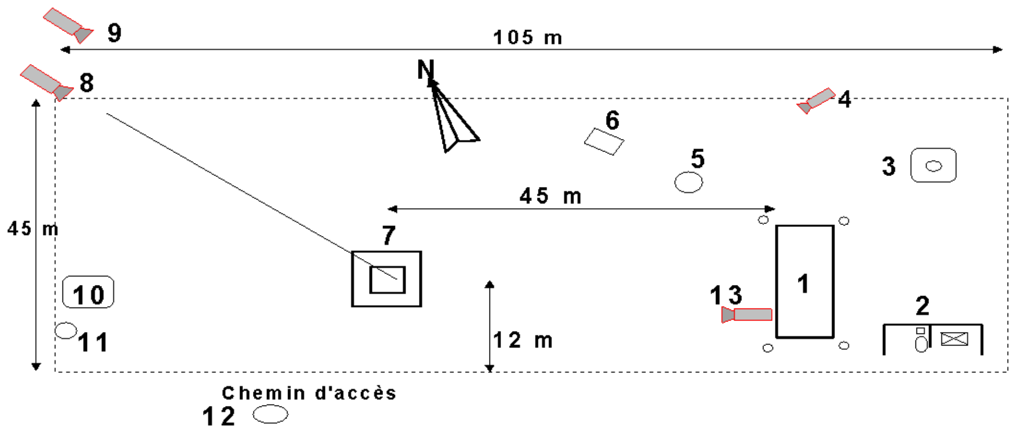
2. Triggering station

Located on a plateau 2 km from the INPE testing zone, the station covers an area of about 5000m². The red laterite in the ground provides a high resistivity equal to about 1000 Ω.m.
The station is designed to be upgradeable and is built using light, modular structures (fig.2).
There are three main parts :

- the Control Room (CR),
- the Testing & Firing Platform (TFP),
- the Test Zone (TZ).

2.1. Control Room (CR)

Comprising a light metal building measuring 12m x 2.5m, the CR is designed both to provide protection for the engineers and act as a data collection station.
It is protected from direct impacts by a meshed cage, with both the building and the cage having just one earthing point (R=21Ω). Power is provided by a 17kW stationary generator built into the protection device.
The acquisition systems are protected by overvoltage arrestors and UPSs, which provide full backup for up to 10 minutes.
Optical fiber is used to connect the outside sensors to the CR, while pneumatic tubes are used to operate the equipment so as to preserve the integrity and galvanic insulation of the Faraday cage.



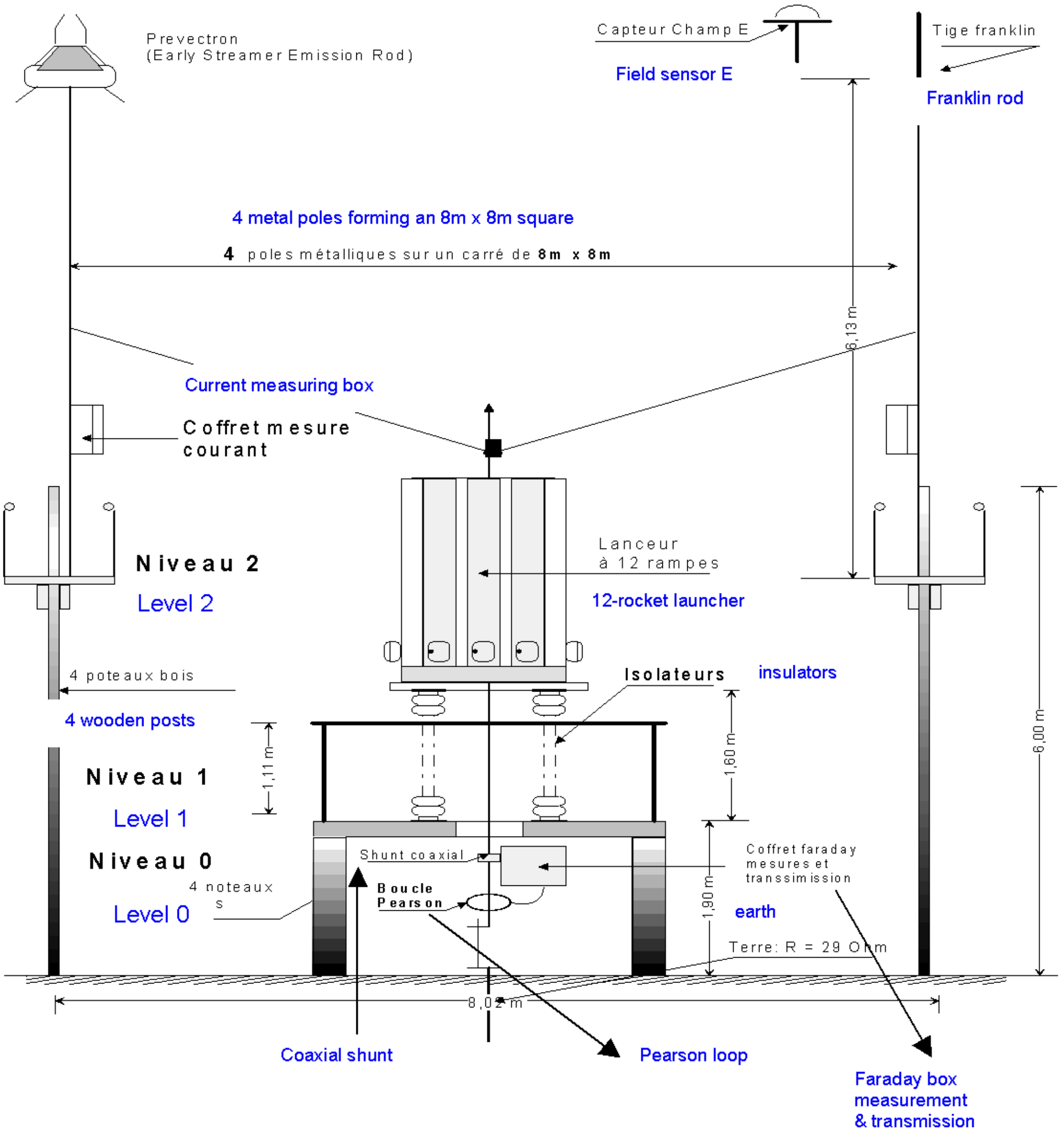
Key

1 Control room,
2 Stationary power generator, air compressor & fuel tank,
3 Electrical field sensor (firing sensor),
4 HYDRO-QUEBEC's experiment : automatic video camera (natural & triggered flashes) 75m away
5 San Jose Dos Campos University's experiment (INPE) : Vertical component of electrical field radiated,
6 Campinas University's experiment (UNICAMP) : Electromagnetic induction in a meshed cage,
7 Firing, lightning conductor test and measurement platform (INDELEC),
8 CR-operated video camera (INDELEC), 50 m away
9 HYDRO-QUEBEC's experiment, automatic camera for natural & triggered flashes, 0.8km away,
10 GPS shelter (INPE Cachoeira),
11 Geodesic marker,
12 Insulated tree,
13 HYDRO-QUEBEC : high-speed video camera (8000 fps).

Fig. 2. The Cachoeira Paulista triggered flash station. INPE Center, Brazil

Fig. 3. Testing & Firing Platform (TFP).

2.2. Testing & Firing Platform (TFP)



The are three distinct sections to the firing platform (fig.3)

Section '0', ground level, where the following are found :

- current measurement using a 1mΩ coaxial shunt and electro-optical converter signal transmitter,
- a lightning strike counter,
- general earth using crows feet & vertical stakes. Earth resistance = 29 Ω.

Section '1' (h=2m) – the rocket section. The launcher allows up to 12 rockets to be launched during a single storm. Each rocket can be fitted with either an LRS-G, or an LRS-A system. LRS-A rockets can be set up with between 50 and 400m of Kevlar, with an additional 600m of copper. The optimum lengths are 100m & 600m, since the stepped leader which builds up at the base of the copper wire has to be able to grow naturally over a number of 'steps' before it reaches the sensors. The average length of a step is approximately 20m.

The rocket engines used provide a maximum speed of some 220m/s, ensuring satisfactory triggering conditions.

Section '2' (h=5m) is the lightning conductor testing platform.

The highest point, i.e. the rod, or the ESE, on all three lightning conductors are positioned 11.5m from the ground, while the fourth corner of the platform is fitted with a telescopic mast. This allows an electrical field sensor to be positioned at the same height as the lightning conductors. The sensor has a dynamic range of 300kV/m and a bandwidth of 5kHz – 150MHz, meaning the build up of the electrical field and – more importantly – the electrical field generated by the stepped leader can be monitored.

The base of each of the 3 lightning conductors is connected electrically to the launcher's central mast.

2.3. Test Zone (TZ)

As can be seen in fig. 2, the cleared area around the launch platform and the CR is reserved for current and future experiments.

There are currently two experiments being carried out, or in preparation :

- measurement of the vertical component of the electrical field using a capacitive aerial : INPE, San Jose Dos Campos. (Rep.5, fig. 2);
- measurement of the electromagnetic induction radiated inside a mesh structure: UNICAMP, Campinas University. (Rep. 6, fig. 2).

To follow events, automatic & triggered video monitoring equipment was used both on site and remotely by INDELEC and Hydro-Quebec.

2.3.1. INDELEC video monitoring

A video camera ('8', fig. 2), located 50m from the launcher and controlled from the CR using a fiber optic link, allows the engineers to see the point of impact on one of the tips, or on the ground.

The precise point of impact is determined using a second video camera housed in the CR and which displays the electrical field at ground level on the screen during the triggering process.

2.3.2. Hydro-Quebec video monitoring

HYDRO-QUEBEC uses two types of video monitoring:

- an automatic monitoring system consisting of 2 cameras – the first 75m from the launcher ('4', fig. 2), the second 800m away ('9', fig.2) – triggered optically (when a flash occurs) and/or electromagnetically (induction loop).
- a monitoring system triggered during firing. The camera is housed in the CR and provides up to 8000 frames per second (fps).

3. Experiment to compare lightning conductor performance

3.1. Organization of the tests

The devices being tested (3) are arranged in such a way that they are all within the expansion zone of a given 'stepped leader'; the distance separating each device – 8m – is calculated so as not to interfere with the other two and was determined following simulation tests carried out by ECL in Lyon, France.

Each of the three masts is wired up to measure the current in the upward leaders with a dynamic range of 10A (fig. 4).

Above the sensor head are located :

- a 5mΩ coax shunt able to withstand current up to 60kA, 500 Joules in the case of return stroke;
- a Faraday box containing a 12V independent power supply and an electro-optical transmitter with a 1MHz bandwidth.

The whole assembly is sheathed and insulated galvanically and operated pneumatically from the CR.

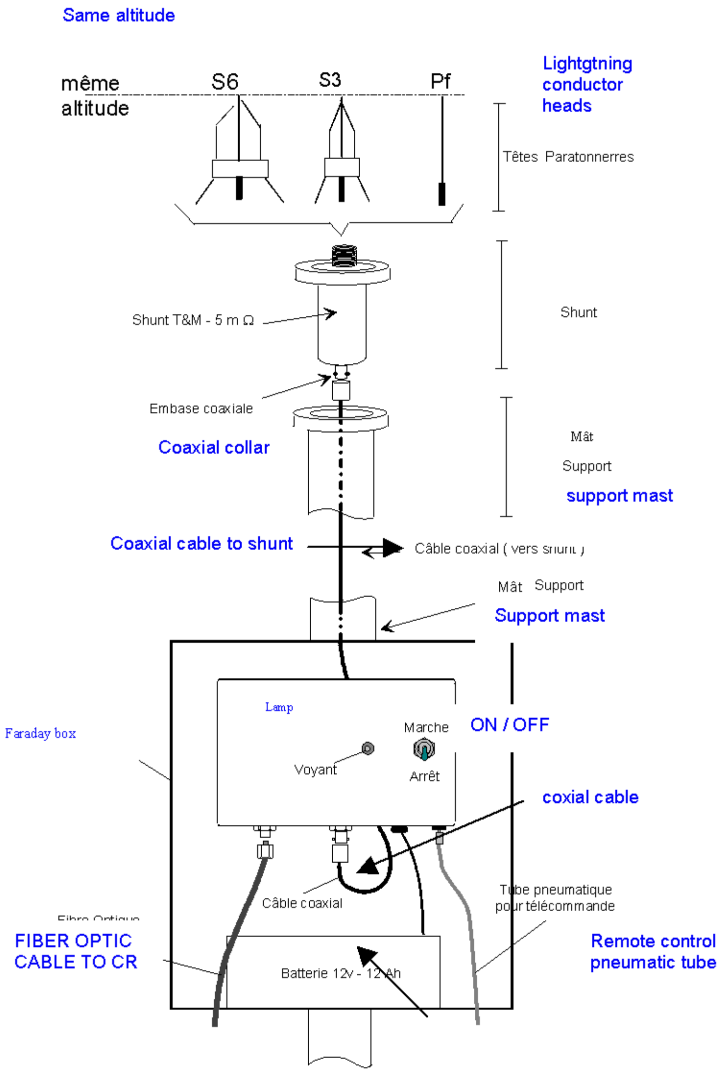


Fig. 4. Instrumentation setup.

3.2. Acquisition & measurements

The three measurements (upward leader current on the lightning conductors, downward leader electrical field & total arc current) are sent to the CR over an optical acquisition & transmission network.
Once inside the control room (CR), the measurement cables are routed toward 2 low-speed acquisition systems (Pc 4s) and two high-speed LeCroy digitizers.

3.2.1. Low-speed acquisition (Pc 4s).

Given the uncertainty surrounding the time delay before the streamers appear subsequent to rocket launch, it was necessary to design an acquisition system combining a large memory capacity with a sampling rate in line with the speed of the streamers.
The specific system used is known as a Pc 4-second system and has the following specifications:

- 4 independent tracks (0 – 10V), 2MHz sampling rate;
- variable acquisition time up to 6 seconds.

The system is triggered at T0 via the launch control panel for a duration of 4 seconds. In this way, the test devices can be monitored continually as the rocket travels upward; important in so far as it is during this brief period that the generation of upward leaders is most likely.

3.2.2. High-speed acquisition.

High-speed acquisition is provided by a LeCroy digital oscilloscope operating in 'windows' mode. The number of acquisition windows was set at 10.
The 4 tracks are attributed to the three test devices and the 'stepped leader'.
Acquisition times are 2 ms, with a 1 ms pretrigger.
Acquisition is triggered using a trigger slide, which offers several different triggering methods :

- on the return stroke current (level 3 kA),
- on the optical flash (optical sensor with 8°
- on the stepped leader field (30 kV/m).

The three different triggering methods can be used in isolation, or combined (OR, AND operators).

3.2.3. Sensor specifications

- **Electric field sensor E.**
  Thomson E 10 sensor
  Range : 0 - 316 kV/m (position 0/100 kV/m)
  Bandwidth 150 MHz.

The sensor is driven by a Mélopée P100 chain.

- **Return stroke current coax measuring shunt.**

  R = 1mΩ, band 30 MHz, I max. : 60 kA.

Redundant measurement of the return stroke current is provided by an independent 5mV/A Pearson loop, meaning that, should the main measurement fail, each return stroke's maximum discharge value, if not its amplitude.

- **Test device shunts.**

  Coax shunts,
  R= 5 mΩ, 500 joules.

The electrostatic field at ground level (firing mill) is measured by CEA sensors, using independent power supply and optical connections.

The site is constantly monitored by an E2000 storm warning device.

Fig. 5 provides an overall view of the current measuring & observation setup.

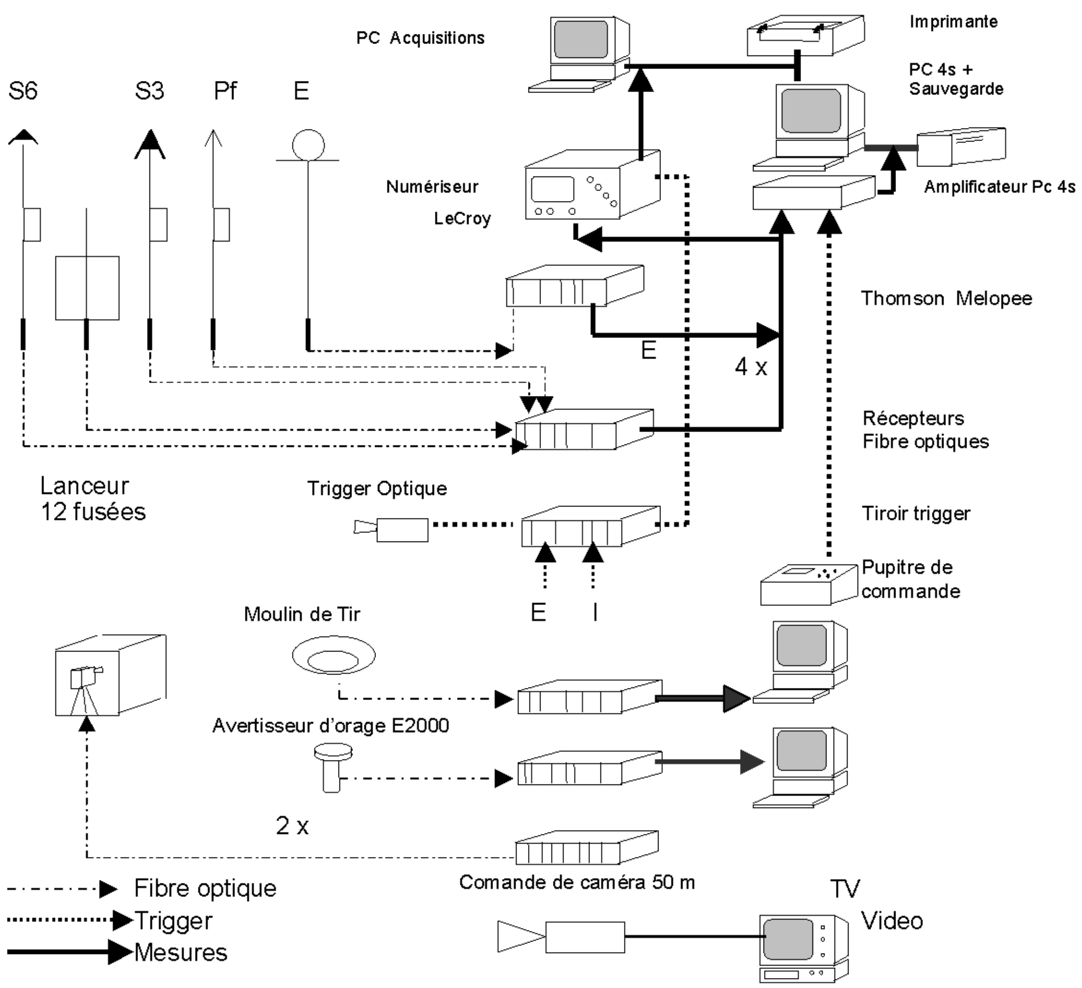


Fig. 5. Synoptique des mesures et acquisitions de la campagne 2000/2001 sur le site du Brésil.
Translation from top : Acquisitions PC,Printer,PC 4s & backup,eCroy digitizer,PC 4s amplifier,Fiber optic receivers,12-rocket launcher,Optical trigger,Trigger slide,Control panel,Firing mill,E2000 storm warning device,50m camera control,Fiber optic,Trigger,Measurements

4. Initial results.

4.1. Triggered lightning

Firing started early 2000 and the electrical field triggering levels showed themselves to be higher than those witnessed in France : –10 to –12kV/m as opposed to –4 to –8kV/m. Atypical situations are common – fig. 6 shows one example where 2 technically accurate LRS-A launches (field amplification under the effect of the copper wire, followed by discharge leader) did not reach the ground.

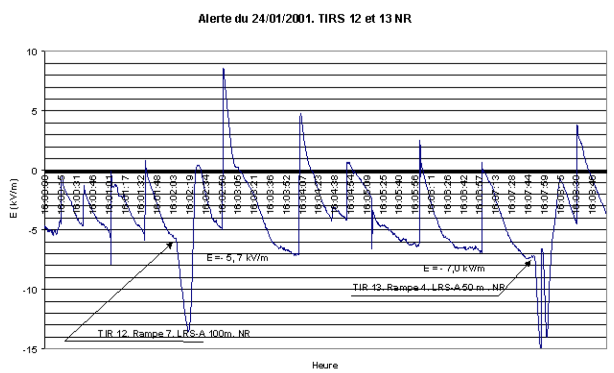


Fig.6. LRS-A launches. Triggering leaders.

So far, no rational explanation has been put forward for these atypical and difficult triggering conditions. The 600-meter lengths of copper wire are longer than those used in both Florida and France (500m), in order to satisfy the specific requirements of lightning discharges in tropical regions.

- cumulonimbus base high above ground level,
- high level of discharge within and between clouds,
- very high ground resistivity, etc.

The number of events triggered and measured thus far (mid-campaign 2000/2001) is relatively low compared to a Florida campaign.

A series of connected launches (LRS-G) were carried out to check the acquisition systems. These resulted in low-intensity discharges (13,9 kA ; 0,4 C) with 2 return strokes.

Three LRS-A were launched with 100 meters of insulating wire connected to the ground in close proximity to the lightning conductor protection zone, within a radius of approximately 100 meters (see Fig. 7).

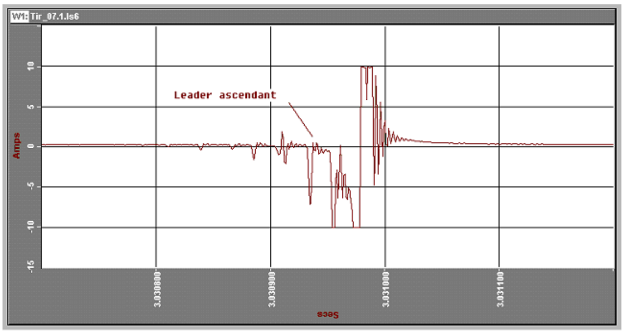
- *the twisting lower section corresponds to the 100m Kevlar gap;*
- *the 260m straight section corresponds to the length of wire unraveled prior to priming;*
- *the launcher is located in line with the straight portion of the channel.*

Fig. 7. Flash 03 Nov. 23, 2000.(Photo. O.Pinto/INPE)

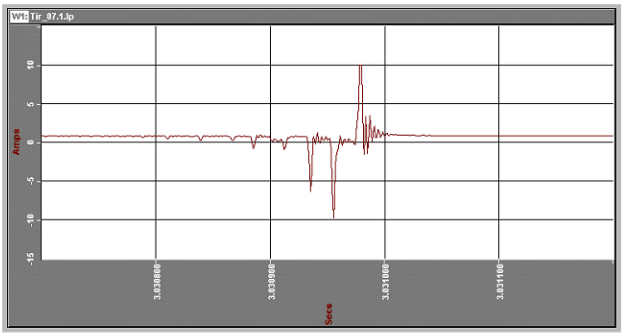
Because the launches did not connect with the test devices and the high-speed radiated field had not been installed at the time, overall current could not be measured. However, the lightning conductors' acquisition systems recorded current signals attributable to the leaders on an ESE and on the rod tip.

Fig. 8 shows the shape and amplitude of said current signals for an S6 ESE and for the rod tip. The first pulses (weak coronas with no spread) appear simultaneously on the S6 ESE and on the tip. Thereafter, the shape of the current on the S6 ESE shows the build up of an upward leader which spreads out until the first return stroke appears (saturation induction). In respect of the rod tip, the comparable amplitude corona show unsuccessful attempts at priming.

Given that the amount of data so far gathered is insufficient and that it was recorded using unproven configurations, no conclusion can be drawn on the viability of the experiment. In our opinion, now the setup has been properly burnt in, we will require at least 30 or 40 significant trigger events (stepped leader connecting to the test devices' upward leaders) in order to draw any viable conclusions.



a) S6 type E.S.E



b) Rod tip

Fig.8. PC 4s recordings of pulses on the test devices.

4.2. Natural flashes.

The video monitoring provided by Hydro-Quebec's 2 automatic cameras allows us to monitor site activity when there are no experiments being conducted and monitor the test devices.

A number of interesting photos were taken Jan. 25 & Dec. 25, 2000 by the automatic cameras located 72 & 800m from the platform. They clearly show the light given off by a leader several meters in length at the tip of the S6 ESE, while none of the other devices showed any signs of activity. In both instances, the effect is visible over at least 4 frames, i.e. more than 130ms (30 fps).

Fig. 9 (a) & (b) illustrate the two events.

Note : The precise position of the upward leader in relation to the ESE was checked by superimposing picture (b) over a daytime picture.

a) January 2000 - camera 72m from platform

b) December 2000 - Camera 800m from platform

Fig. 9. Leader on S6 ESE. **(Photos HQ/C.Potvin)**

Hydro-Quebec's Redlake camera provides a high-speed film (up to 8000 fps) of the top of the test devices during launch. During a storm, it also provides photos (fig. 10) showing the development of the stepped leaders before the natural discharge flows down to the ground.

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Photo 1 : t = d. Note the two forks, most likely emanating from the same charge pocket; the glow at the end of the stepped leader can clearly be seen on the right-hand fork..

Photo 2 : t = d + 1 ms. The 2 forks are still in competition.

Photo 3 : t = d + 2 ms. The left-hand fork begins to glow and expand. The glow at the end of the stepped leaders can still be seen.

Photo 4 : t = d + 4 ms. The left channel reaches the ground first, while the junction between the stepped leader and the streamer from the ground can be made out at the bottom of the picture (first twisted section).

Fig. 10. Image taken of a natural discharge by the Redlake camera set at 1000 fps. (Clichés HQ. C.Potvin).

5. Conclusion

The following conclusions can be drawn from the experiments carried out at the INPE's Cachoiera Paulista lightning survey station in Brazil :
Storm activity at the site was extremely low in February, March, November & December 2000 and early 2001. The long, dry periods witnessed are not conducive to the formation of convective storms. At an altitude of 700m, the station is halfway between the ocean and the local foothills, giving it what should be a favorable location.

So far, conditions have been very different from those encountered in France and the US : firing ranges of around –10 to –11kV/m (Florida & France –4 to –8 kV/m), plus the high number of discharges within and between clouds, etc. combined to make triggering difficult, meaning the average success rate fell from 60% to 38%.

The first question to be asked, given the high altitude of the cumulonimbus cloud base, concerns the length of the triggering systems' copper wire. The length was increased from 500m (Florida & France) to 600m, though this would still appear insufficient. To resolve this issue, tests are to be conducted using 800 – 900 meter lengths.

The LRS-A launches resulted in ground-level discharges some distance from the sensors. At the time of writing, we have no meaningful explanation for this phenomenon and the number of events (4) is too low to draw any conclusions.

On a more general note, all the systems installed at the station (power supplies, safety systems, instrumentation & acquisition systems) are faring well and operating conditions are excellent.

Regarding the survey designed to compare the performance of the various lightning conductors, the first two campaigns produced the following results among others :

- recordings of the upward currents on the ESE and single rod lightning conductors for triggered lightning (§4.1);
- video evidence showing the naturally-occurring upward tracers on the ESEs (§4.2).

Collation of the results from the full fours years of experimentation will be required, however, to draw any meaningful conclusions.

References.

[1]. St-Privat Campaign 1996. A. Eybert-Bérard et al. CEA DTP/STI/LASP97-07/AEB
[2]. Advance survey of the Cachoeira Paulista site. Electrical Field Measurements. INDELEC report. A. Eybert- Bérard 1999.