An experimental study of leaders initiated by single and advanced (ESE) lightning rods

Triggering site of Cachoeira Paulista (SP) Brazil.

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Abstract: 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 advanced lightning conductors, so-called Early Streamer Emission (ESE) rod. 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 main results of the previous campaigns are set out herein.

1.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 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 100 m in length – is first unrolled. 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 mechanisms 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 year 2000, thanks in no small part to the invaluable help provided by HINDELET company 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 Centro dos Pesquisas Desenvolvimento (CPqD), Campinas (SP), Brazil and FRANCE TELECOM rejoined the pioneers.

2. 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 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.

Activities on the site, started in 1999, by two experiments –the first one, on 6 months, consisted to appraise the stormy potential of the area by static E field recording,[2] - the second one, still in progress, involving natural lightning strikes on the sensor systems, 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' downloads, 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. In March 2004, none of the lightning rods had been still struck.

3.Triggering station

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

- the Control Room (CR)
- the Firing and Testing Platform (FTP),
- the Testing Zone (TZ).

3.1. 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.
This building is protected from direct impacts by a meshed cage, with both building and cage having only one grounding point (R= 21Ω). Power is supplied by a 17 kW generator inside the Faraday cage.
The acquisitions systems are protected by over voltage arrestors and Uninterruptible Power System (UPS), will provide full backup for up to 10 minutes.
Optical fibers are used to link the outside sensors into the acquisition systems inside the CR, while pneumatic tubes operate the equipment power so as to preserve the integrity and galvanic insulation of the Faraday cage.

3.2. Firing and Testing Platform (FTP). (Fig 1)

There are three distinct sections to the firing platform:

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 grounding, using 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 LRS-G or LRS-A triggering spool technique. LRS-A rockets are equipped of spools including 100 m of insulated Kevlar cable, followed by typically 500 up to 800 m of copper wire. The air gap of 100 m is needed to allow the downward stepped leader emerging from the lower tip of copper to grow naturally over a meaningful number of steps before to reach the triggering facility. The average length of a step is supposed to be roughly of 20 to 30 meters.
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.

3.3. Test Zone (TZ)

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.
- measurement of the electromagnetic induction radiated inside a mesh structure: UNICAMP, Campinas University.

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

3.3.1. INDELEC video monitoring

A video camera 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.

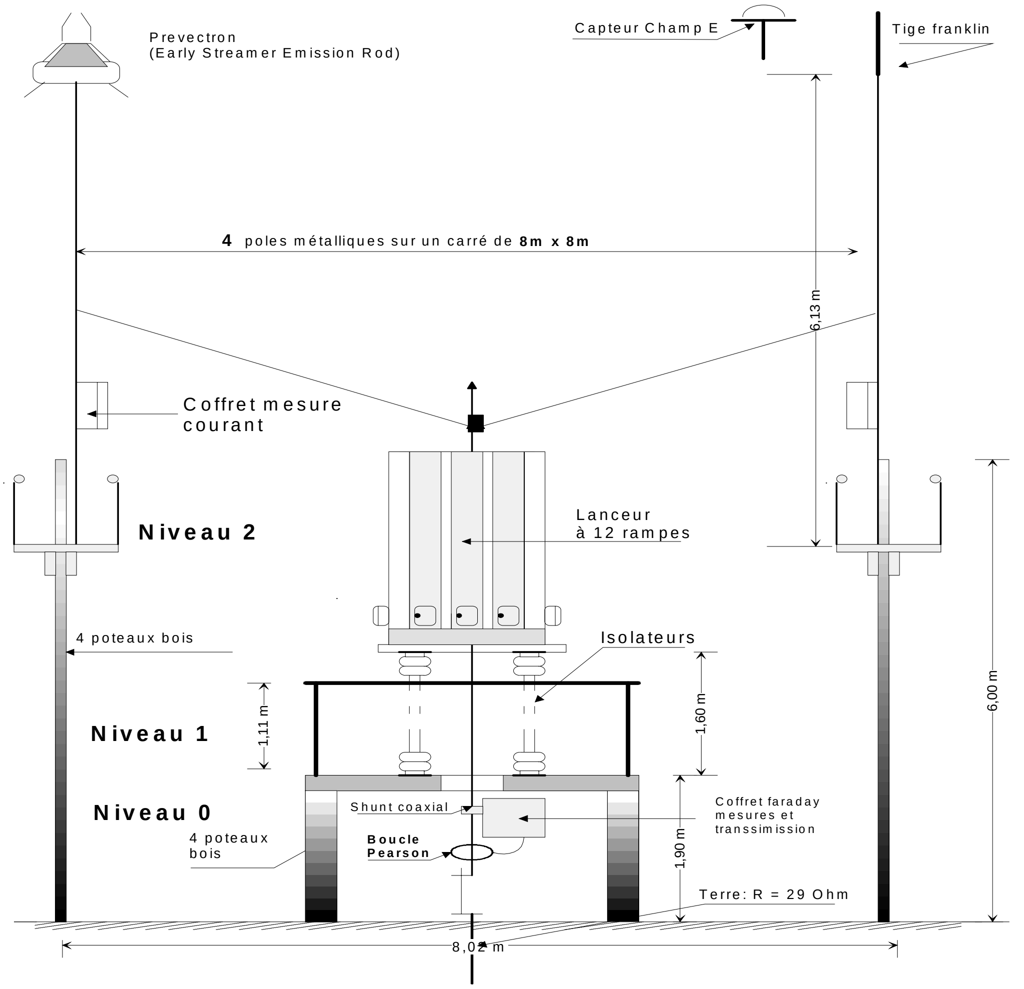

Fig 1. Firing and testing platform (FTP)

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.

3.3.2. Automatic Hydro-Quebec video monitoring

HYDRO-QUEBEC provides us 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– 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).

4. Experiment to study the leaders initiated by single and advanced lightning rods. (ESE)

4.1. 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 Ecole Centrale de 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. 2).

Above each sensor head are located :

- a 5mΩ coax shunt able to withstand current up to 60kA, 500 Joules (return stroke peaks)

Along each mast:

- a Faraday box containing a 12V independent power supply and an electro-optical transmitter with a 1MHz bandwidth.

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

4.2. Acquisition and measurements

The three measurements: upward leader current on the lightning conductors, downward leader electrical field and total arc current are linked to the CR over an optical acquisition and transmission network.

Once inside the control room (CR), the measurement cables are routed toward a low-speed acquisition system (Pc 4s) and two high-speed LeCroy digitizing oscilloscopes operating in ‘burst ‘ mode. The total of acquisition ‘windows’ is set at 10. The acquisition time of each windows is 2ms, with 1 ms of pre-trigger. Resolution of 100 ns.

4.2.1.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.

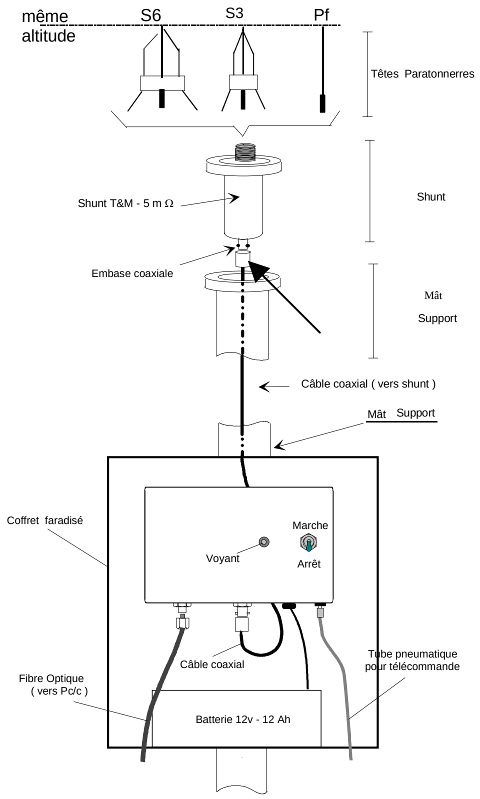

Fig. 2. Upward leaders measuring systems

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 4 seconds.

The system is triggered at "zero time", 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.

4.2.2. High-speed acquisition.

High-speed acquisition is provided by a LeCroy digital oscilloscope operating in "burts" mode. The number of acquisition windows is set at 10.
The 4 tracks are attributed to the three test devices and the 'stepped leader'.

The 4 tracks are attributed to the three test devices and the 'stepped leader'.
Acquisition times are 2 ms, with a 1 ms pre trigger.
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° field)
- on the stepped leader field (30 kV/m).

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

Since the 2003 campaign, the High speed acquisition system , has been improved by an optical sensor of 150° of field, allowing to trigger on the natural flashes occurring in the field of the sensor.

4.2.3. Sensors specifications

- **Electric field sensor E. (**PRANA)
  Range : +/- 310 kV/m
  Bandwidth 150 hz ->1Ghz
  Calibration: +/- 100 kV/m

The sensor is driven by a Thomson Mélopée data acquisition system TSN 250 .

- **Return stroke current measurement.**

I Rs measurement is obtained by a specific coaxial shunt sensor:
R = 1mΩ, band 30 MHz, I max. : 60 kA.

- **Upward leader current measurements.**

Each lightning rod in test is instrumented by a coaxial shunt of 5 mΩ, (500 joules); the measurement is limited to 10 Amps, with resolution of few milli amps.
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 storm warning device. (SDO 340).

The figure 4, provides an overall view of the currents, E field and optical measuring systems.

5. First results.

5.1. Triggered lightning

Triggered lightning activities on the brazilian site, started early 2000 and showed great difficulties to trigger with LRSA technique and atypical situations are common. The figure 3, shows one example where two LRS-A shots (field amplification under the effect of the copper wire, followed by discharge leader) did not reach the ground, but somewhere in the cloud level.

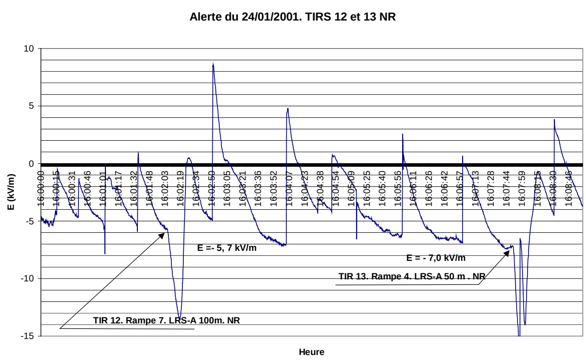

Fig 3. LRS A launches, with cloud discharge

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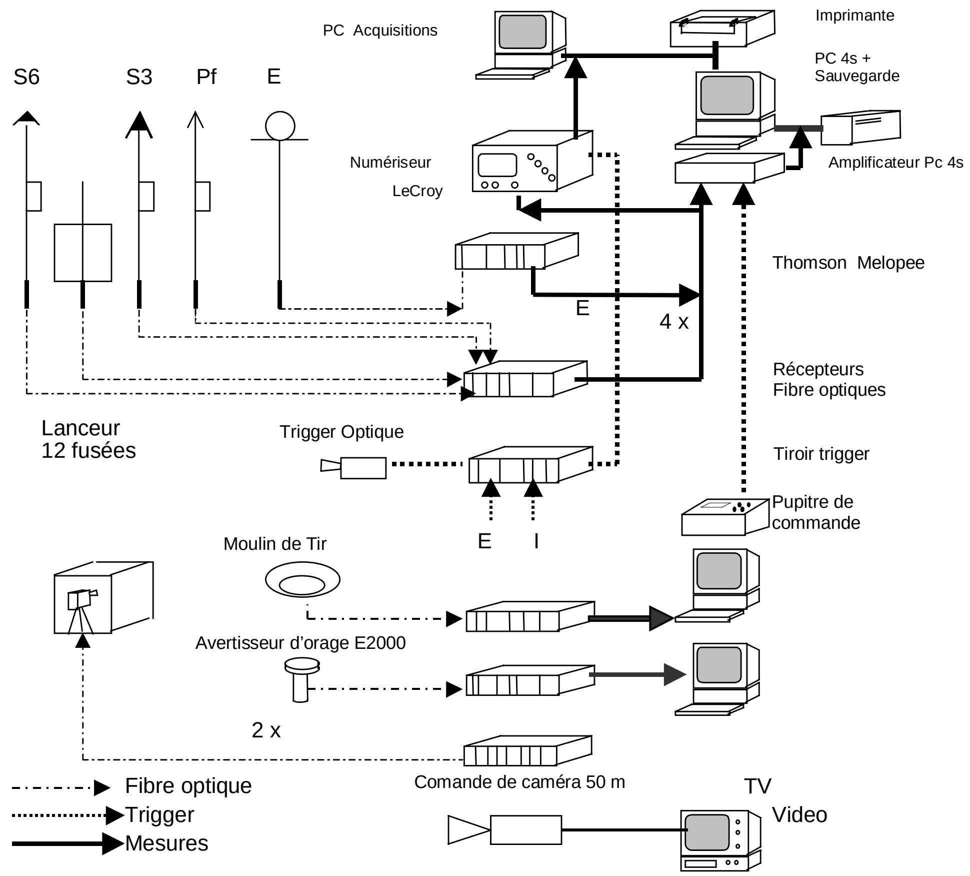


Fig. 4. Firing and testing platform

Since 2003 rational explanation has been put forward for these atypical and difficult triggering conditions:

- Altitude of cumulonimbus basis higher than we know in Florida or in France,
- high level of intra cloud and cloud to cloud discharges ,
- high ground resistivity, etc.

In order to satisfy the specific requirements of lightning discharges in tropical regions, all the triggering system has been improved during the 2003 campaign:

- a new specific propellant motor has been studied and constructed by the Laboratory of Combustion and Propulsion (LCP, INPE, Cachoeira). This motor has features (max speed of 250 m/s at 600 meters of altitude), superior to those of the motor used previously.
- The insulating Kevlar part has been increased from 100 to 300 meters, in order to facilitate the development of a downward stepped leader from the lower tip of cooper
- wire. At least 3 or 4 stepped leaders are susceptible to be developed.

So as now the tool is much more adapted to the tropical triggering conditions.

To illustrate the need of this improvement, the picture 5, shows a LRSA launch with 100 meters insulating gap. We assume that this gap is probably not enough long to get a natural stepped leader development, between the lower part of the copper wire and the ground. So this kind of striking doesn't seem to be as a representative in terms of lightning rods test.

- *the twisting lower section corresponds to the 100m Kevlar gap;*
- *the 260m straight section corresponds to the length of wire unrolled prior to priming;*

However, the lightning conductors' acquisition systems recorded current signals during all the phases of the flash. The graph fig 6, shows for the given devices in test:

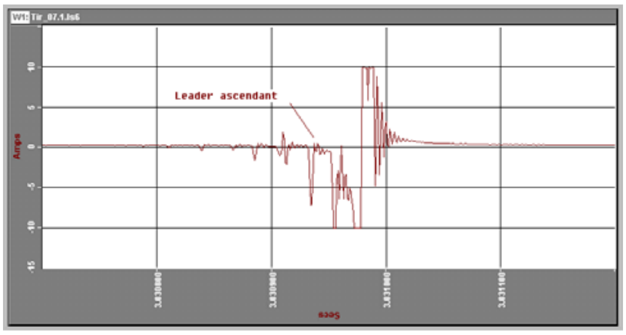
(a): ESE lightning rod called S6;

(b): Single lightning rod,

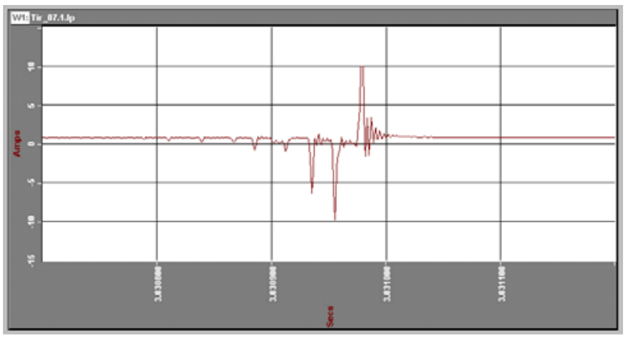
The shape and the amplitude of currents. The first pulses characterized by weak coronas without spread, appear simultaneously on the S6 ESE and on the classical tip. Thereafter, the shape of the current on the S6 ESE shows clearly the build up of an upward leader which spreads out, more than 10 amps, until the first return stroke appears (last part of the curve, showing the effect of the RS induction). In respect of the single rod tip, the comparable amplitude corona show unsuccessful attempts to move in upward continuous streamer.

Been given the applied difficulties on the one hand, of the weak activity observed on the other hand until this day and in finally of the number of statistically necessary data, we appraise at least 30 events in order to draw any viable conclusions.

Fig. 5. Triggered lightning by LRSA technique. **(Photo. O.Pinto/INPE)**



a) Advanced lightning rod (ESE), S6 model



b) Single rod tip

Fig.6. Upward leader on S6 and corona on single rod .

5.2. Natural flashes.

The two automatic video cameras, provided by Hydro-Quebec, allows us to supervise the storm site activity when there are not any conducted experiments.
A number of interesting photos were taken Jan. 25 and Dec. 25, 2000 by the automatic cameras located 72 and 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).
The two video pictures Fig 7, (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. 7. Leaders on S6 (ESE). **(Photos HQ/C.Potvin)**

A Redlake high speed camera, first monitored by Hydro-Quebec (years 200/2001), then by INPE (San Jose Dos Campos, 2003/2004) provides a high-speed film (up to 8000 fps) of the top of the lightning rods in test during the phase of the 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.

***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 arestill 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. 8. Natural discharge got by the Redlake camera set at 1000 fps. (Clichés HQ. C.Potvin).

6. Conclusion

The following conclusions can be drawn from the experiments carried out at the Brazilian site.
The stormy activity over the site was revealed extremely low and anomalous during these three last years, influencing by this fact on the quantity of events triggered and measured. The assignment of this climatic anomaly to the only influence of EL Nino is probably excessive. In fact the geographical location of the site, to the center of a large plateau surrounded by mountains culminating to more of 2000 m of altitude, is not really appropriate for the emergence of convective storms.
So far, conditions have been strongly different from those encountered in France and USA: firing ranges of around –10 to –11kV/m (Florida and France –4 to –8 kV/m), plus the high number of intra clouds discharges, combined to make triggering difficulties, meaning the average success rate fell from 60% to 38% up to 2002/2003 campaign. Again since 2003/2004 campaign and, after improvements brought on the triggering system, the rate of success went up again to 50% in 2003 and even to 70%, during the 2004 campaign(*).
(*). Connected launches only (LRS-G) .
Today, we think having the well adapted tool to conduct experiments around both natural and triggered lightning, with the affordable goal to study the leaders initiated by single and advanced (ESE) lightning rods. Unfortunately, the last campaign, characterized by a calamitous stormy activity didn't allow us to achieve the tests on the LRSA technique improvements. Indeed only connected launches (LRS-G) have can be led, either on the launch pad either at the top of a new 30 meters high metallic tower, erected for CPQD and France Telecom experiments.
In terms of Return strokes current measurements, triggered lightning in Brazil are characterized by an amplitude average of about 25 kA, against 13 kA in Florida, with an average of 4 RS per flash.
The LRS-A launches devoted to the upward leaders experiment despite the difficulties encountered have given some interesting results:
- recording of the upward currents on the ESE rod, who can be considered as being an upward streamer. In same time no evidence of upward streamer at the tip of the single lightning rod. (§5.1),
- two events from automatic video cam, showing natural upward streamers on the ESE rods (§5.2).
The number of events is still too low and collation for more results are required, to draw any meaningful conclusions.
On a more general note, all the systems installed at the Cachoeira Paulista triggering site (instrumentation and acquisition systems) are faring well and operating conditions are excellent. Furthermore since 2004, the site is monitored under 220 V commercial power from INPE network, bringing a substantial comfort of work.

7. 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.