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Revisiting test data of ESE rods in Cachoeira Paulista (Brazil, 2000-2005)

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ABSTRACT

A field test campaign using triggered lightning took place in Brazil during years 2000–2005 to, among other objectives, assess the action and performance of ESE (Early Streamer Emission) rods, in competition with an ordinary Franklin rod at certain distance. During the test period, only two proper attachments (altitude triggering technique) occurred to objects installed on the firing & testing platform of the test facility: the Franklin rod and an electric-field antenna. The other objects on the platform, two ESE rods, failed to intercept these lightning flashes. Other results involving flashes to the surroundings and tests with classic triggering technique are also presented and discussed. Although the test outcomes cannot be considered proof against ESE lightning rods, due to test condition constraints and the low number of events (not statistically significant), they raise serious doubts about the claimed higher efficiency of these devices.

1. Introduction

One of the motivations for this paper is to bring to light one more test case in which ESE (Early Streamer Emission) rods did not appear to perform as well as claimed. The herein evidences against the ESE performance are not statistically relevant (given the small number of events), and may be questionable under certain aspects of the test conditions, but could be added to other questionable performances under natural or triggered lightning, as reported in Camp Blanding, Florida (1993-1995) and St. Privat d'Allier, France (1996) [1,2], and New Mexico [3].

During the rocket-triggered lightning test campaign at INPE (National Institute for Space Research) campus in Cachoeira Paulista – SP, Brazil (2000-2005), with downward leaders originated by altitude triggering technique (the most representative of natural lightning), an ordinary Franklin rod and an electric-field antenna were struck by lightning, while two ESE rods, under similar conditions, failed to intercept lightning. This remarkable result as well as others involving ESE rods have never been reported in the publications that followed the campaign, except by a short mention in [4].

This paper provides a short report on the tests and is organized as follows: basic information on the test facilities and test conditions are given in Section 2, test results are presented and analyzed in Section 3, followed by discussions and conclusions in Section 4.

Explanations of the working principle of Franklin rods and ESE rods can be read in [1] and [2]. The determination of their volume and radius of protection are shown in [4]. An account on the current situation of ESE is made in the introduction of [4].

2. Test facilities and conditions

The rocket-triggered lightning test facilities were built during the late 1990s by the initiative of industry (INDELEC), universities in France and Brazil and research institutes in Canada, Brazil and France. General and detailed descriptions of the test site and of the test campaign can be found in papers [6–10], report [11], eBook [12] and a PhD Thesis [13], which provided valuable information to this analysis.

The test facilities were located at -22.6868° (lat.) and -44.9847° (long.), at the INPE campus in the county of Cachoeira Paulista, in São Paulo state, Brazil. Such test facilities are no longer available, having been dismantled a few years after the 5-year campaign (can be seen on Google Earth, Historical imagery, select year 2004).

Fig. 1 shows the firing & testing platform in the foreground, with the measuring & launching control room in the background, housed in a properly adapted 40' container. The platform and control room are 45 m away from each other (platform center to nearest room edge). Four masts were installed at the corners of the wooden platform: two of them were equipped with ESE devices, one of them was an ordinary Franklin rod, and the last one held an electric field antenna. ESE-1 and ESE-2 were devices with triggering advance times of 60 µs and 30 µs,

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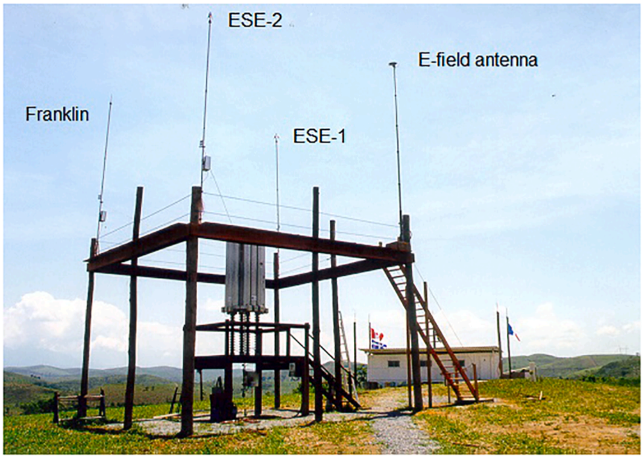

Fig. 1. Firing & testing platform; measuring & launching control room; ESE and Franklin rods; electric field antenna; rocket launching tubes at platform center.

respectively, claimed by the manufacturer. The side of the square platform was 8 m long. The tips of the four objects were at 11.5 m from the ground. Fig. 2 shows the platform viewed from the control room.

The rockets (up to 12 in the launching tubes at the center of the platform) could fit either classical or altitude triggering technique, depending on how the copper and Kevlar wires were wound on their spools.

In the classical technique, the rocket flies up unspooling a copper wire, which is connected to ground via launching tubes. Lightning initiated by this technique typically exhibits an ICC (initial continuous current) that is established by the upward leader emitted from the tip of the copper wire attached to the rocket, which current is strong enough to vaporize the trailing wire. The ICC can be followed by dart leaders and return strokes as observed in natural lightning [5,14,15].

An important feature of this technique is that the lightning current initially flows through the launching tubes, but depending on the current duration, stroke time intervals and wind velocity, the channel can be pushed sideways and connect with some other conducting structure that in this case can be any of the rods or the antenna shown in Fig. 1. Of course, this is not a valid situation for evaluating the interception efficiency of any lightning rod.

In the altitude technique, the rocket usually spools out a portion of insulating Kevlar followed by a portion of copper wire. In this way, there is no wire coming down to the ground and a downward leader is emitted from the lower end of the copper wire in the air, reproducing more closely the initial processes of natural negative downward lightning, which is especially desired when the attachment to grounded structures is concerned [5,14,15].

The classical (grounded wire) and altitude techniques may appear as LRS-G and LRS-A in some figures, respectively, to be in consonance with abbreviations used in some of the referred papers, even though no definition has been found for LRS initials. The word 'TIR' (French for 'shot) may also appear in some figures.

The data set consists of photos, videos, channel luminosity, electric field from fast response antenna and field-mill, current waveforms from current sensors (shunt and current transformer) and estimated peak currents from magnetic cards and from the local lightning detection network (LPATS/IMPACT sensors) operating at the time. Images, current and electric field were the most used data in this analysis.

Images were taken from different directions and distances, some interesting ones being taken by a VHS camera on one of the shelter windows (control room), about 45 m away from the platform center, practically the same view as the photo in Fig. 2. Fig. 3 shows all the cameras used in this study. The relative positions of the rods and the antenna in each image presented in this paper can be inferred from this figure, as the cameras (A to F) taking the pictures are displayed in the captions of figures.

The distances of the cameras are related to the center of the firing & testing platform. The directions and distances were checked through satellite image (Google Earth), as they were not precisely displayed in the diagrams in [11] and [13]. The distances were corrected with respect to the distances given in [10,11] and [13], based on satellite image and on the known locations of the cameras, by the authors who participated in the campaigns. The precision of their distances is not critical as no length measurement was made based on them.

Some analyses used relative distances between lightning channels and structures on ground (platform and control room). In these cases, the directions of the cameras are more important. The directions shown in Fig. 3 are believed to be reasonably good for finding the areas where lightning hit the ground (see Fig. 6).

The still camera "E" is not mentioned in the known published papers. One of the photographs taken by this camera is shown in Fig. 9.

The constructive details of the grounding system are not available.

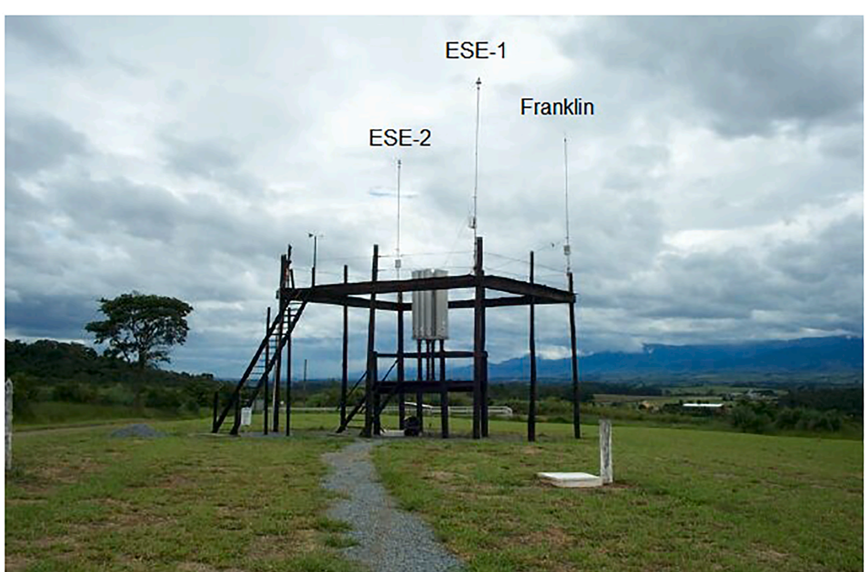

Fig. 2. Firing & testing platform viewed from the control room; electric field antenna had not been installed yet, when this photo was taken.

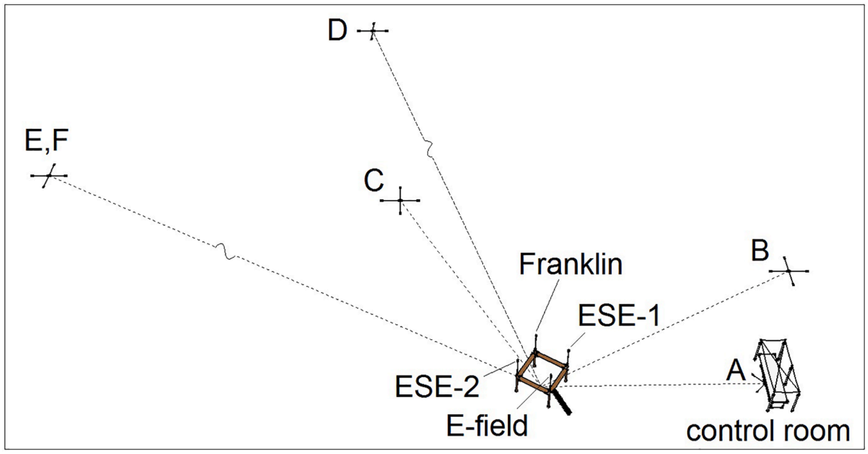

Fig. 3. Cameras used in the analyses.
A: Video camera in control room (50 m).
B: HYDRO-QUEBEC video camera (72 m).
C: INDELEC video camera (66 m).
D: HYDRO-QUEBEC video camera (1.1 km).
E: INPE still camera (1.1 km).
F: INPE video camera (1.1 km).

According to [8], the grounding resistance was 29 Ω in a soil of 1000 Ωm resistivity. The grounding system was common to all three lightning rods, as their grounding cables were bonded together before passing through the high current sensor down to the grounding system. The electric field antenna was not grounded.

There is a wealth of information about the site, measuring equipment, sensors, cameras, rocket-launching system etc., all well integrated in this test facility, the description of which is not the objective of this paper. So, again, please refer to [6–13] for more detailed and precise information about the test facilities.

3. Test results and analysis

A total of 57 launches (shots) were made during the test campaign. The campaign was divided into six seasons as shown in Table 1, along with the number of shots and the number of successful shots, i.e. those that successfully triggered lightning. The numbers are divided according to the triggering technique: A (altitude) and C (classical). Although the number of altitude triggering shots was higher (58%) than classical (32%), with 10% not identified in the data set, the triggering efficiency with altitude technique was lower: 9 in 33 (27%), against 12 in 18 (67%) for classical.

Table 2 summarizes the successful shots, the triggering technique, copper and Kevlar wire lengths, and the points of impact. While all triggered lightning in classical technique (100%) struck objects on the platform, as expected, only two out of the nine successful altitude triggered lightning (22%) struck objects on the platform. Such lower efficiency is natural since the downward leaders from triggered lightning in altitude are free to wander off the launching platform and strike the surrounding area. In fact, it depends on the competing attractiveness

Table 1
Campaign seasons and number of shots.

Season	Period (year/month)	Number of shots	Triggered lightning
1	2000/02	1 (A)	1 (A)
2	2000/11 – 2001/02	13 (A)	3 (A)
		8 (C)	2 (C)
3	2001/11 – 2002/02	10 (A)	2 (A)
		2 (C)	2 (C)
4	2002/12 – 2003/01	6 (A)	2 (A)
		1 (C)	1 (C)
5	2003/12 – 2004/03	1 (A)	0 (A)
		3 (C)	3 (C)
		2 (U)	-
6	2004/12 – 2005/02	2 (A)	1 (A)
		4 (C)	4 (C)
		4 (U)	0 (U)
Total	2000/02 – 2005/02 (5 years)	57	21
		33 (A)	9 (A)
		18 (C)	12 (C)
		6 (U)	0 (U)

A/C = altitude/classical; U = unidentified whether A or C.

Table 2
Successful shots, triggering techniques, copper and Kevlar wire lengths, and points of impact.

Season	Shot (TIR)	A/C	Copper wire (m)	Kevlar (m)	Hit the platform	Point of impact
1	0	A	600	100	No	G*
2	2	A	600	100	No	G
	3	A	600	100	No	G*
	9	A	600	100	No	CR*
	11	C	600		Yes	LT/F
	18	C	600		Yes	LT/F
3	22	A	600	100	No	CR*
	27	C	600		Yes	LT/F
	29	C	600		Yes	LT/F
	33	**A**	**800**	**30**	**Yes**	**F**
4	34	C	600		Yes	LT
	36	A	800	100	No	G
	40	A	800	100	No	G
5	41	C	600		Yes	LT
	45	C	600		Yes	LT
	46	C	600		Yes	LT
6	48	C	600		Yes	LT
	49	C	600		Yes	LT/ESE-1
	51	**A**	**800**	**10****	**Yes**	**A**
	55	C	600		Yes	LT
	57	C	600		Yes	LT

A/C = altitude/classical.
Point of impact: G = ground; CR = control room; LT = launching tubes; F = Franklin rod; ESE-1 (ESE-1 rod); A = (electric field) antenna; LT/F means that lightning hit the launching tubes and was pushed by wind to the Franklin rod (likewise for ESE).
* The point of impact outside the platform is clearly within the claimed attractive volumes of ESE rods.
** Rough estimate from images.

between objects on the platform and in the surrounding area.

The normal copper wire and Kevlar lengths were 800 m and 100 m, respectively, as in Table 2. Variations of these lengths were tried to improve the triggering efficiency. The variations eventually applied to unsuccessful shots do not appear in Table 2.

In altitude technique, the height from which a downward leader starts to progress can be considered as the Kevlar length, as it is the first portion of the wire to be unspooled.

Thesis [13] was very helpful for this analysis, as its content is detailed and well organized. However, it only covers up to season 4 (Table 1), shot #40 (Table 2).

3.1. Altitude technique – flashes to objects on the platform

The applicable shots in this section are #33 and #51, in bold letters in Table 2. These two shots are very significant because they readily convey the idea that the ESE rods on the platform did not have any better interception efficiency than the other two objects: an ordinary Franklin rod and an antenna.

Fig. 4 shows the lightning strike to the Franklin rod (shot #33). This flash had its current parameters analyzed in [6]. Although it is clearly stated in [6] that the flash connected to the tip of the Franklin rod, it may not have attracted the attention of most readers about the fact that it implied failure of ESE rods under competing circumstances.

Fig. 5 is an image of the lightning strike to the electric field antenna (shot #51). It is interesting to see that the lightning flashed over through the platform wooden pillar under the antenna, as the antenna and its mast were not grounded.

The camera used to take each image is listed in the respective figure caption. The cameras positions are shown in Fig. 3.

3.2. Altitude technique – flashes to the surroundings

Fig. 6 depicts the total attractive area given by the high objects on the platform and on the control room, as well as estimates of the locations where shots #0 and #3 hit the ground. Shots #9 and #22 attached to the conductors of the isolated LPS (lightning protection system) of the control room, consisting of five 7.3 m vertical rods interconnected by catenary wires. Fig. 7 shows that the control room, including its LPS, is within the claimed protection volume provided by ESE-1 (the calculation method comes from [16], and can also be found in [4]). The indicated protection areas and volume were calculated for peak current of 10 kA, a relatively common peak current value for triggered lightning [17], to illustrate how far the protection claimed by ESE proponents could go.

Fig. 5. Lightning strike to the electric field antenna (shot #51); altitude technique; camera A.

Table 2 shows that, out of the nine successful altitude-triggered lightning events, only two struck the platform, as described in Section 3.1. Five others struck the surrounding ground, and two struck the control room. Of the seven triggered lightning flashes that missed the platform, four had their points of impact identified from photo and video images and are marked with an (*) in Table 2 as cases where the impacts were within the claimed attractive volumes of the ESE rods, particularly ESE-1, which has an extended protection range.

Figs. 8 and 9 show altitude triggered lightning after shots #0 and #3. The distance from ESE-1 to point of impact for shot #0 is between 10 and 15 m and from ESE-1 to #3 is between 60 and 80 m. In both cases, the strike points are within the protection area of ESE-1 as displayed in Fig. 6, but also for ESE-2 if the peak current data of both flashes are considered: -54 kA and -19 kA (LPATS/IMPACT).

Shots #9 and #22 are two additional cases presenting evidence of altitude triggered lightning missed by both ESE, since lightning struck the control room located inside the protection volume of both ESE, see Fig. 10. The highest peak currents of these two cases are 28.5 kA and 44 kA, respectively, measured by magnetic cards.

Fig. 4. Lightning strike to the Franklin rod (shot #33); altitude technique; camera B.

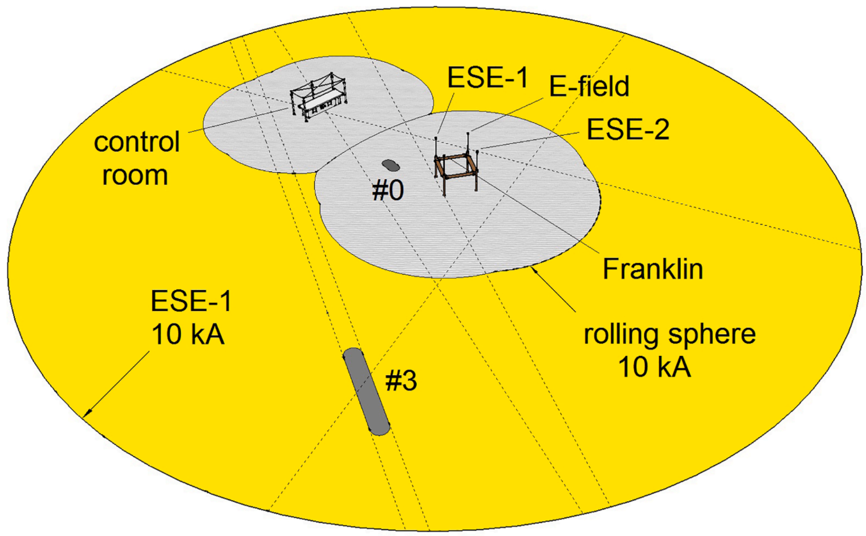

Fig. 6. Claimed attractive area at ground level of ESE-1 (yellow) and attractive areas according to conventional rolling-sphere method (light gray), both for 10 kA lightning peak current; areas where shots #0 and #3 likely struck the ground (dark grey).

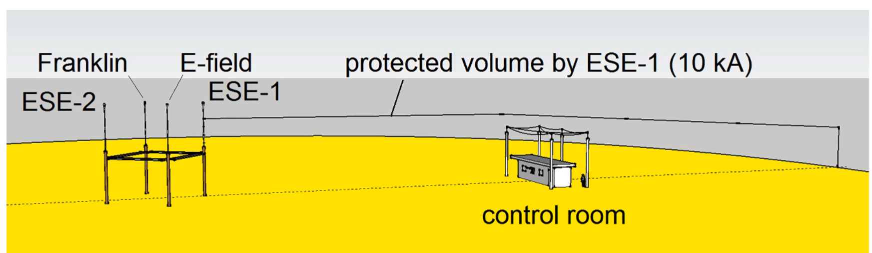

Fig. 7. Upper boundary of protected volume provided by ESE-1 for 10 kA peak current.

Fig. 8. Altitude triggered lightning (shot #0) strikes the ground at some 10 to 15 m from ESE-1; camera A.

3.3. Classical technique – channels pushed to objects on the platform

Table 2 shows that, of the 12 classical triggered flashes that successfully struck the platform, seven struck the launching tubes and remained connected to them, while the other five initially struck the launching tubes but had their channels pushed sideways by the wind until they attached to the lightning rods. In these latter events, the channel jumped to the Franklin rod four times (shots #11, #18, #27, and #29) and to the ESE-1 rod once (shot #49).

Shots #27 (to Franklin) and #49 (to ESE-1) are shown in Figs. 11 and 12, respectively. The pictures are taken from video frames selected to represent similar stages of the two discharges on the two figures: ICC, subsequent return strokes, channel leaning to one side due to wind and jumping to rod.

Note in the two small boxes in Fig. 11c that both ESE-2 and Franklin rods emit streamers (or leaders) toward the ionized channel, even though the channel was already connected to ground (via launching tubes).

Fortunately, shot #27 was also captured by another camera located on the opposite side of the platform, allowing a better interpretation of the event, as shown in Fig. 13.

Fig. 13 shows that the wind is not pushing the channel directly over the Franklin rod, as it may look like in Fig. 11, but to somewhere in between the Franklin and ESE-2 rods. Fig. 13b shows streamer emissions from both Franklin and ESE-2 rods of similar intensity, and nothing from ESE-1. Interestingly, in Fig. 13c the channel connects to the Franklin rod and ESE-2 remains emitting streamer or leader towards the channel. The available waveforms for this case are too compressed in time to show here, but indicate that the three rods emitted streamers, all clamped at the same level (10 A) and synchronized with the 3 strokes of this flash (-41 kA, -19 kA and -22 kA, measured with the high-current shunt).

It is opportune to clarify what seems a mistake in [8], regarding the connection of a triggered lightning to ESE-1 rod. (Note: ESE-1 is referred to as S6, and ESE-2 as S3 in [8]). The image of such connection ("Fig. 5" in [8]) corresponds to shot #49, the very same shown in Fig. 12d that is a classical triggered event. Next, in [8], a description of the connection and of the acquisition systems is made. Following that, an oscilloscope screen with acquired waveforms, presumably of the same event, is

Fig. 9. Altitude triggered lightning (shot #3) strikes the ground at some 60 to 80 m from ESE-1; camera E.

presented ("Fig. 7" in [8]). However, the shown waveforms are in fact from another lightning flash: the altitude-triggered flash, shot #51, the one that hit the electric field antenna, as presented in Section 3.1 (Fig. 5).

The waveforms in "Fig. 7" in [8], repeated with adaptations here as Fig. 14 for convenience, come from three sensitive current channels (limited to 10 A), designed to measure low current values associated with streamer emissions from the three rods, and a fourth channel to record the electric field from the antenna on the platform. Indeed, by the current waveforms in Fig. 14, there were streamer emissions from all three rods in the shot #51 event, being the ESE-1 current stronger than those of the other two rods (the plateau at ESE-1 current indicates the limitation at 10 A).

No high peak current was measured in this event because the antenna was not connected to the launching tubes, which are grounded by a conductor monitored by high current sensors. The authors of [8] tried to explain the unexpected electric field behavior (channel "E-field" in Fig. 14), by saying that the "E field sensor was disturbed for an unknown reason". Apparently, they were not aware that that sensor was struck by the lightning flash triggered by shot #51.

Two additional interesting observations can be made about the current waveforms in Fig. 14. Firstly, all the three rods initiated streamers. The evidence is on the waveforms themselves. All the three currents presented a typical characteristic of UUL (unconnected upward leader), that is: they increase in one direction (negatively, in this case) and invert polarity when the downward leader channel connects somewhere else, as the charges injected in the UUL channels return to ground [18]. ESE-1 current was higher and even caused saturation of the low current sensor (clamped at 10 A), possibly due to a stronger influence of the descending leader. Secondly, the Franklin rod was the farthest rod from the antenna, yet it exhibited current of comparable amplitude and waveform as that on ESE-2. This observation indicates that, under similar conditions, ESE-2 did not outperform the Franklin rod. Moreover, the characterization in [8] of these currents as an "inductive effect" is unfounded.

Another noteworthy observation from the waveforms in Fig. 14 is that all currents commenced virtually simultaneously (5 μs/div. time scale). No significant temporal advancement in streamer initiation was observed for either ESE-1 or ESE-2 compared with the Franklin rod.

4. Discussions and conclusion

The test data of the triggered lightning test campaign at INPE campus in Cachoeira Paulista (2000-2005) were revisited, focusing on the performance of ESE rods.

The results of 21 successful lightning triggering (out of 57 rocket launches), were divided into three situations:

1. Altitude triggering (A) lightning that struck objects on the firing & testing platform;
2. Altitude triggering (A) lightning that missed the platform, striking the ground or structures in the surroundings;
3. Classical triggering (C) lightning that initially struck the launching point, as expected, but had their channels displaced and jumped to one of the rods under test.

Although one might question the validity of any of the three test situations described above as a means of disproving the claimed

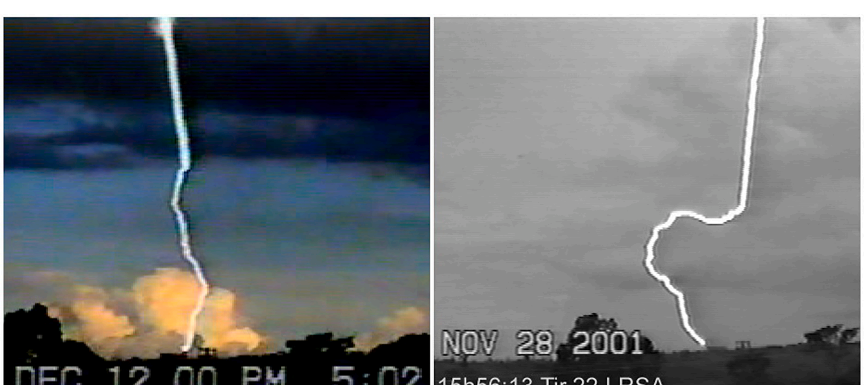

Fig. 10. Altitude triggered lightning strikes to control room; shot #9 (left) and #22 (right); camera F.

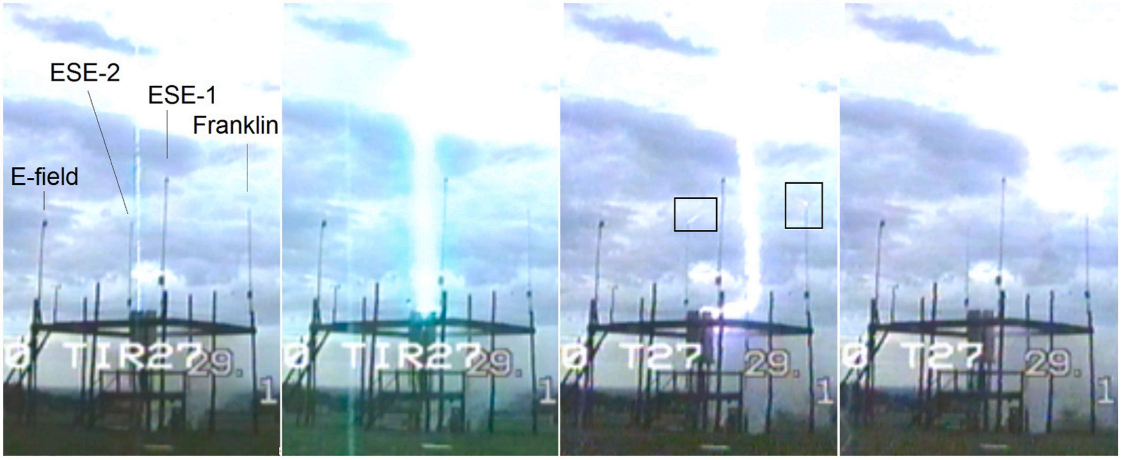

Fig. 11. Classical triggered lightning (shot #27); a) Wire burns with ICC; b) Subsequent return stroke; c) Another return stroke with channel apparently leaning to Franklin rod; d) Channel jumps to Franklin rod; camera B.

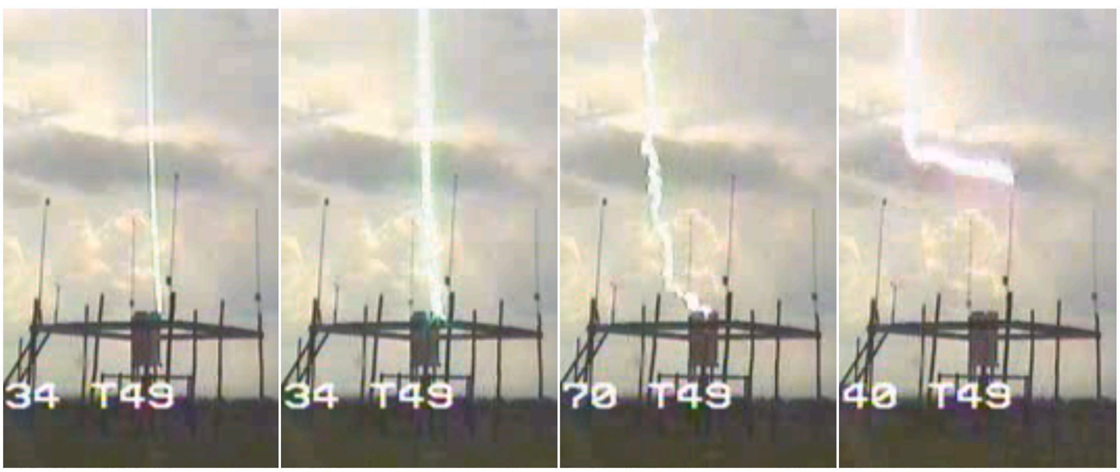

Fig. 12. Classical triggered lightning (shot #49); a) Wire burns with ICC; b) Subsequent return stroke; c) Another return stroke with channel apparently leaning to the space between ESE-1 and antenna; d) Channel jumps to ESE-1; camera B.

performance of ESEs, the outcomes in all three cases were unfavorable to the ESE.

It is important to clarify that the authors had no intention to endorse or debunk the ESE device, but to review the test data from Cachoeira Paulista with focus on the ESE performance, and to share the results. The main reason is that no published paper treating the subject as intended in this work, i.e. the ESE performance as a whole in the entire test campaign, has been found by the authors. Another reason is that reporting facts and measurements collected over five years of testing is more valuable than relying on the persistent rumors about the poor performance of ESE rods during these tests.

In situation 1, defined above, only two altitude triggered lightning hit objects on the platform: the Franklin rod and the electric field antenna, the latter was not even grounded. The score was Franklin = 1, antenna = 1, ESE-1 = 0, ESE-2 = 0. Although statistically not relevant, this result may reinforce a collection of observations that ESE did not perform as expected in triggered and natural lightning tests [1–3]. One may argue that the Kevlar length was too short in shots #33 and #51 (see Table 1), which indeed it was, but the counterargument highlights the questionable validity of standardized ESE tests in laboratory [16]. In the lab test, a 1-m ESE rod competes with a 1-m single rod (in terms of time to emit a streamer) and the gap between the rod tip and the high-voltage plate above can be as short as 1 to 3 m. In addition, the waveforms in Fig. 14 show that there was no noticeable time advance to emit streamer between the three rods just before the connection (to the antenna), especially considering Franklin and ESE-2 rods which were under similar conditions with respect to the approaching leader.

In situation 2, the results imply a more serious unfavorable performance of ESE, because there were four altitude triggered lightning that struck locations unarguably within the protection area provided by the ESE rods. Note that Kevlar length was 100 m in these cases.

In situation 3, the conditions are not conducive to conclusions about the performance of the ESE, especially because the initial quasi-vertical channel moves and leans according to the wind. Nevertheless, four flashes (out of five) connected to the Franklin rod and just one connected to an ESE rod. It is very interesting to see in Fig. 13 what appears to be a competition between Franklin and ESE-2 to make connection to a channel moving approximately in the middle of the two rods (shot #27). Streamers emerge from the rod tips toward the channel in between.

As conclusion, the Cachoeira Paulista test data have indicated unfavorable performance of two ESE rods against a Franklin rod and an electric field antenna disposed at close distance as idealized by the test designers, and the surroundings.

CRediT authorship contribution statement

José Claudio de Oliveira e Silva: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology,

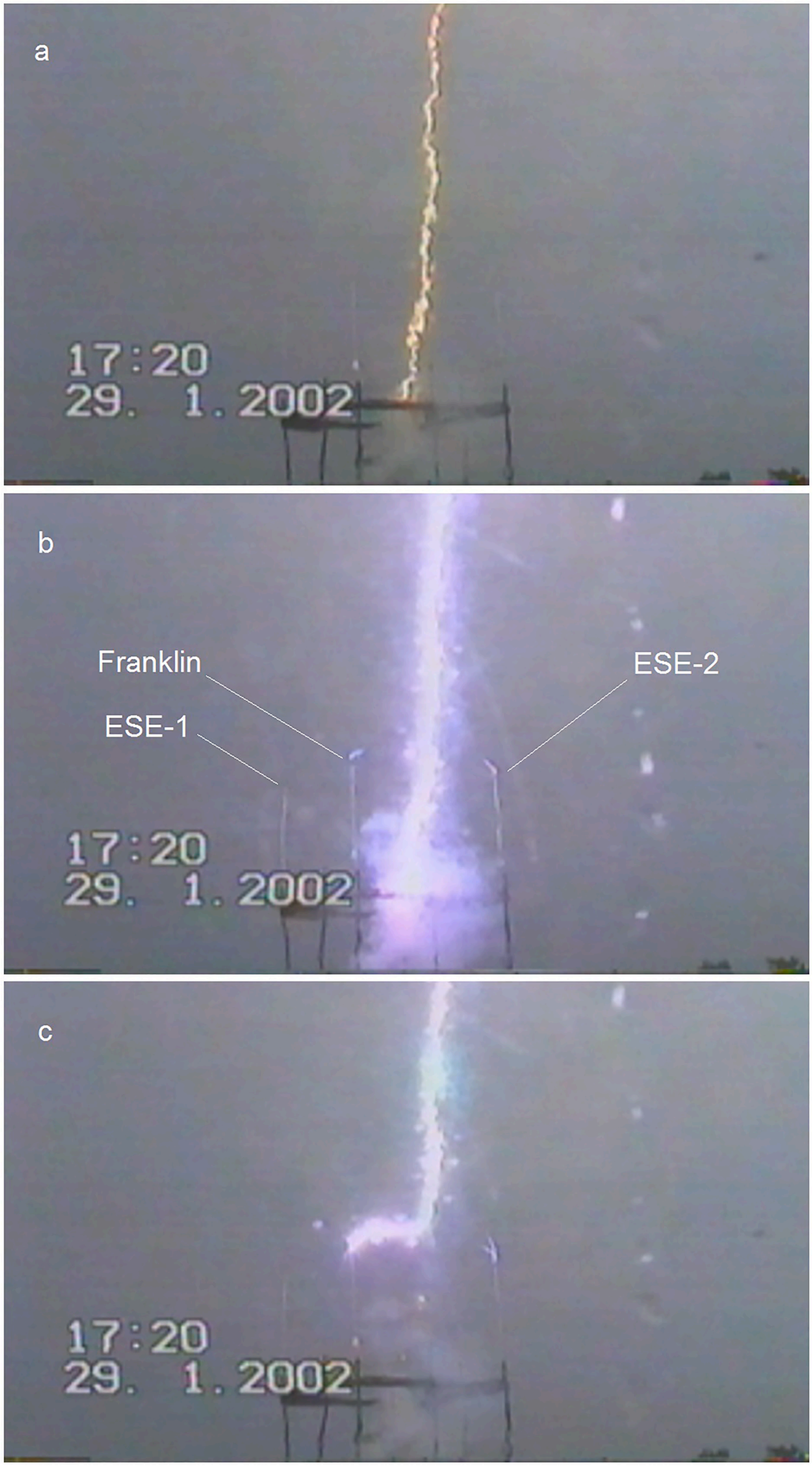

Fig. 13. Classical triggered lightning (shot #27); camera C.

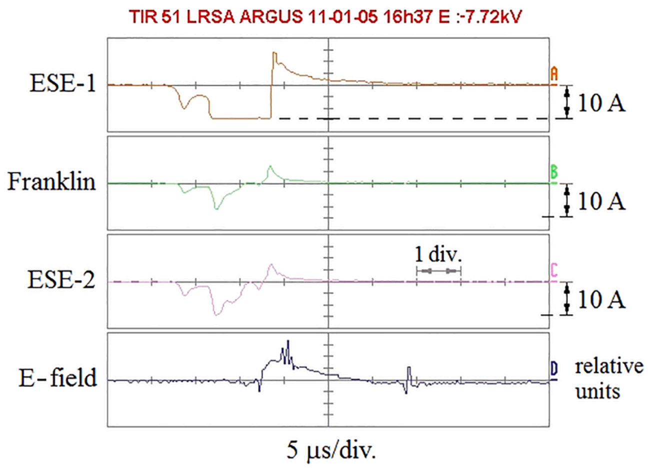

Fig. 14. Shot #51 current waveforms on ESE-1, Franklin and ESE-2 rods, and electric field from antenna on firing & testing platform. Adapted from "Fig. 7" in [8].

Investigation, Formal analysis, Data curation, Conceptualization. **Marcelo M.F. Saba:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Natália Nunes Solórzano:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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