# Analysis of terrain and atmospheric conditions for upward flashes in Sao Paulo-Brazil

Carina Schumann, Marcelo M.F. Saba, Amanda Romão de Paiva Electricity Atmospheric Group INPE – National Institute for Space Research São José dos Campos, Brazil

> Wolfgang Schulz, Gerhard Diendorfer OVE Service GmbH, Dept. ALDIS Vienna, Austria

*Abstract*— Since 2012 upward flashes have been observed in two locations in Sao Paulo City: Jaraguá Peak and Paulista Avenue. TV and Radio towers are located on the top of a steep hill called Jaraguá Peak. Paulista Avenue is a very busy complex of several buildings with tall towers on top. Upward flashes were registered from towers for both locations. For one of the events we observed upward leaders from both locations even though they are 11 kilometers apart. In order to understand which meteorological and terrain conditions are propitious for upward leader initiation, 83 flashes were analyzed and the results are presented in this paper. An analysis of the mountain profile and a comparison between Jaraguá Peak and other towers around the world used in lightning incidence studies is shown in this paper. The analysis is done by using 3 methods to calculate the effective height of the towers proposed by the literature.

Keywords—Upward flashes, Initiation conditions, Effective height

#### I. INTRODUCTION

Two different modes of upward flashes have been observed in the world. These modes are known as self-initiated or othertriggered upward flashes [1]. In case of other triggered upward flashes, preceding cloud-to-ground or intracloud flashes are responsible for a sudden change of the atmospheric electric field resulting in the triggering of upward flashes from nearby towers [1, 2].

The mountain where towers were built and the effect on the enhancement on environmental electric field are a point of interest for analysis since 1965 [3]. The concept of effective height, considering the height of the tower and the place where it is located when compared with the surrounding terrain, are Marco Antonio da Silva Ferro Atmospheric Science Division IAE – Institute of Aeronautics and Space Sao Jose dos Campos, Brazil

> Tom A. Warner ZT Research Rapid City, USA

correlated by some authors with the percentage of upward flashes.

Eriksson [4] suggested that the effective height of towers  $(H_s)$  on top of mountains could be calculated based on the percentage of upward  $(P_u)$  flashes registered on these towers by the equation (1):

$$P_{\mu} = 62.8 \ \ln(H_{\rm s}) - 315.5 \tag{1}$$

Eriksson [5] updated his equation (1) based on new observations to equation (2):

$$P_{\mu} = 52.8 \ln(H_{\rm s}) - 230 \tag{2}$$

Rizk [6] assumes that the occurrence of upward lightning in a tower is based in two factors: minimum ambient ground field and a complex function of ground field, structure height and terrain.

Rizk's method suggests that an upward positive leader can be launched from the structure when the electric potential  $U_i$  at the top of structure exceeds the 'continuous leader inception potential'  $U_{lc}$  (in Volts), which is given by:

$$U_{lc} = \frac{1556x10^3}{1 + \frac{77.8}{R}} \tag{3}$$

where R is in meters and a function of the mountain base radius (a) and the structure height (h) given by:

$$R = \frac{2(h+a)}{\left[1 + \frac{2a(h+a)}{(h+a)^2 - a^2} - \frac{2a(h+a)}{(h+a)^2 + a^2}\right]}$$
(4)

The electric potential  $U_i$  at the tip of the structure located on the top of mountain is a function of height of structure, mountain and the ambient uniform electric field  $E_g$ , given by the equation 5 and assuming the geometry of the mountain as semihemisphere.

$$U_i = E_g \cdot (h+a) \cdot \left[ 1 - \frac{a^3}{(h+a)^3} \right]$$
(5)

Rizk concluded that two criteria for occurrence of upward flashes are important:

$$U_i \ge U_{lc} + x_o E_{\infty} ln\left(\frac{E_i}{E_{\infty}}\right) \tag{6}$$

$$E'_g \ge E_\infty$$
 (7)

Where  $E_i$  is the minimum positive streamer gradient and  $E_{\infty}$  is the final quasi-stationary leader. In this paper we assume the values of 400kV/m and 3kV/m respectively in order to compare with [7]. Rizk [6] uses 5m/s for  $x_0$  that is a parameter proportional to the upward leader speed.

In order for the upward flash to occur the  $E'_g$  (mean ambient electric field) must to exceed 3kV/m.

Wakai [8] observed that towers on hill summit are struck more frequently than towers on flat areas.

In this work, we will present the characteristics probably relevant for the initiation of upward lightning of towers located in São Paulo city and compare with other towers in the world.

### II. LOCATION

Sao Paulo city is located in southeastern Brazil. It is one of the 40 most populous cities in the world and 25 out of the 50 tallest buildings in the country are located in Sao Paulo. The average ground flash density for this area is 15 flashes/km<sup>2</sup>/year.

Although there are many tall buildings and structures in Sao Paulo city, in the last 3 years we have observed upward flashes in two locations: Jaraguá Peak and Paulista Avenue.

## A. Jaragua Peak

Jaraguá Peak is a steep hill – 318 meters above the surrounding terrain – located inside the urban area. It rises 1239 meters above sea level (see Figure 1). There are two tall TV towers and several other smaller communication towers located on this peak. The average flash density for this area is a noticeable high-density anomaly of up to 45 flashes/km<sup>2</sup>/year located over Jaraguá Peak [14] and probably a result of a high occurrence rate of upward lightning.



Figure 1: Jaraguá Peak – 318 meters above surrounds terrain [9].

## B. Paulista Avenue

Paulista Avenue is located in downtown Sao Paulo. It is one of the most important avenues of the city with several towers (height up to 212 meters) on tall buildings (Figure 2).

Even though it is not located on steep hill, Paulista Avenue is located on one of the highest areas of the city.

Paulista Avenue is 11 km apart from Jaraguá Peak.



Figure 2: Paulista Avenue – Towers with height up to 212 on top of tall buildings [10]

#### III. EQUIPMENT AND DATA

Upward flashes in Brazil were registered with high-speed cameras distant about 5km from the towers. Three cameras Phantom: v711, v310 and Miro4 were used to record the data. BRASILDAT and RINDAT were used to determine distance, classification of the flash and peak current.

All upward lightning discharges recorded in Brazil are negative upward flashes, initiated by positive upward leaders [11].

76 negative upward flashes that occurred in 28 thunderstorm days in Sao Paulo, Brazil, were analyzed in this work.

## IV. RESULTS

## A - General Characteristics of the upward flashes in Sao Paulo

72 flashes were recorded in Jaraguá Peak and 3 flashes in Paulista Avenue. A special case was recorded simultaneously in both locations.

Two criteria were used to determine if cloud-to-ground flashes triggered an upward leader (from one or more towers): the time between events and the video observation of the leader propagation along the cloud base.

For 6 cases, no events just prior to the initiation of the upward flashes were detected by LLS. 93% (65 out of 70) upward flashes were triggered by a positive cloud-to-ground. The remaining 5 cases were triggered by negative cloud-to-ground flashes. None of the events were triggered by negative cloud-to-ground flashes. In Gaisberg Tower, 15 out of 23 negative upward flashes were triggered by positive cloud-to-ground flashes and 8 by intracloud events. Also, none of them were triggered by negative cloud to ground flashes. Opposite results were found in observations from Säntis Tower, in Switzerland, where all upward flashes were triggered by events of the same polarity [12].

#### **B** - Atmospheric characteristics

Regarding the atmospheric conditions favorable for the initiation of upward flashes, radiosonde data was analyzed. Figure 3 shows the individual values for cloud base height based on the radiosonde data closest to the time of the upward flashes occurrence, i.e. maximum of 3 hours between radiosonde and lightning events. 6 out of 28 radiosonde data were not available and only 3 out of 28 were more than 3 hours apart from the time of upward flashes occurrence. These 3 values are not shown in Figure 3.

The cloud base height for thunderclouds that produced upward flashes ranged from 900 to 1600 meters with 1040 meters above ground level on average.

From a concurrent study being performed in Rapid City, South Dakota, USA, the cloud base ranged from 1200 to 3600 with 3000 meters above ground level on average [13].



Figure 3: Cloud base height

Schumann et al., [14], using optical data from high speed video records, obtained a mean height of the horizontal propagation of 1920 m (ranging from 3380 to 1232 meters). From Schumann et al. [14] and the analysis of radiosonde results, the authors suggest the idea that the leader propagates horizontally between lower positive cloud center and cloud condensation level (shielding layer).

# C – Terrain Characteristics

In order to compare the terrain characteristics of Jaraguá Peak with other towers around the world used in lightning incidence studies, the methods to calculate the effective height of the towers proposed by Eriksson [4, 5] and Rizk [6] were applied using the same criteria to determine the mountain height. In this study, the height of the mountains was determined using the following procedure:

- identify the steepest side of the mountain;
- trace the profile of the mountain in this direction;
- calculate the difference in altitude between the highest point on top of the mountain and a point 1 km apart on the direction of the steepest side of the profile.

As shown in Figure 4, we used Google Earth® to obtain the profile of the mountain in the direction of the steepest side. Figure 4 shows two different cases: the first one (Säntis Tower), where the peak of the mountain is located at the border of a plateau, and the second one (Jaraguá Peak) where the altitude changes abruptly at 1 km away from the peak. The electric field intensification must be different for each of these two cases.



Figure 4 – Profile of the mountains Säntis Tower and Jaraguá Peak.

Using this procedure for other towers we have summarized in Table 1 information for 16 towers [7, 15-25] around the world:

- Column 2: height of tower structure;
- Column 3: Mountain (terrain) height determined by profile analysis for 1 km described above;
- Column 4: Mountain (terrain) height found in the literature;
- Column 5: Percentage of upward flashes reported in the literature. In the case of Jaraguá Peak, this percentage is based on our observation;
- Column 6: Number of flashes per year reported in the literature. Different method of observation as Highspeed cameras, standard cameras, dI/dt, current measurement were used;
- Column 7: Effective height calculated by Risk's method for the mountain (terrain) height reported in the literature;
- Column 8: Effective height calculated by Risk's method for the mountain (terrain) height determined by profile analysis for 1 km;
- Column 9: Effective height calculated by Eriksson's method described in [4] for the mountain (terrain) height determined by profile analysis for 1 km;
- Column 10: Effective height calculated by Eriksson's method described in [5] for the mountain (terrain) height determined by profile analysis for 1 km;
- Columns 11 and 12: Literature values for comparison [7, 15]

For this analysis, due to the complexity (proximity of large number of towers) Paulista Avenue and Rapid City towers were not considered.





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|----------------------------------|--|-----------|--------------------------------------|--|--------------------------|------------------|--------------------|--------------------|-------------------------------|-------------------------------|----------------------------|---------------------------------------|-----------------------|--------------|-----------------------------|-----------------------------|-----------------------|--|
| Heff by<br>Shindo 201            |  | Column 1  |                                      |  |                          |                  |                    | ***                | 380                           | ***                           | 240                        | 175                                   | ***                   | ***          | 630                         | ***                         | 820                   | 380                                      |
| Heff by<br>Zhou 2010             |  | Column 11 |                                      |  |                          |                  |                    | *<br>*<br>*        | 324                           | *<br>*<br>*                   | 113                        | 145                                   | *<br>*<br>*           | *<br>*<br>*  | 274                         | *<br>*<br>*                 | *<br>*<br>*           | 198                                      |
| Heff by<br>Eriksson -<br>1984    |  | Column 10 |                                      |  |                          |                  |                    | 424                | 518                           | 252                           | 102                        | 176                                   | 605                   | 487          | 518                         | 238                         | 518                   | 293                                      |
| Heff by<br>Eriksson -<br>1978    |  | Column 9  |                                      |  |                          |                  |                    | 379                | 442                           | 253                           | 125                        | 192                                   | 437                   | 422          | 442                         | 243                         | 442                   | 285                                      |
| Heff by Risk 1994                | literature<br>Mountain                           | Column 8  |                                      |  |                          |                  |                    | 304                | 346                           | 251                           | 118                        | 186                                   | * *                   | * *          | 479                         | 364                         | 526                   | 400                                      |
|                                  | Mountain<br>Surrounding<br>by 1km                | Column 7  |                                      |  |                          |                  |                    | 296                | 221                           | 327                           | 134                        | 215                                   | 205                   | 327          | 354                         | 364                         | 439                   | 400                                      |
| Number of<br>Flashes per<br>year |  | Column 6  | 20                                   | 23                                     | 30                       | 75               | 12                 | 15                 | 19                            | 10                            | 44                         | 7                                     | 11                    | 31           | 54                          | ***                         | 120                   | 21                                       |
| Pu [%]                           |  | Column 5  | 66                                   | 100                                    | 92                       | 100              | 46                 | 89                 | 100                           | 62                            | 14                         | 43                                    | *66                   | 97           | 100                         | 59                          | 100                   | 70                                       |
| untain                           | Literature                                       | Column 4  | 0                                    | 0                                      | 0                        | 0                | 0                  | 60                 | 288                           | 0                             | 80                         | 200                                   | N/A                   | N/A          | 800                         | 600                         | 006                   | 640                                      |
| a = Mo                           | This work<br>method<br>(1km profile<br>analysis) | Column 3  | 0                                    | 0                                      | 0                        | 0                | 0                  | 50                 | 64                            | 06                            | 107                        | 253                                   | 300                   | 318          | 456                         | **009                       | 623                   | 640                                      |
| h Tower                          |  | Column 2  | 200                                  | 433                                    | 540                      | 553              | 634                | 250                | 160                           | 250                           | 60                         | 60                                    | 22                    | 130          | 100                         | 40                          | 124                   | 70                                       |
| Location                         |  | Column 1  | Fukui Thermal Power Plant<br>[16,25] | Empire States Building [11, 16,<br>17] | Ostankino Tower [11, 16] | CN Tower [16,21] | Tokyo Skytree [16] | Brixton Tower [20] | Peissenberg Tower[11, 16, 19] | Chrischona Tower [11, 16, 24] | CSIR Research mast [7, 16] | Morro do Cachimbo Station<br>[16, 18] | Eagle Nest Tower [16] | Jaragua Peak | Gaisberg Tower [16, 22, 23] | TV Tower on Mount Orsa [16] | Säntis Tower [12, 16] | Tower on Mount San Salvatore<br>[11, 16] |

\* Described on reference as: "Most of all flashes are upward flashes" it was considered 99%

\*\* Location not found - considered the same of the literature for comparison

\*\*\* - Not Available

## V. SUMMARY

For lightning events at Jaraguá Peak, cloud base heights determined from radiosonde measurements are shown for the first time. In Sao Paulo, using high-speed cameras to record upward flashes, it was possible to observe the leader propagation close to cloud base. Using radiosonde data for the thunderstorm days (maximum of 3 hours between lightning event and radiosonde measurement) in which upward flashes were recorded, it was found that cloud base height ranged from 900 to 1600 meters with a mean value of 1040 meters above ground level.

For 16 towers in different regions of the world, in which lightning incidence studies were performed, three methods to calculate the effective height of the towers on top of mountains were applied using a common procedure to determine the height of the mountains used in the calculations. The results are shown at the Table 1.

The suggested criteria to determine the height of the mountain makes it possible to compare the impact of the effective height of the tower on the number of flashes per year, percentage of upward flashes, etc. Even though, it is important to consider that different locations have different number of thunderstorm days, season duration and other parameters.

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