LIGHTNING EVENTS SIMULATION BUDGETING FOR THE RAIOSAT PAYLOAD ON-BOARD COMPUTER

Lázaro C. Camargo[1], Jhonathan O. Murcia-Piñeros[2], Walter A. Dos Santos[3], Kleber Naccarato[3], Rodolpho V. de Moraes[4]

[1] Researcher, National Institute of Space Research INPE, lazaro.camargo@inpe.br
[2] Postdoctoral researcher, ICT/UNIFESP, jhonathan.pineros@unifesp.br
[3] Researchers, National Institute of Space Research INPE, Av. Dos Astronautas 1758 Jd. Da Granja, São José dos Campos, São Paulo, Brazil.
[4] Professor, Institute of Science and Technology ICT/UNIFESP, Av. Cesare Monsueto Giulio Lattes, 1201 - Eugênio de Melo, São José dos Campos - SP, 12247-014

***Keywords**: RaioSat, lightning flash simulation, Monte Carlo simulation, small satellites.*

Extreme weather events are increasingly common in Brazilian territory, and to assist in the study and generation of meteorological forecast models, the monitoring of lightning occurrences becomes extremely important. The Atmospheric Electricity (ELAT) group of the Earth System Science Center (CCST) proposed the Cubesat RaioSat mission, to assist the existing ground network for monitoring lightning occurrences. The RaioSat mission will have, as a space segment, a CubeSat of three units (3U) with a mass of 6 kg and dimensions of 10 x 10 x 30 cm, with an on-board computer and an attitude control system to meet the requirements for imaging rays and having the following payloads: Camera in the IR range (infrared) with sensor and an optical filter, a GPS (Global Positioning System) for low orbit applications, VHF (Very High Frequency) receiver of the SDR (Software Defined Radio) type operating in the 80 - 200 MHz band, to record the electromagnetic signatures and validate the lightning detections performed by the IR camera. The objective of this work is to present a simulation of lightning events for estimating requirements to the RaioSat payload on-board computer. The methodology is to implement Monte Carlo simulations, where the random input variables are the location of the storms, the size, and duration, and the number of lightning generated, and to verify if the satellite sensor can observe the phenomenon. First, the orbit of the nanosatellite RaioSat will be simulated. Next, the coverage region of the RaioSat mission will be defined, to calculate the limits of the regions of interest. For mesh usage, the inputs are the GIS of Brazil and the mesh size, and the output is the node, latitude, and longitude. Then, to simulate the occurrence of lightning, the Monte Carlo method will be used, first using pseudo-random, then generating the storms (latitude, longitude, elliptical size, duration, and severity), and the occurrence of lightning events (latitude, longitude, and intensity). Finally, the sensor coverage of the RaioSat mission will be simulated, initializing the Field Of View of the camera (footprint), and the intersections of the sensor footprint with the simulated lightning events. In the future, the Monte Carlo method will be changed to a Machine Learning model, to develop an application like EGSE for the RaioSat mission

1. Introduction

Lightning flashes are natural phenomena described as atmospheric discharges. They describe three types of trajectories, cloud-to-ground, ground-to-cloud and, cloud-to-cloud. This natural phenomenon is related to natural disasters, being a problem for the population and the infrastructure in locations with a high incidence of storms, which is proportional to the number of cloud-to-ground discharges [1]. In Brazil as the rest of the world, a huge amount of money is estimated in damages as a consequence of the lightning strikes events [2]. To improve our knowledge about the generation of lightning flashes and to improve the forecast of these events, is necessary to collect data from the storms. Brazil has a ground network (or ground stations), named BrasilDAT, to collect meteorological data along the country. However, a larger number of stations are distributed in the south of the country, reducing the observations in the north and northeast regions, specifically in the Amazonian region [3] due to its extension. Searching to improve the coverage in these regions, and at the same time to increase the data collection of lightning flashes above Brazil, it is proposed the development of the RaioSat mission.

A Smallsat (3U nanosat) will be the space segment of the mission, which is projected to carry a CCD Camera with a UHF sensor to detect and collect the data from lightning flashes, these two instruments are the payload of the mission [4]. Due to the nature of the lightning flashes (aleatory in position and short time duration, lower than one second), it is difficult to estimate the number of lightning flashes that could be detected by the satellite during the passage above Brazil. This analysis is necessary to determine the feasibility of the mission and to select the best orbit to increase the coverage of the storms. For this reason, the aim of this paper is the lightning events simulation to analyze the number of possible events detected for the RaioSat Payload On-Board. The first part of the analysis required the model of the lightning flashes distribution or events distribution, the determination of the satellite position above Brazil, as a function of time, and the interaction between the sensor Field Of View (FOV) and the lightning flashes to detect the events. These three topics are presented in Section 2. The Monte Carlo experiment is described in Section 3, and the results from the Simulations are presented in Section 4. Finalizing the paper presented the conclusion.

2. The RaioSat Simulation Models

In this Section are presented the lighting flashes distribution, the satellite orbit, and the sensor-event interaction.

2.1. Lightning flashes distribution

The number of lightning flashes in some parts of the south and southeast Brazilian regions, was larger than 270 000 for the period 2018-2019. This data is collected and reported by the research group in atmospheric electricity (ELAT), which is part of the National Institute for Space Research (INPE) [5, 6]. The south and southeast regions of Brazil present a large incidence of lightning flashes, followed by the central-west region, the north region (which is located in the Amazonian region), and the last, with a lower incidence of flashes, is the northeast region. The quantity of lightning flashes per square kilometer per year (flashes/km^2/year) is the measurement used to present the data collected from the observations made from the passage of satellites, the measured is defined as lightning flash rate density. The mean annual flash rate in Brazil is larger than 15 flashes/km^2/year, as was reported in [7, 8]. A detailed lightning flash rate density over Brazil was presented as a map, from data analyzed by the INPE, ELAT, and the National Operator of the Electrical System (ONS), showing four regions from the period 1998-2013. A low incident region is observed in the northeast (mean of 2 flashes/km^2/year), two large incident regions, one in the central region and the other one in the south of the country (mean of 15 flashes/km^2/year), and the rest on Brazil as a median incident (mean of 8 flashes/km^2/year) [9]. From this data, it was calculated the number of lightning flashes daily inside each region. It is important to say that the data from lightning flash rate density represent a mean value uniformly distributed along the year, this means that is most probable to observe a large value of flashes daily during the rainy season (October to March), but, this data doesn't allow to determine or discretize over the time. Then, if the daily value of events is calculated from the lightning flash rate density, the most probable is a uniform distribution around this mean value. The other part is the location of the event or the lightning flash geographical coordinates (longitude and latitude), which in this case is modeled as a pseudo-random uniform distribution inside the four regions previously described. Figure 1 presents the larger (red color) and lower (blue color) regions modeled as ellipsoids. The dots represent the lightning flashes or events daily, with geographic random distribution. The horizontal axis is the longitude in degrees and the vertical axis is the latitude.

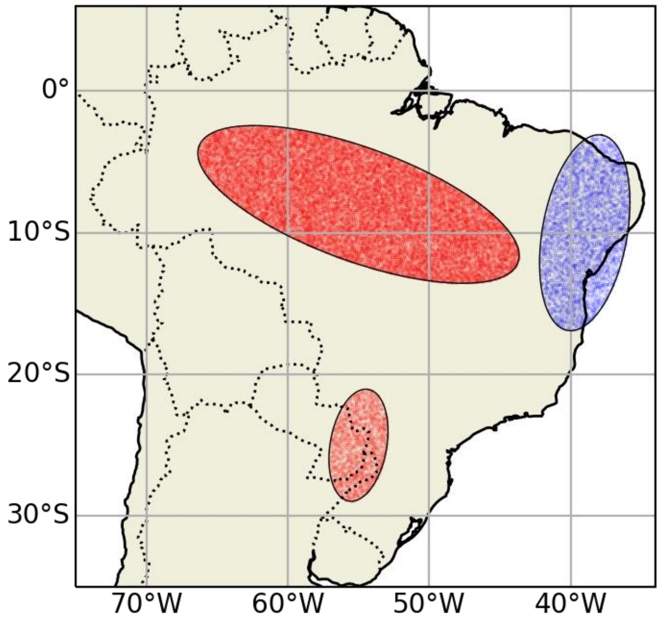


Figure 1: Daily lightning flashes simulated for high and low regions.

Table 1 presents the mean value of daily flashes calculated for the regions, a mean value of 185397 events are generated daily over Brazil. However, as was presented with the distribution along the year, in this case, the daily distribution as a function of the hour of the day is not presented in the scientific literature, which means that in mean, each 0.46 s a lightning flash is generated over Brazil.

Table 1: Daily events by region.

Region	Flashes/km^2/year	Mean daily events	Color in Figure 1
Center	15	36960	Red
South	15	3250	Red
Northeast	2	3230	Blue
Rest of Brazil	8	138557	Grey in Brazil

2.2. Modelling the satellite orbit

From the mission requirements, the space segment is projected to operate in a circular Low Earth Orbit (LEO), Sun Synchronous inclined at 98°. The geographic projection of the satellite´s orbit is presented in Figure 2 as red dots, and the blue square represents the sensor´s footprint. The orbit is modeled from the two-body problem, with the origin of the inertial at the center of the Earth. Cowell´s method is selected to propagate the orbit. The spherical perturbation of the gravitational potential (J2) is included in the dynamical equations of motion, and a numerical integrator Runge-Kutta-Felhberg 4/5 is selected to integrate numerically the equations of motion and to calculate the satellite position as a function of time. Small step sizes below 0.4 s as selected to propagate the orbit. The complete model of the orbit, perturbation, equations of motion, and numerical integrator is available in [10]. A circular orbit of 650 km of altitude and 98° of inclinations, allows the total coverage of the Brazilian territory in ten days (see Figure 3).

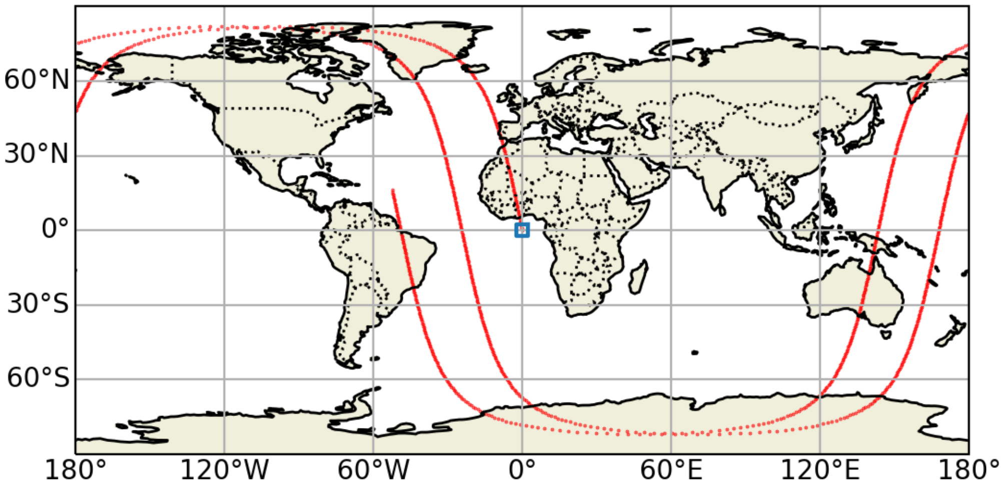
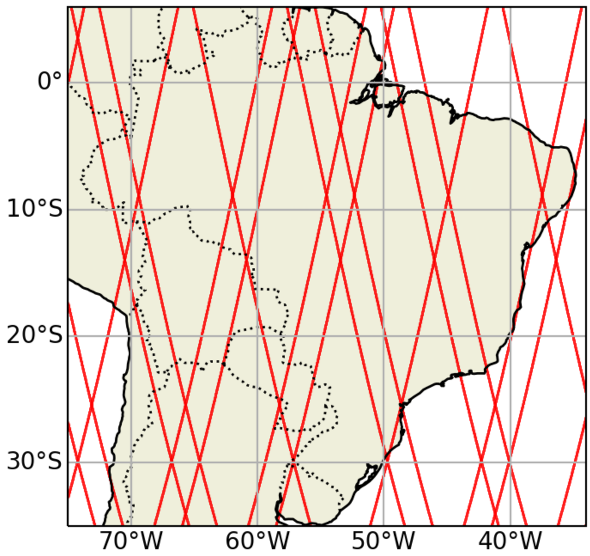


Figure 2: Satellite orbit ground track.



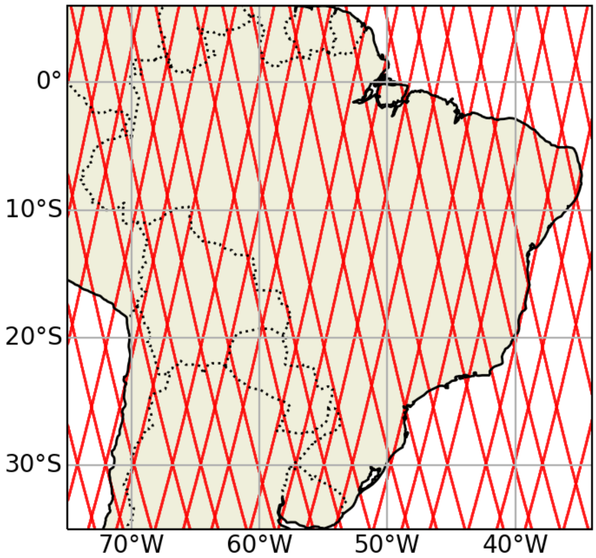


Figure 3: Satellite´s passages over Brazil for 5 days (left) and 10 days (right).

2.3. The footprint of the sensor

The last part of the model is the footprint of the sensor. The footprint is the area above the satellite, observed or sensed by the payload. This region changes as a function of time and the satellite position. The sensor is simulated with a square footprint, rotated in the direction of the orbit of the satellite. From preliminary analysis [4], it was estimated a FOV of 44°. Figure 4 presents the FOV (blue square) and one aleatory event (red dot) at the same instant of time. In this case, the aleatory is in Brazil, and at the same time, the satellite is above the south of the Indian Ocean, then the sensor does not detect the event. An event is detected when the satellite is above Brazil, and at the same time, the aleatory event is generated inside the FOV of the sensor.

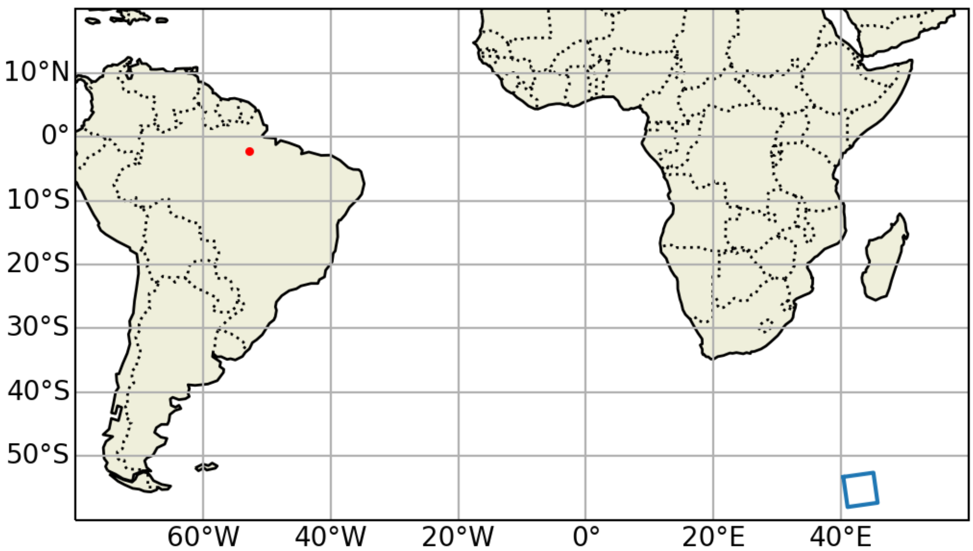


Figure 4: Footprint of the sensor and aleatory event.

3. The Monte Carlo Experiment Evaluation

Section 2 presented the models to generate the Monte Carlo simulation for aleatory events, calculate the passage of the satellite over Brazilian territory, and determine the position of the footprint of the sensor. All of the models were scripted in Python, using the Numpy, Matplotlib, and Cartopy libraries.

The first part of the experiment consists of the daily pseudo-random generation of the lightning flashes or events above Brazil, using the data from the lightning flash rate density. More than 180 000 events are generated in random locations in Brazil, and also are distributed uniformly throughout the day. The data of the events is saved, and the information on the time of the event is shared with the orbital model, to calculate the satellite position at the same instant as the time of the event. If the satellite is over Brazil, the data is saved and sent to the last module of the script, the model of the sensor. With the geospatial data of the event and the satellite position above Brazil at the same time, the last algorithm calculates the position of the event to the vertices of the FOV to determine if the event is inside or outside of the perimeter of the footprint. An event inside the FOV is classified as detected. The mean time of the passage of the satellite over Brazil in one day is above 2 500 s, and in this time more than 5 000 aleatory events are generated randomly.

The calculations of the events (quantity, time, and position) in one day, with the passage of the satellite and the calculation of the detection of these events, are defined as a simulation. At the beginning of each simulation, the pseudo-random number generator changes the total number of events, his position, and time along the day. Each lightning is instantaneous, and then the duration of the event is no longer than the step size of the propagation of the orbit. At the end of each simulation is generated a list of the events detected. The Monte Carlo method is applied over 1000 simulations, changing randomly the events.

4. Results and discussion

The Monte Carlo method was used to simulate the lightning flashes distribution. In a mean passage of the satellite with a duration of around 2 500 s more than 5 000 flashes are generated. However, the small size of the footprint and the instantaneous and random nature of the event, difficult the detection. Results of 1000 simulations show a low incidence of detections, lower than 5% of the simulations detected less than two events, and 95% of the simulations did not detect the events, even when thousands were generated at the same time of the passage, because these appear outside of the area of the sensor. Then is most probable the event occur in a large area of the Brazilian territory than in the small area of the FOV of the sensor.

There is another reason to justify the quasi-null detection of the flashes, and it is the time distribution of the event, because the model of the events is uniform, and not taken into account the possibility of having more events concentrated in specific hours of the day, nor events at the same time.

To increase the probability of detection, two technical solutions could be the increase in the FOV of the sensor, and/or the use of a smallsats constellation to increase the time of the passage over Brazil.

5. Conclusions

There was presented a method to model the random lighting flashing events, from the data of lightning flash rate density, collected by the ELAT/INPE. The model was integrated into an orbital propagator and a model of the sensor to calculate the probability of detection of the events. Monte Carlo simulations were applied, showing a low probability of detection, lower than 5% of the events detect less than two events.

The low probability of detection is attributed to the lightning flashes generation model because it is not taken into account the different distributions and/or concentration of events throughout the day. Then, it is necessary a more accurate model to generate the events and calculate the probability of detection. In addition, technical solutions could be analyzed, like a large sensor, and the use of a SmallSats constellation. The improvement of the time distribution of the lightning flashes could be used to model and configure the satellite to passage over Brazil at the same time as the larger flashes concentration, finding better orbits to the passage above the large concentration of storms.

Acknowledgments
The authors wish to express their appreciation for the support provided by Science and Technology Institute (ICT – UNIFESP) and by the National Institute for Space Research (INPE).
This work was supported by grants # 2019/26605-2 and # 2016/24561-0, from São Paulo Research Foundation (FAPESP); grants # 406841/2016-0, 301338/2016-7 and 303102/2019-5 from the National Council for Scientific and Technological Development (CNPq); grant # 88882.317514/2013-01 from the National Council for the Improvement of Higher Education (CAPES).

References

[1] INPE, Instituto Nacional de Pesquisas Espaciais. Mortes por Raios – Infográfico, São José dos Campos, 2021. Disponível em: <http://www.inpe.br/webelat/homepage/menu/el.atm/mortes.por.raios.-.infografico.php>. Acesso em: 22 ago. 2022
[2] ANEEL, Agência Nacional de Energia Elétrica. Relatório de Análise: Desligamentos Forçados do Sistema de Transmissão – Edição 2018. Brasília (2018) 685.
[3] K. P. Naccarato, et al. First performance analysis of BrasilDAT total lightning network In Southeastern Brazil. Proceedings. GROUND & LPE, 5. Bonito, (2012)
[4] A. Cassiano, et al., CubeSat Development for Lightning Flashes Detection: RaioSat Project, Journal of Aerospace Technology and management 12 (2020) 80-93.
[5] INPE/ELAT. Mapa do bienio 2018/2019, available at http://www.inpe.br/webelat/homepage/menu/infor/incidencia.de.descargas.no.pais.php, 2022.
[6] U. A. Barretto, R. L. Novais, F. J. Barbosa, Uma análise da espacialização das descargas elétricas atmosféricas e do comportamento das mortes causadas por raios no estado da Bahia, Revista Brasileira de geografia física 14 (2021) 1909-1923.
[7] D. J. Cecil, D. E. Buechler, R. J. Blakeslee, Gridded lightning climatology from TRMM-LIS and OTD: dataset description, Atmospheric research 135-136 (2014) 404-414.
[8] M. Peterson, D. Mach, D. Buechler, A global LIS/OTD Climatology of lightning flash extent density, JGR Atmospheres 126(8) (2021) 1-23.
[9] ONS. Mapa de densidade de descargas atmosféricas 1998-2013, avalible at: http://www.ons.org.br/paginas/sobre-o-sin/mapas, 2022.
[10] D. A. Vallado, Fundamentals of astrodynamics and applications 4 ed., Microcosm Press, 2013, 517-601