São Paulo Lightning Mapping Array (SP-LMA): Network Assessment and Analyses for Intercomparison Studies and GOES-R Proxy Activities

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ABSTRACT: A 12 station Lightning Mapping Array (LMA) network was deployed during October 2011in the vicinity of São Paulo, Brazil (SP-LMA) to contribute total lightning measurements to an international field campaign [CHUVA - ***C***loud processes of t***H***e main precipitation systems in Brazil: A contrib***U***tion to cloud resol***V***ing modeling and to the GPM (Glob***A***l Precipitation Measurement)]. The SP-LMA was operational from November 2011 through March 2012. Sensor spacing was on the order of 15-30 km, with a network diameter on the order of 40-50km. The SP-LMA provides good 3-D lightning mapping out to150 km from the network center, with 2-D coverage considerably farther. In addition to supporting CHUVA science/mission objectives, the SP-LMA is supporting the generation of unique proxy data for the Geostationary Lightning Mapper (GLM) and Advanced Baseline Imager (ABI), on NOAA's Geostationary Operational Environmental Satellite-R (GOES-R: scheduled for a 2015 launch). These proxy data will be used to develop and validate operational algorithms so that they will be ready to use on "day1" following the GOES-R launch. The SP-LMA data also will be intercompared with lightning observations from other deployed lightning networks to advance our understanding of the capabilities/contributions of each of these networks toward GLM proxy and validation activities. This paper addresses the network assessment and analyses for intercomparison studies and GOES-R proxy activities.

1. INTRODUCTION

1.1 Background

The next generation NOAA Geostationary Operational Environmental Satellite-R (GOES-R), presently under development and scheduled for a 2015 launch, will offer improved observing capabilities to monitor, track, and predict weather that include the Geostationary Lightning Mapper (GLM) and the Advanced Baseline Imager (ABI) instruments. The GLM, building on the heritage of the NASA Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS), will detect *total* lightning (i.e., both ground and cloud flashes) with storm scale resolution (i.e., on the order 8-12 km), high detection efficiency, and millisecond timing [Boccippio et al., 2002; Christian et al, 1992; Christian et al., 2003]. The ABI is a visible and infrared imager that offers significant improvements over the current generation of GOES imager in spectral-band coverage, spatial resolution, and frequency of sampling.

Proxy data, which play an important role in the mission preparation phase, are employed to develop and validate operational algorithms so that they will be ready for use on "Day 1" following the launch of GOES-R. In developing proxy data products for GLM, several existing lightning measurement systems are being used, ranging from the space-based LIS to a variety of ground-based detection networks. Lightning Mapping Array (LMA) network data are of particular interest since these networks also detect *total* lightning, which the GLM will detect. LMA is a regional lightning detection system [Goodman et al., 2005] that deploys 9 to 12 VHF receivers to provide 3-D mapping of lightning channels (i.e., 3-D mapping out to about 150 km from center of the LMA network, 2-D detection out to 250+ km, with diminishing detection efficiency with distance). Since LMA detects different processes in a flash than GLM (i.e., LMA detects optically weak breakdown processes, GLM will detect energetic, optically bright return strokes and recoil streamers), LIS data, which is similar to what GLM will detect, is used to tune LMA observations to produce a total lightning GLM proxy data set.

*1.2 **Target-of-Opportunity***

A target-of-opportunity to acquire unique proxy data for GLM and ABI presented itself in Brazil during the period November 2011 through March 2012 in association with the international CHUVA field campaign. The focus of CHUVA is revealed in the campaign title: "***C***loud processes of t***H***e main precipitation systems in Brazil: A contrib***U***tion to cloud resol***V***ing modeling and to the GPM (Glob***A***l Precipitation Measurement)." The new understanding of cloud processes and precipitating systems gained from this experiment will contribute to improved precipitation retrievals for tropical storm systems, which has direct applicability to the GOES project. To take advantage of this opportunity, a São Paulo LMA (SP-LMA) network was deployed in October 2011 and operated for 5 months in support of CHUVA and GOES-R objectives. Thunderstorms occur regularly at this location and season, associated with the South Atlantic Convergence Zone (SACZ), local convection, and orographic enhancement of precipitation. The measurements obtained from the SP-LMA will provide for the first time total lightning measurements in conjunction with SEVIRI (Spinning Enhanced Visible and Infrared Imager on the Meteosat Second Generation or MSG satellite) observations. As the CHUVA opportunity was formulated, a broad community-based interest developed among lightning providers for a comprehensive lightning location system (LLS) intercomparison and assessments study. Other LLSs included Earth Networks (ENTLN, BrazilDat)), LINET, World Wide Lightning Location Network (WWLLN), Vaisala (TLS200 and GLD360), and the RINDAT (INPE), STARNET (USP), ATDnet (Met Office). In addition, electric field mills, field change sensors, high speed cameras and other lightning sensors were deployed at selected locations.

2. PROJECT DESCRIPTION

*2.1 **Instrumentation and Technical Approach***

We deployed 12 portable LMA (2nd generation) sites for SP-LMA as shown in Figure 1. As described in Goodman et al. [2005], a LMA system locates the peak source of impulsive VHF radio signals from lightning in an unused television channel (channel 8 for eleven stations, channel 10 for one) by measuring the time-of-arrival of these signals at different receiving stations in successive 80 µs intervals. As these signals are located, an accurate three dimensional channel image is mapped out. Figure 2 schematically illustrates the time-of arrival approaches used with LMA. Global Positions System (GPS) receivers at each station provide both accurate signal timing and station location knowledge required to apply this approach.

***Figure 1.** Portable LMA detection station*

2.2 *Network Configuration and Operations*

The SP-LMA network configuration is depicted in Figure 3. The CHUVA dual polarization X-band radar located near São Jose dos Campos. Since a LMA provides good 3-D coverage out to 150 km, this coverage overlapped nicely with the areal coverage of the CHUVA dual polarization radar (especially toward the west). As noted previously, the LMA provides 2-D detections out to 250+ km (and often sees lightning even farther away). The "modus operandi" for SP-LMA was similar to that used by the DC Metro Area LMA in the United States, in which all the stations are connected to the internet for real-time processing and display of decimated data, and post real-time processing of the full data sets. For the latter processing, the full data were downloaded during low storm activity periods. During this project, collaborating scientists in the United States monitored, managed and processed the data remotely from the National Space Science and Technology Center (NSSTC) in Huntsville, Alabama, while the Brazilian collaborators provided local maintenance/operation support. We operated parallel servers in the U.S. and Brazil to provide both redundancy and improve local Web access. The SP-LMA was operated from late October 2011 until April 2012, when the system was shut down, packed up and shipped back to the United States. The archived data sets are available from the CHUVA archive for follow-on investigations supporting CHUVA, GOES-R, or other precipitation studies.

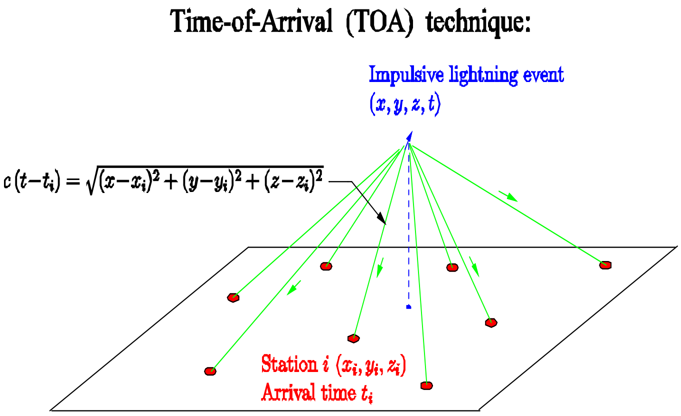


Figure 2. *Illustration of the time-of-arrival method used by the LMA. The times, t_i, when a signal is detected at $N \geq 4$ stations are used to solve for the 3-D source location (x, y, z, t) of the impulsive breakdown processes associated with a discharge.*

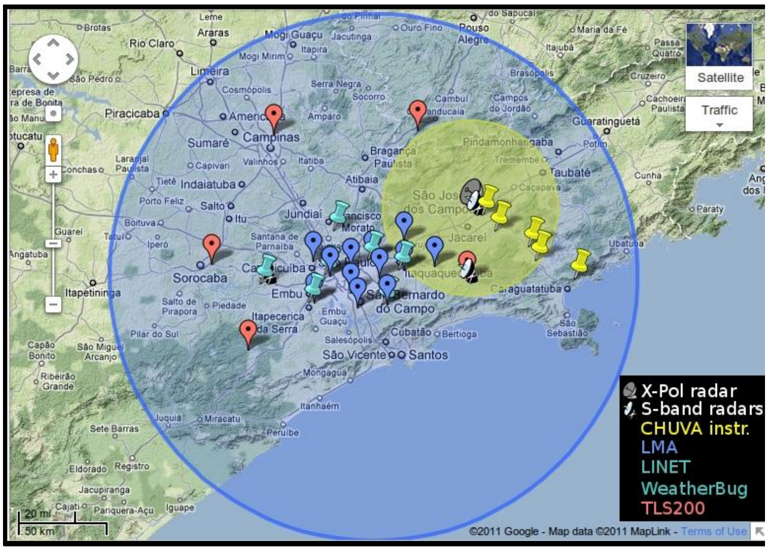


Figure 3. *Location of the SP-LMA stations and some other CHUVA systems. The blue circle represents area of 3-D lightning mapping and red circle shows region of optimum radar. Question marks show other potential locations for the X-band radar, while the flags and yellow "stick pin" are instrument sites. Other S-band radars are shown on either side of the SP-LMA.*

3. SCIENCE OBJECTIVES

The primary science objective from a GOES-R perspective is to combine and leverage the observing assets associated with the international CHUVA field campaign (and in particular with the Vale do Paraiba campaign component) with the U.S. supplied portable LMA network to generate and evaluate proxy data sets for GLM and ABI that include simultaneous total lightning and SEVIRI observations. The SEVIRI instrument, with its 12 spectral channels (4 visible, 8 infrared), provides an excellent proxy source for the GOES-R ABI, while the ground-based LMA provides total lightning observations that, when adjusted appropriately, serve as an excellent proxy of what GLM would detect. Research topics being investigated include "Day 1" Algorithm testing/validation, and new products associated with Cell Tracking, Lightning Jump, Quantitative Precipitation Estimation (QPE), Aviation Weather, Lightning Forecast and Warning, as well as combined sensor products. In support of this core objective, and the main focus of the rest of this paper, we provide an assessment of the SP-LMA network and analyses that can be used to support the intercomparison studies and the GOES-R proxy activities.

From the CHUVA point-of-view, the participation/contribution of the regional SP LMA is to provide total lightning, lightning channel mapping and detailed information on the locations of cloud charge regions for the thunderstorms investigated during the Vale do Paraiba field campaign. Science questions that the LMA data is helping to address in CHUVA include: 1) *How do cloud microphysics and electrification processes evolve during the cloud life cycle?*, 2) *How to improve precipitation estimates and cloud microphysics descriptions by using conventional and polarimetric radar?*, 3) *What is the contribution of aerosol in the process of cloud microphysical development and precipitation formation?*, *and* 4) *What are the average characteristics (3D cloud processes) of the main regimes of precipitation in Brazil?* .

4. ANALYSIS AND DISCUSSION

4.1 ***Network Assessment and Noise Reduction***

After installation of the LMA stations, a strong noise source, not identified during the site surveys, was discovered at longitude -46.6830 and latitude -23.5438. It was subsequently determined to be caused by a channel-9 television transmitter. We found that the one LMA station operating on channel 10 (closest to the noise source) was less affected by this noise signal than our other LMA stations operating on channel 8. This may be due to the fact that the video carrier, located at a lower frequency in the allotted pass band, has stronger signal than the audio carrier. The noise also contains 60 Hz and higher harmonics that likely comes from the TV sync pulse for the horizontal scans. There are a few other noise sources but they contribute an insignificant percentage of the data.

It is imperitive that the dominant noise source in the SP-LMA dataset be drastically reduced or eliminated before using this data to calculate general network statistics or intercompare with other systems. If one is only comparing individual flashes, then one may or may not need to reduce the noise, as lightning signals will typically dominate noise in the 80. μs sample window. The majority of the noise tends to be concentrated within a short horizontal distance from the center of the noise source and at altitudes lower than 5 km. As already noted, the noise signals is typically at a lower signal strength than lighting sources, which reduces the impact of noise when thunderstorms are underway in the region. We have found that eliminating data within 1 km of the noise center typically gets rid of more than 90% of the data on an "all noise" (i.e., non thunderstorm) day. On days when there is lots of lightning this procedure only removes about 2% of the data. However, this is understandable as lightning signals dominate the noise (meaning noise makes up a smaller percentage of the total data on active lightning days).

Hence, we believe that the best way of reducing the noise in the SP LMA – and the procedure we have adopted - is to eliminate the all data within ~1 km of the channel-9 noise source (physically a TV tower) before grouping the data into flashes. In addition, we require that flashes contain 5 or more sources. The great advantage of this approach is that we remove most of the noise yet without eliminating lower altitude sources from lightning, as these are often useful in identifying cloud-to-ground strokes in a flash. These two criteria (~1

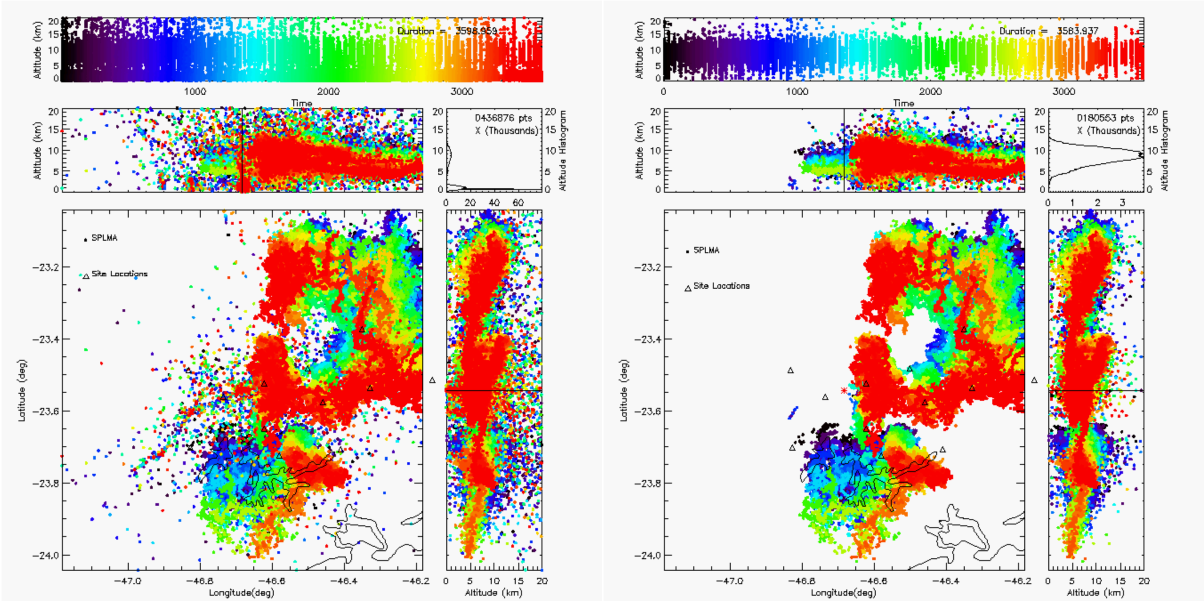


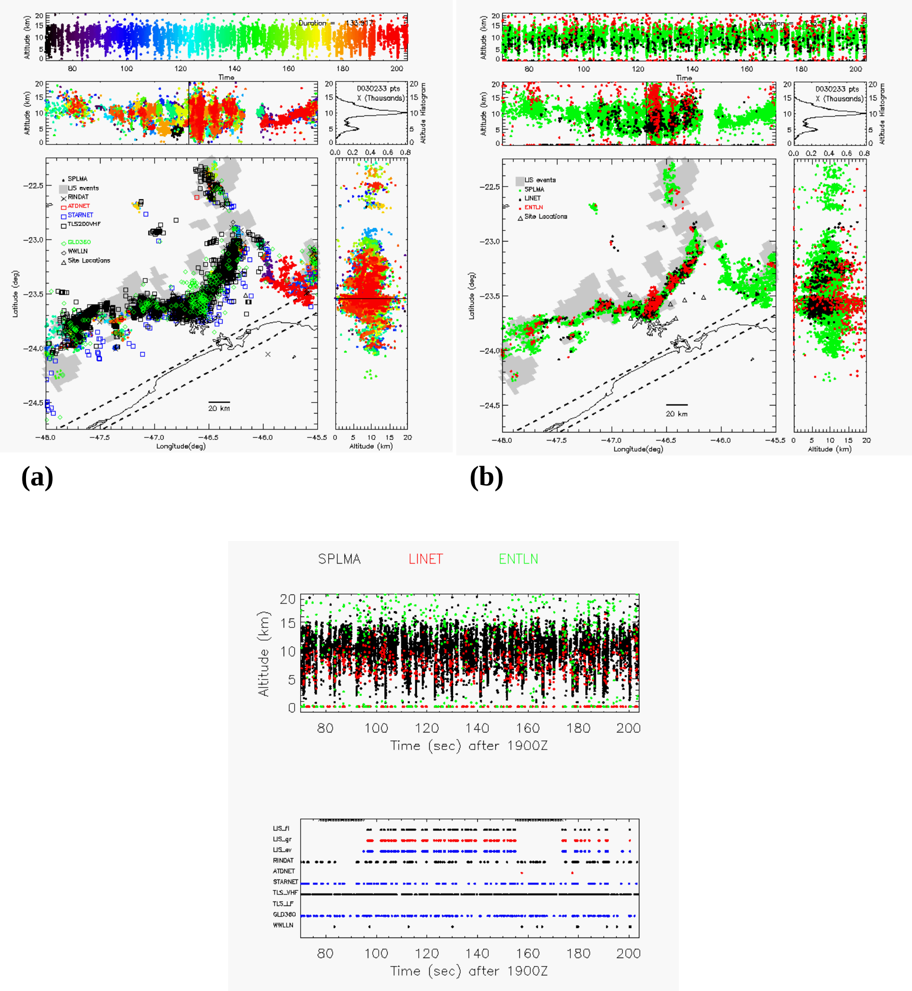
Figure 4. *SP-LMA observations on 27 February 2012 from 0300 to 0400 UTC, a day with moderate lightning activity and also excessive noise. Plot on left contains all data, including significant noise events. Plot on right contains mostly lightning events with the noise removed (data removed include all events within 1 km of channel-9 TV tower, and all flashes containing less than 5 events).*

km removal of data around noise source, requiring 5 or more sources per flash) are based on histogram plots of the number of sources per flash and plots of the percent noise removed as a function of distance from the noise source (neither one shown in this paper). Some days require either a lower (e.g., 0.5 km) or higher (e.g., 1.5 km) distance limit be used from the center of the noise source.

Figure 4 provides an example from 27 February 2012 for an hour of SP-LMA observations from 0300 to 0400 UTC, a day with moderate lightning activity and also excessive noise. This example illustrates how our noise filter procedure described above eliminates noise that would interfere with proper interpretation and intercomparison of the SP-LMA data, while retaining, and not adversely diminishing, the lightning derived events. In this Figure 4, the left panel corresponds to the full data with no noise removed. The right panel is the result with the noise and all flashes with less than 5 points removed. The red asterisk in the center of the plan view in the right panel marks the location of the channel 9 TV tower. The TV tower is also located by the vertical line in the altitude versus longitude (above the plan view) and the altitude versus latitude (side of plan view) plots in both panels. It is easily observed that the highest percentage of the resulting noise contribution occurs within a short distance from this tower. Before applying our “noise filter,” the lightning activity histogram with altitude (small square box, second row right in each panel) was dominated by noise events (many at low altitude, close to the tower). Applying the procedure removes the majority of the noise events in the data and results in altitude histogram in the right panel dominated by lightning events. Removing SP-LMA data within 1 km of the TV tower noise source eliminated 52% (mostly all noise) of the data for this hour. Removing flashes with less than 5 events eliminated an additional 7.7% of the remaining data and removed many random scatter flash locations, particularly at higher altitudes.

4.2 Analysis and Intercomparisons

In this section, we provide examples of the SP-LMA data, along with other data sets that will be available to characterize in detail the SP-LMA observations, and support GOES-R proxy activities, LLS network intercomparison studies, and CHUVA precipitation investigations.



(a) **(b)**

(c)

Figure 5. *Coincident lightning observations on 10 February 2012 at 1900 UTC during a LIS overpass. (a) Observations from SP-LMA and the 2D LLS networks. (b) Observations from the 3D LLS networks including SP-LMA (green), ENTLN (red), and LINET (black). (c) Simultaneous observations shown as a function of time for all networks, now with SP-LMA (black), ENTLN (green), LINET (red).*

Figure 5 is an example of data acquired 10 February 2012 coincident with a LIS overpass from approximately 1901:10 to 1903:24 UTC. This presentation format in 5a, 5b (also used in Figure 4) is referred to as an xlma plot. In this plot format, the top plot corresponds to time versus altitude (for Figure 5 it is time in seconds after 1900 UTC). The next "row" has two plots, with the first being altitude versus longitude (left), and the second is activity versus altitude (right), also referred to as the altitude histogram. The final "row" consists of a latitude-longitude plan view map of lightning activity (left) and altitude versus latitude plot (right).

In the case of Figure 5, the data are limited both temporally and spatially to the LIS overpass limits (total time 133.917 s). In the plan view maps, LIS pixels are indicated by grey squares of denoting the pixel footprint, while the dashed black lines are the southern edge of the corners of the LIS focal plane full field-of-view. Figure 5a shows the active 2-D lightning ground sensors (e.g., there is no TLS200LF for this day) in the plan view map and the SP-LMA data in time-altitude, altitude-longitude, altitude-latitude plots, and plan view. Figure 5b shows the same time period with SP-LMA (green), ENTLN (red), and LINET (black). Figure 5c shows all the data of all the LLS networks detected during this time interval in a form that easily shows the coincidences between the observations. During this interval, there are two LIS FIFO full overflow (black X's at the top of the

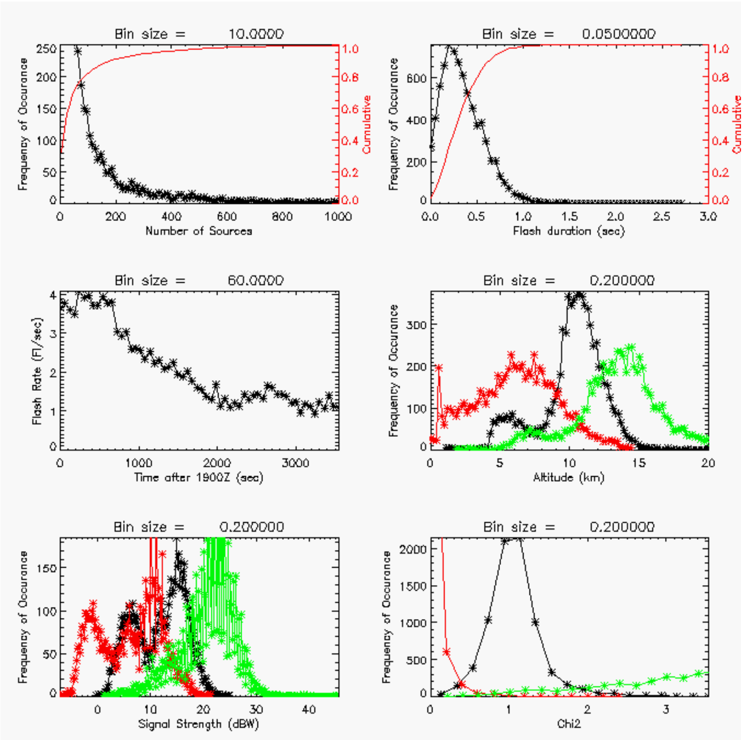


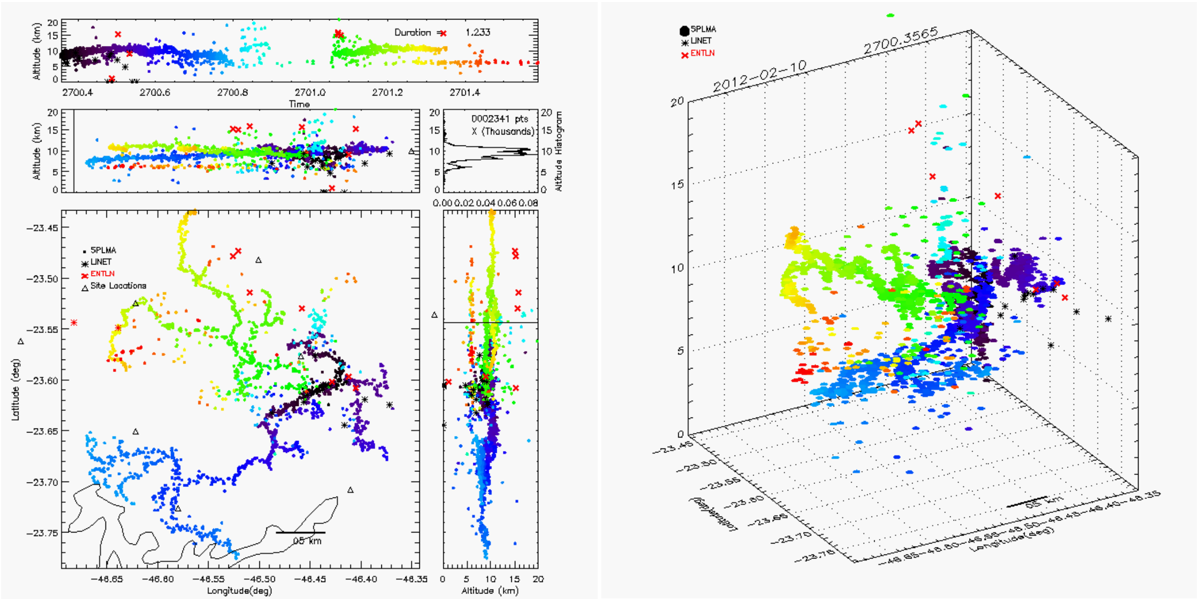
Figure 6. *Top two plots are histograms (black) and cumulative distributions (red) for the number of sources per flash (top left) and the flash duration (top right). Other statistics include flash rate as a function of time of hour (middle left), altitude distribution (middle right), signal strength (bottom left) and Chi-square (bottom right). For the altitude, signal strength, and Chi-square, the minimum (red), mean (black), and maximum (green) for each flash has been plotted.*

bottom plot) from ~76 to 90 and ~165 to ~172 seconds after 1900 UTC. In this region, this is caused by excessive noise sources being generated on the LIS focal plane array from radiation occurring in the South Atlantic Anomaly (SAA). No data is acquired by LIS during the short intervals that the FIFO buffers remains overflowed.

Typically, SP-LMA detects more than 10 times the number of source events than ENTLN or LINET. In the current version of the ENTLN data analysis which has been shared (and plotted here), there appears to be an artifactual high altitude bias (we leave this to ENTLN to figure out the issue). In general, all the ground based systems display good location agreement but there often are large differences in the number of sources detected. Also we find that in some areas there are LIS pixels that lit up but no lightning detected in those areas by ground sensors. This may be caused by reflections off of left over clouds in those areas that have no lightning (yet to be verified). For the previous hour (1800 UTC), lightning was detected in those areas by ground sensors.

Figure 6 shows a variety of SP-LMA statistics generated to better characterize the overall operation of the LMA network. These statistics are for one hour of data on 10 February 2012, beginning at 1900 UTC. These plots only contain flashes with 5 source events or more.

As a final example of the richness of the SP-LMA data in illustrating flash and storm charge structure, Figure 7 shows a single large SP-LMA flash (2341 source events and 1.233 seconds in duration) in (a) the xlma format and (b) the three dimensional representation. LINET (black *'s) and ENTLN (red x's) data are also shown on both plots. Distance scales are indicated on the plots. Interestingly, neither LINET nor ENTLN had many sources for this flash. This hour had 36 flashes that contained more than 1000 sources.



(a) **(b)**

Figure 7. *Extensive flash observed on 10 February 2012 by the SP-LMA with duration of 1.233 seconds illustrating the richness of the SP-LMA data set in revealing structural detail of flash and storm charge structure.*

5. FINAL COMMENTS AND ACKNOWLEDGEMENTS

We look forward to the exciting science returns that will result as the analysis of the CHUVA lighting data sets unfold. We gratefully thank the NOAA GOES-R program and the participating organizations in the United States and Brazil (NASA MSFC, UAH, NOAA, USP, INPE CPTEC, and INPE DGE) for the successful deployment and execution of the SP-LMA. We also extend appreciation and thanks to all the other collaborating science groups and lightning location networks.

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