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The GOES-R Geostationary Lightning Mapper (GLM)

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ABSTRACT

The Geostationary Operational Environmental Satellite R-series (GOES-R) is the next block of four satellites to follow the existing GOES constellation currently operating over the Western Hemisphere. Advanced spacecraft and instrument technology will support expanded detection of environmental phenomena, resulting in more timely and accurate forecasts and warnings. Advancements over current GOES capabilities include a new capability for total lightning detection (cloud and cloud-to-ground flashes) from the Geostationary Lightning Mapper (GLM), and improved cloud and moisture imagery with the 16-channel Advanced Baseline Imager (ABI). The GLM will map total lightning activity continuously day and night with near-uniform storm-scale spatial resolution of 8 km with a product refresh rate of less than 20 s over the Americas and adjacent oceanic regions in the western hemisphere. This will aid in forecasting severe storms and tornado activity, and convective weather impacts on aviation safety and efficiency. In parallel with the instrument development, an Algorithm Working Group (AWG) Lightning Detection Science and Applications Team developed the Level 2 (stroke and flash) algorithms from the Level 1 lightning event (pixel level) data. Proxy data sets used to develop the GLM operational algorithms as well as cal/val performance monitoring tools were derived from the NASA Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) instruments in low Earth orbit, and from ground-based lightning networks and intensive prelaunch field campaigns. The GLM will produce the same or similar lightning flash attributes provided by the LIS and OTD, and thus extend their combined climatology over the western hemisphere into the coming decades. Science and application development along with preoperational product demonstrations and evaluations at NWS forecast offices and NOAA testbeds will prepare the forecasters to use GLM as soon as possible after the planned launch and checkout of GOES-R in late 2015. New applications will use GLM alone, in combination with the ABI, or integrated (fused) with other available tools (weather radar and ground strike networks, nowcasting systems, mesoscale analysis, and numerical weather prediction models) in the hands of the forecaster responsible for issuing more timely and accurate forecasts and warnings.

1. Introduction

The Geostationary Operational Environmental Satellite R-series (GOES-R) is the next block of four satellites to follow the existing GOES constellation currently operating over the Western Hemisphere (http://www.goes-r.gov). The GOES-R system is a joint development between the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) with NASA responsible for the space segment (spacecraft and instruments) and NOAA responsible for the overall program

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and ground segment. GOES-R is scheduled for launch in late 2015, and the second satellite (GOES-S) is scheduled for launch in 2017.

Improved spacecraft and instrument technology will support the expanded detection of environmental phenomena, resulting in more timely and accurate forecasts and warnings. Advancements over current GOES include a new capability for total lightning detection (cloud and cloud-to-ground flashes) from the Geostationary Lightning Mapper (GLM) and a 16-channel Advanced Baseline Imager (ABI) providing a two-fold improvement in spatial resolution (0.5–1 km in the visible to near infrared, and 2 km in the infrared > 2 km) and factor of five improvement in temporal refresh rate for the cloud and moisture imagery (Schmit et al., 2005). The GLM will map total lightning activity continuously day and night with near-uniform storm scale spatial resolution of 8 km over the Americas and adjacent oceanic regions in the western hemisphere. This will aid in forecasting severe storms, tornado activity, and convective weather impacts on aviation safety and efficiency. The Americas are indeed notable for their intense thunderstorms and lightning from tornado alley in the Southern Great Plains of the U.S. to the almost daily thunderstorms (>300 days per year) over Lake Maracaibo (Goodman et al., 2007; Albrecht et al., 2011; Cecil et al., 2012), to the extreme flash rates (>1000 fl min^{-1}) associated with mesoscale convective systems in the La Plata Basin (Cecil et al., 2005; Zipser et al., 2006).

Section 2 describes the spacecraft and GLM instrument capabilities. Sections 3–6 describe the parallel efforts of the GOES-R Algorithm Working Group (AWG) Lightning Detection Applications and Development Team and Risk Reduction Science Team, who are developing the Level 2 algorithms, cal/val performance monitoring tools, new applications, and training material for forecasters. Owing to the lack of an existing lightning mapper in geostationary orbit, proxy total lightning data from the NASA Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM) satellite launched in 1997 as well as regional lightning testbeds are being used to develop the pre-launch algorithms and applications, and also to improve our knowledge of thunderstorm initiation and evolution.

2. GOES-R and the GLM instrument

Fig. 1 shows the 3-axis stabilized GOES-R satellite and its six instruments. The GOES-R space segment is composed of the spacecraft bus, instruments, auxiliary communications payloads, and the launch vehicle (an Atlas V 451). The spacecraft is designed for 10 years of on-orbit operation preceded by up to 5 years of on-orbit storage. The spacecraft bus is approximately 5.5 m in length with a mass of 2800 kg and end-of-life power capacity > 4000 W. The full instrument suite consists of the Earth viewing ABI and GLM, solar pointing SUVI and EXIS, and the SEISS and Magnetometer to measure the in-situ space environment. The auxiliary communications payload contains the antennae, transmitters, receivers, and transponders to relay processed imagery data and provide the auxiliary communications services.

The GLM will provide early indication, tracking, and monitoring of storm intensification and severe weather, enable increased tornado warning lead-time, and provide data continuity for climate change and variability studies over the western hemisphere by extending the combined LIS (1997–present) and Optical Transient Detector (OTD, 1995–2000) research mission time-series for another 20 years (Goodman et al., 2000, 2007; Albrecht et al., 2011; Chronis et al., 2008). The GLM measures radiances at cloud top from all types of lightning (in-cloud and cloud-to-ground) during day and night, which is key to its utility because the in-cloud lightning dominates in severe storms. Additionally, a rapid increase or "jump" in total lightning associated with vigorous updraft intensification serves as a precursor signature for the occurrence of tornadoes and other severe weathers (hail, wind) at the ground (Williams et al., 1999; Gatlin and Goodman, 2010; Schultz et al., 2011).

The GLM conceptually is a high speed event detector operating in the near infrared. Because of the transient nature of lightning, its spectral characteristics, and the difficulty of daytime detection of lightning against the brightly lit cloud background, actual data handling and processing is much different from that of a simple imager. As with LIS, a wide field-of-view (FOV) lens combined with a narrow-band interference filter is focused on a high speed Charge Coupled Device (CCD) focal plane. Signals are read out in parallel from the focal plane into real-time event processors for event detection and data compression. The resulting event detections are formatted, queued, and sent to the satellite's Local Area Network (LAN).

The GLM performance characteristics are summarized in Table 1. The GLM 1372 × 1300 pixel CCD focal plane will stare continuously at storms from the GOES-E (75 W) and GEOS-W (137 W) position (Fig. 2). For comparison, the low Earth-orbiting LIS and OTD instruments each had a 128 × 128 pixel CCD providing total observation time of only ~90 s (600 km × 600 km instantaneous coverage) to 3 min (1300 km × 1300 km instantaneous coverage) for a given storm within its field of view (FOV). Even though GLM is in geostationary orbit and has nearly hemispheric FOV coverage, its resolution at nadir is equivalent to that of OTD (i.e., 8 km) and increases to only ~14 km at the edge of the FOV. The near-uniform spatial resolution across the GLM FOV is accomplished by a novel variable pitch pixel CCD focal plane design that has larger pixels near the center and smaller pixels towards the outer edges of the CCD (Christian and Aamodt, 2011). The flash detection efficiency (probability of detection) requirement is 70% detection with 5% false alarms (non-lightning events reported as lightning). The 70% flash detection is a GLM instrument Level 1 operational requirement performance specification stated in the Level 1 Requirements Document (refer to Goodman et al., 2012a, b). The specification was developed/accepted by the user community as the minimum achievable flash detection during a 24-hour period anywhere in the GLM field of view that would still provide operationally useful total lightning data. At the time of the GOES-R Program Critical Design Review (CDR) in November 2012 the vendor estimated that their design would achieve 86% flash detection, well above the stated requirement. A combination of spatial, temporal, and spectral filtering is used to achieve the high detection efficiency as with the LIS instrument (Christian et al., 1989; Mach et al., 2007). A solar blocking filter at the front aperture of the instrument works in combination with a solar rejection filter to limit out-of-band light from entering

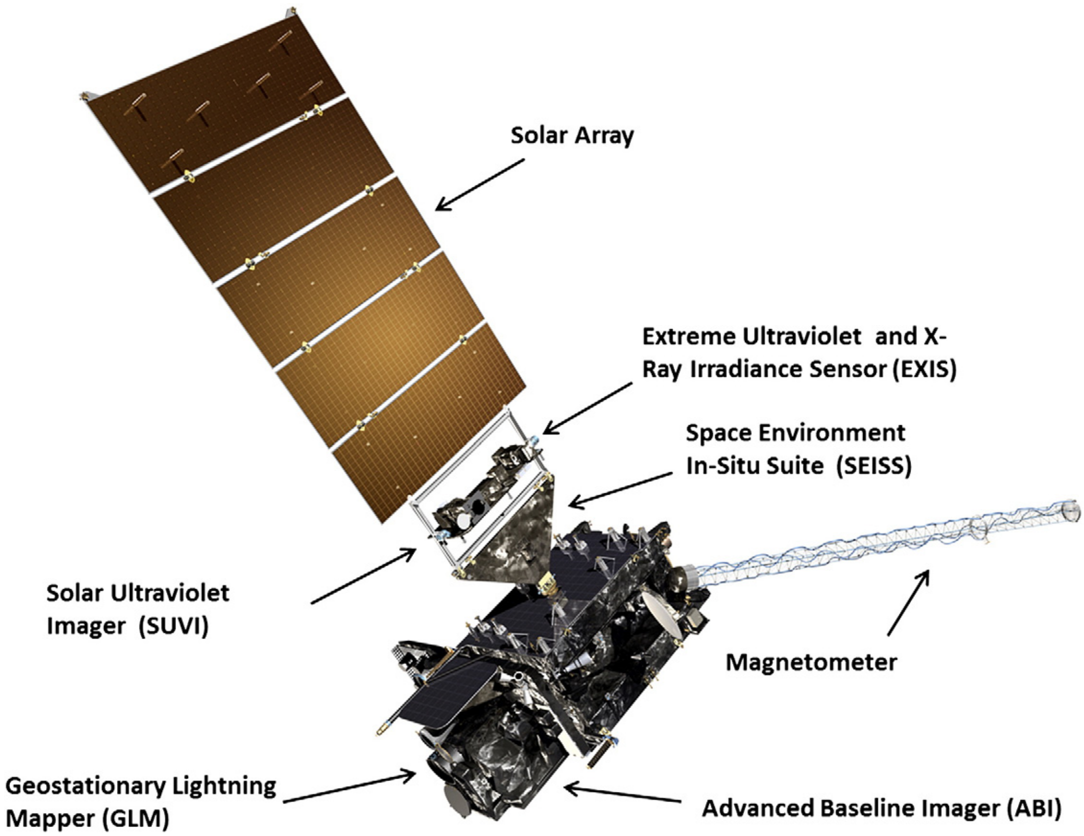


Fig. 1. The GOES-R spacecraft and instruments.

the instrument (Fig. 3). The additional 1-nm narrow-band interference filter as with the LIS instrument ensures the 777.4 OI (1) oxygen triplet is passed to the detector.

The GLM detection efficiency is expected to exceed the 70% performance requirement with flash detection perhaps as high as 90%. This is accomplished, in large part, by increasing the telemetry downlink rate to 7.7 mbps which allows for a lower threshold setting to detect weak lightning optical pulses and ground processing that will filter out the non-lightning events. The telemetry downlink is sized to also accommodate the background data, which are reported every 2.5 min to aid in navigation and registration. While the LIS used similar filters in its ground processing algorithms, the LIS only had a telemetry bandwidth of 8 kbps and needed a higher threshold setting to avoid buffer overflow and saturation during overpasses of storms with high flash rates. Because the GLM is an operational instrument, minimal latency is important. The instrument vendor is allocated 10 s to collect, filter, geo-locate and time tag the raw data into Level 1B lightning events. After Level 1B processing (instrument data at full resolution with radiometric and geometric correction applied to produce parameters in physical units), the Level 2 Lightning Cluster Filter Algorithm (LCFA) described in the GLM AWG Algorithm Theoretical Basis Document (ATBD) performs temporal–spatial clustering of the lightning event data into groups (akin to return strokes and k-changes) and flashes (Mach et al., 2007; Goodman et al., 2012a,b). The concept of the LCFA is closely based on the heritage OTD/LIS data processing algorithm in that it builds a parent–child tree-structure that identifies the clustering of optical events into groups, and groups into flashes (Fig. 4). The three components of the GOES-R Lightning Detection product (event, group, flash) provide continuity with the combined LIS/OTD climatology that begins in April 1995 with the launch of the OTD. This component information can then be used to locate the initiation, propagation and horizontal extent of an individual flash within the GLM field of view. The

Table 1
GLM performance characteristics.

CCD imager	1372 × 1300 pixels
FOV (across)	Full disk
Pixel FOV (nadir)	8 km
Pixel FOV (corner)	14 km
Wavelength	777.4 nm
Frame rate	2 ms
Downlink data rate	7.7 mbps
Product latency	<20 s
Total mass	125 kg
Average operational power	405 W
Volume (height, width, depth)	149 cm × 63.5 cm × 65.8 cm

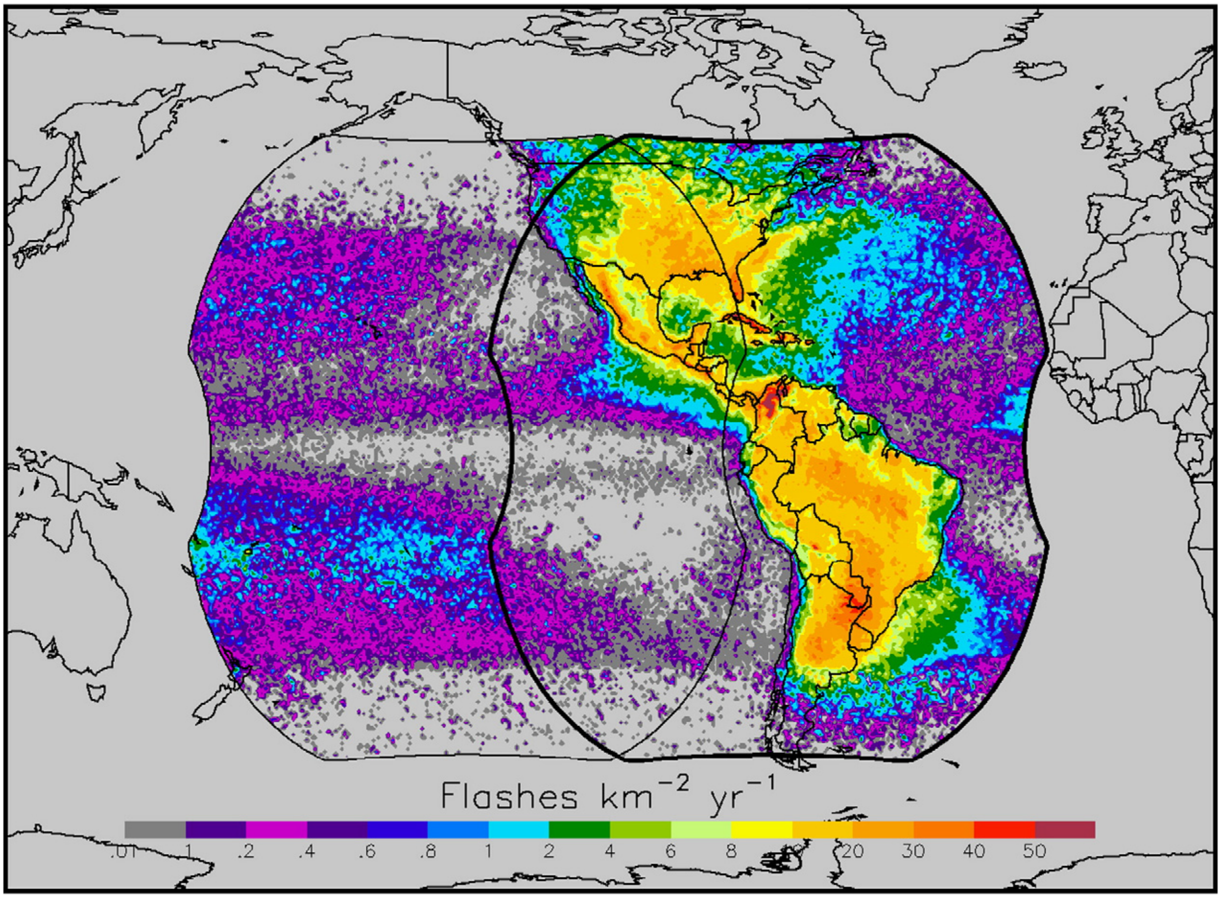


Fig. 2. Combined FOV view from the GOES-R series constellation (75 W, 137 W) superimposed on 10-yr of lightning observations from the NASA Lightning Imaging Sensor on board the Tropical Rainfall Measuring Mission (TRMM/LIS) and Optical Transient Detector (OTD) low earth-orbiting satellites (Cecil et al., 2012).

entire data production chain from event detection at the satellite to user access via satellite downlink from the GOES Rebroadcast (GRB) or the NOAA Satellite Operations Facility (NSOF) is designed to be <20 s.

3. Ground processing algorithms

3.1. Primary sensor data

The LCFA only requires the Level 1b pixel-level event data as input. This includes the event pixel time-stamp, the (x, y) pixel address within the focal plane array, the associated geolocation of the center of the event in latitude/longitude coordinates, the raw event amplitude in counts, and the calibrated event optical energy (in Joules). The input data are time ordered.

To obtain this dataset, the satellite data stream needs to be decoded, filtered, and clustered, and output to the appropriate file. The LCFA only generates the lightning dataset. Specifically, the LCFA receives as input the Level 1b pixel-level optical “event” data and processes this data into more convenient lightning data products that are easily utilized by the scientific research and broader operational user communities. Therefore, the LCFA must ingest the event data and assemble the higher level clustered lightning data products (event, group and flash), and in so doing, generate derived lightning characteristics associated with these higher level products. It will also interrogate individual flashes, groups, and events on a statistical basis to see if they are associated with lightning or noise. Definitions of the basic data\classes that drive the LCFA are provided below.

3.1.1. Background data

The AWG Lightning Detection product does not use the background scene information in the LCFA, but it has been included here for perspective. A background image is a “snap shot” of the background estimate made possible by the GLM Real-Time Event Processors (RTEPs); because of the large FOV, the GLM instrument employs several RTEPs. The background image is transmitted in the data stream along with event data. When the transmission of one background is begun, the next background image is captured. New images are sent to the ground every 2.5 min and are available to aid in the GLM navigation and registration. Though the background image is not used by the LCFA, it has valuable scientific uses; e.g., it provides the geographical distribution

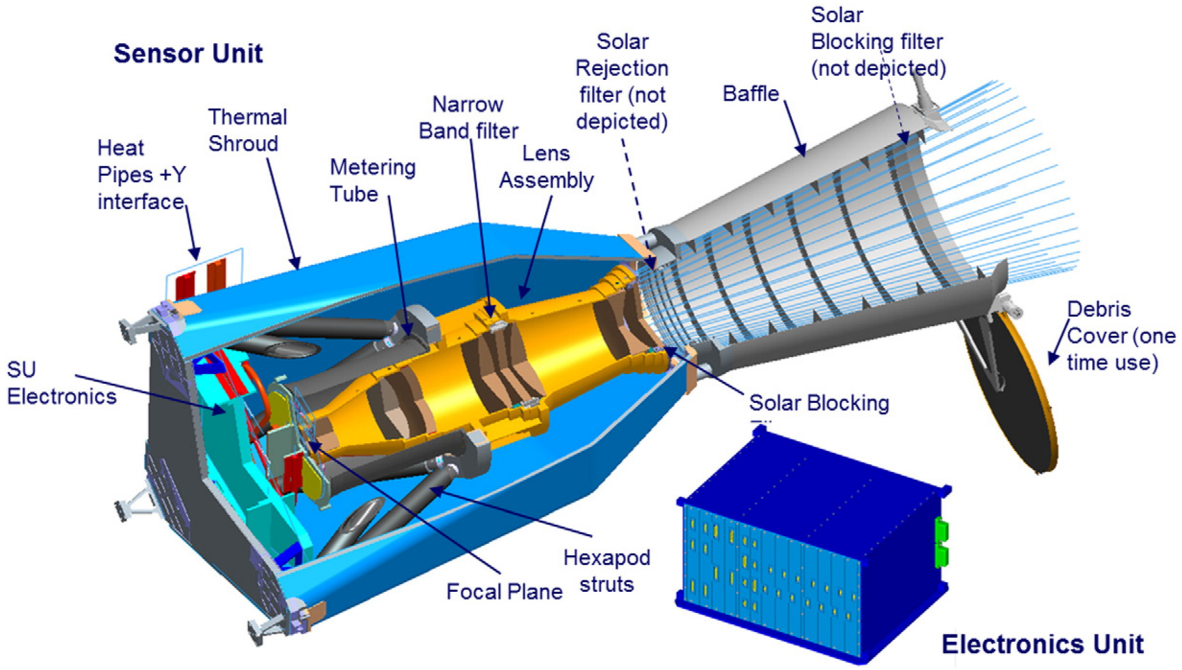


Fig. 3. The Geostationary Lightning Mapper (GLM) consists of a sensor unit (SU) and electronics unit (EU). An engineering development unit prototype was developed before the first production flight model (FM1) to reduce risk in the instrument development.

of clouds in the near infrared over which the lightning occurs and provides a means to monitor any long term change/ performance degradation of the CCD detector (Buechler et al., in press).

3.1.2. Event data

An event is defined as the occurrence of a single pixel exceeding the background threshold during a single frame. In other words, each pixel output from the RTEP produces a

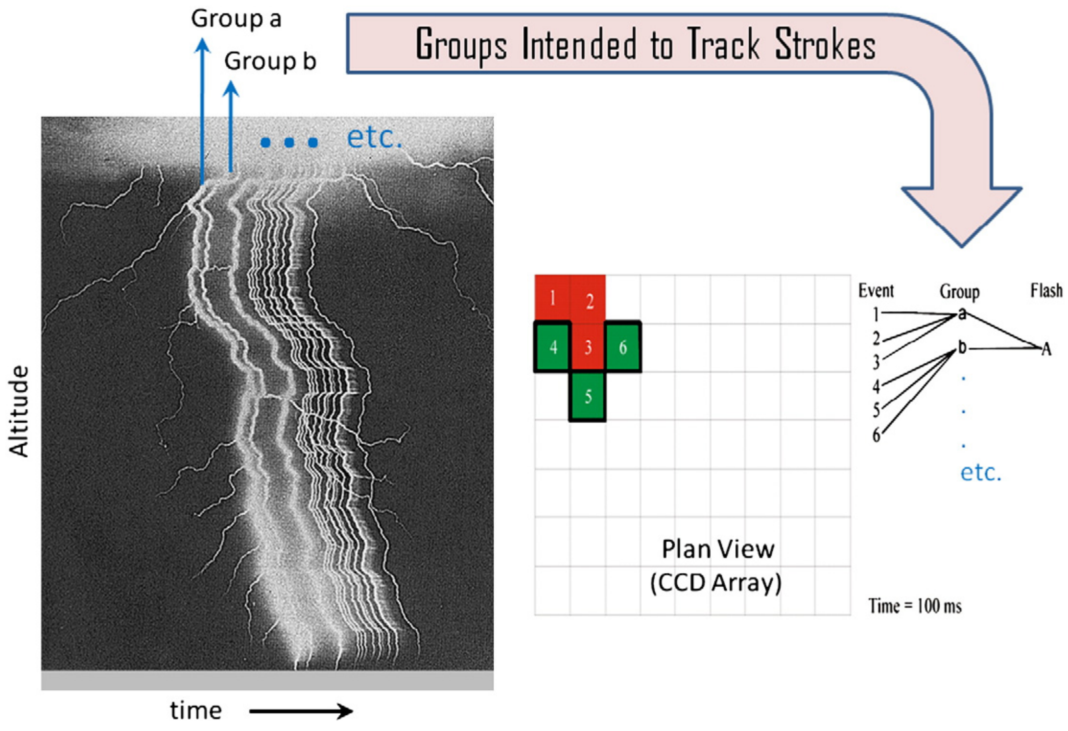


Fig. 4. Optical groups attempt to track bright transient emissions from lightning. Inter-stroke processes (return strokes, k-changes) also produce optical groups [Photograph is of a 12-stroke lightning flash near Socorro, New Mexico; Marx Brook, New Mexico Institute of Mining and Technology].

separate event. The Level 1b GLM instrument data consists of time, (x, y) pixel address, latitude and longitude locations, and calibrated amplitude of the event. An event is the basic unit of data from the GLM.

Although an event can be thought of as a single optical pulse due to lightning, it is possible that multiple pulses occurring within the 2 ms integration window may contribute to an event. Therefore, just as for OTD/LIS, we purposely did not use 'pulse' or 'stroke' (or other similar name) to describe the basic unit of data from the GLM. Note that an event may sometimes not be due to lightning at all. It may be produced by noise in the data stream exceeding the background threshold. In that case, the event is a false alarm. When the LCFA determines that an event has a non-zero probability of being from a non-lightning source, it will be marked as such in the data, but it will still be clustered along with the lightning data.

3.1.3. Group data

A lightning discharge will often illuminate more than one pixel during a single integration time. The result is two or more adjacent events within the same time frame. When these multiple events are adjacent to each other (a side or corner of the events touching), they will be placed in a single group. The formal definition of a group is one or more simultaneous events (i.e., events that occur in the same time integration frame) that register in adjacent (neighboring or diagonal) pixels in the focal plane array. A group may consist of only one event or include many events. The location data for a group will be calculated in Earth-based (latitude/longitude) coordinates. This is done to provide consistent representation in the group/flash processing and because the ultimate goal of the analysis is to locate lightning with respect to the Earth's surface.

Although a group may often correspond to a single lightning optical pulse, it is also possible that multiple lightning pulses occurring within the 2 ms integration window may contribute to a group. A false event due to noise at a pixel exceeding the background threshold can also contribute to a group (although noise groups often contain only one event). Note that if an event can be assigned to more than one group, all of the groups it can be assigned to will be combined into one group (and then the event added to it).

3.1.4. Flash data

A lightning flash consists of one to multiple optical pulses within a specified time and distance. For the GLM algorithm, we define a flash as a set of groups sequentially separated in time by 330 ms or less and in space by no more than 16.5 km (nominally two pixels) in a weighted Euclidean distance format. Note that for two (or more) groups to be considered part of the same flash, any two events in the two groups can meet the 330 ms and 16.5 km spacing. In other words, for the GLM algorithm, we do not use the group centroids to determine if two (or more) groups are part of the same flash. The criteria are based on the heritage Lightning Imaging Sensor and Optical Transient Detector algorithms and their combined 15-years of on-orbit observations as well as published statistics of flash duration. Effectively, the 16.5 km represents a gap of more than one pixel between one flash and the next. A sensitivity study in Mach et al. (2007) showed that this approach is robust. The temporal and spatial rules can be easily adjusted in the GLM algorithm processing software. We will continue to examine the rules closely during the analysis of OTD, LIS, and GLM data to "fine tune" the rules defining a flash. A flash may include as few as one group with a single event or it may consist of many groups, each containing many events. Spatial characteristics for a flash (and all higher level parameters) are calculated in ground coordinates (i.e., latitude and longitude). Fig. 5 provides an illustrative example of a GLM flash with its component event and group data compared to the individual VHF radiation sources of a lightning channel that would be observed by a typical Lightning Mapping Array network.

The above definition of a "flash" will usually produce results that correspond to the customary definition of a conventional lightning flash. Presently, GLM data alone cannot determine if an individual flash is a ground or cloud flash. However, progress has been made in developing an algorithm that estimates the ground flash fraction in a large set of *N* flashes observed by a satellite lightning imager (Koshak, 2010; Koshak and Solakiewicz, 2011; Koshak, 2011). In addition, future applications of the GLM algorithm may incorporate data from ground flash lightning location systems so that flash type can be determined on a flash-by-flash basis. We do acknowledge that, on occasion, distinct conventional lightning flashes may result in a single flash being produced by the GLM algorithm

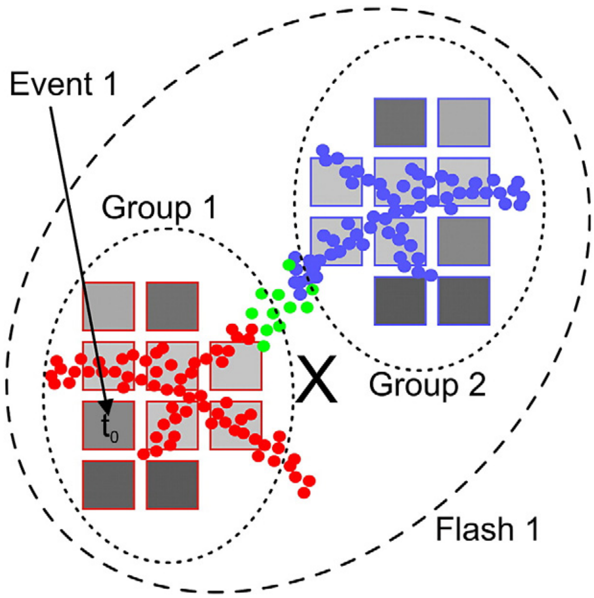


Fig. 5. Illustration of a single GLM flash composed of 2 groups and 20 events relative to a LMA VHF lightning channel. In this example the dots (red, green, blue) are LMA VHF sources and the gray squares are (simulated) GLM data. Time is indicated by color with Red occurring first, Green next, and Blue last. The GLM radiance is indicated by greyscale (darker = greater amplitude). The amplitude weighted flash centroid is indicated by the large X. The time tag for the flash is the time of the first event, labeled t_0. The two groups (red & blue) are close enough in time/space to be clustered into a single flash (16.5 km & 330 ms). In this example, the green LMA pulses did not create an optical pulse large enough to be detected by the (simulated) GLM (below threshold).

Table 2
Correlative lightning data for GLM.

Data source	Instrumentation description	Data coverage	Product
Lightning Mapping Array (LMA)	VHF time-of-arrival network	Regional, ~200 km range	Total lightning
HAMMA (Huntsville Alabama Marx Meter Array)	Electric field-change ΔE time-of-arrival network	Huntsville, AL ~100–200 km	Total lightning
High speed video	High speed digital video camera operating at tens of thousands of frames per second	Individual flash components	Total lightning, primarily channels visible below cloud base
Field Mill Network (Kennedy Space Center)	Electric field network	~40 km	Electric field
Vaisala National Lightning Detection Network (NLDN)	LF Lightning detection network	CONUS	Primarily ground flash location time, peak current, multiplicity, some intracloud
RINDAT	LF lightning detection network	SE Brazil	Primarily ground flash location/time
Earth Networks Total Lightning Network (ENTLN)	LF–HF lightning detection network	Regional-CONUS, Brazil	Total lightning
Met Office ATDnet	VLF lightning detection network	Europe, Africa and adjacent oceans	Primarily ground flash location/time
World Wide Lightning Location Network (WWLLN)	VLF lightning detection network	Global	Primarily ground flash location/time
Vaisala GLD360	VLF lightning detection network	Global	Primarily ground flash location/time
TRMM Lightning Imaging Sensor (LIS)	Optical lightning detection from Low-Earth Orbit	Tropics $\pm 35°$ lat	Total lightning-events, groups, flashes
Airborne GLM Simulator	Optical and Electric field-change ΔE from high-altitude airplane (ER-2, Global Hawk)	Concurrent under-flights of GLM	Total lightning

(e.g., possibly in high flashing rate mesoscale convection systems). Other mismatches between algorithm flashes and actual conventional flashes will undoubtedly also occur. Note that there is no absolute time limit to a flash. That is, as long as subsequent groups are produced in an area within the 330 ms time windows, all groups will be assigned to a single flash. However, practical considerations do limit the total size and time span of a flash. Also note that if a group can be assigned to more than one flash, all flashes it can be assigned to will be combined into one flash (and then have the group added to it).

4. Calibration/validation

The goal of GLM validation is to ensure that GLM product components (event, group, flash) are adequately detected and accurately located in space and time within the required latency. Assessments are determined (primarily) by comparisons to a variety of external (independent) data sources of comparable or higher accuracy in locations for which we have overlapping regions of coverage. As the GLM has a large region of coverage, a variety of techniques need to be applied in varying parts of its domain, depending on the reference data's characteristics. The LCFA algorithm validation addresses several factors including accuracy of the scientific results produced by the algorithm, value of the scientific results, computational speed of the algorithm, feasibility of testing the algorithm (clarity/completeness of algorithm performance metrics, ability to generate laboratory demo results using simulated data inputs), and feasibility of implementing the algorithm on-orbit.

For GLM products, the validation includes comparison with other available data, monitoring LCFA data quality, and statistical analysis. The GLM results will be compared to cloud and other lightning data to verify the GLM performance. The LCFA monitoring flags (metadata) in the L2 data stream indicate problems such as when clustering processing was truncated to meet processing latency limits. The statistical analysis assesses the reasonableness of lightning product statistics.

The GLM lightning product validation will make use of available space-based observations from the LIS and from the following additional sources: (1) available satellite lightning photometers such as the FORMOSAT-2 Imager of Sprites and Upper Atmospheric Lightning (ISUAL) experiment and TARANIS (Tool for the Analysis of RAdiation from lightNIng and Sprites), (2) high altitude long-duration airborne optical and electrical measurements from an Airborne GLM Simulator package that can be flown aboard the NASA ER-2 and Global Hawk UAV, and (3) ground-based lightning and electric field-change detection networks including one or more super-sites such as north Alabama and central Oklahoma where diverse meteorological instrumentation is available for characterizing lightning and their parent storms (Table 2). TARANIS, scheduled for launch in 2015 by CNES/France, will have two cameras and four photometers in a nadir staring configuration offering direct comparison with GLM data. The 2018 planned launch of the Meteosat Third Generation-Lightning Imager (MTG-LI) will allow cross-calibration with GLM over portions of the Atlantic Ocean and South America.

Routine validation will monitor instrument health, instrument degradation, individual pixel sensitivity and Image Navigation and Registration (INR). Instrument health and operation will be monitored by ingesting Instrument Calibration Data and other metadata on a continuous basis. Periodic reports on deep convective cloud analyses (Buechler et al., in press) and other physical target analyses will flag instrument degradation. Periodic reports on pixel fidelity will be used to assess the sensitivity of individual pixels. INR will be monitored using periodic reports on IR background (from ABI and GLM) and laser beacon analysis. If needed, INR can also be assessed using lightning ground truth at night.

4.1. Proxy data

Proxy data and test data sets have been generated from several sources. Some proxy datasets are based on National Lightning Detection Network (NLDN; Cummins and Murphy, 2009) data, some are based on empirically mapping ground-based VHF 3-D Lightning Mapping Array (LMA; Rison et al., 1999) data into optical data, some are based on simply resampling heritage LIS data (Mach et al., 2007) into the GLM FOV and pixel spacing, and some are based on artificial sources. Each type of proxy is used to test different parts of the LCFA and can be used to test subsequent application algorithms (Gatlin and Goodman, 2010; Schultz et al., 2009, 2011).

The advantage of using NLDN data is that it has a broad coverage area (near full GLM FOV) and can extend over long periods of time. The disadvantage of NLDN based proxy is that we have to estimate the contribution (time and spatial) of cloud flashes. An example of NLDN based proxy is shown in Fig. 6. A very electrically active storm day with max rates > 50,000 fl hr^{-1} was identified (July 21, 2003). These data were then used to test the ability of the LCFA to handle large, realistic flash rates. That is, the realistic high flash rates of this storm day allow us to test the LCFA computation speed and determine if the algorithm can comply with data latency requirements. The total flash rates are estimated from the NLDN ground flash rates by making reasonable assumptions about the cloud flash to ground flash ratio. The ratio averages about 2.94 (Boccippio et al., 2001).

The advantage of VHF based proxies is that the flash detail provided by the VHF mapping is actually greater than what is seen by the GLM instrument (Thomas et al., 2000). The disadvantage of VHF based proxies is their limited spatial and temporal extent. The data are limited to within a few hundred kilometers of the network center. Storms that move outside the range of the network are not detected. To create a proxy that contains realistic spatio-temporal thunderstorm evolution, concurrent LIS and ground-based lightning VHF observations have been compared to construct an empirical model that is capable of mapping VHF lightning observations to optical emissions. This approach, for example, allows one to simulate the spatio-temporal characteristics of event-based (pixel-level) data detected by GLM by applying the empirical model to a database of VHF lightning observations from several thunderstorms.

Fig. 7 shows the display output of a tool that animates the coincident data files by inter-comparing the event and flash components from LIS and LMA data to develop an empirical mapping between the two. The map is then used to convert LMA data from case study storms into GLM resolution pixels to produce a Level 1b proxy. Ground-strike networks such as the NLDN can provide additional information to characterize the proxy data. The LMA does not identically measure the same ΔE electric field-change process more closely associated with the optical pulse events detected by the LIS or with the GLM (Christian and Goodman, 1987; Goodman et al., 1988; Thomas et al., 2000; Mach et al., 2005). While the LMA provides high detection efficiency at the flash level, it is sensing physical processes in the flash that do not produce much light. Hence the correspondence between LMA & LIS is possible on a flash-to-flash basis, but not on the sub-flash details. For this reason we envision an Airborne GLM Simulator package for on-orbit check-out and routine performance monitoring to verify the optical signals observed by GLM and those confirmed by the optical and electric-field change measurements taken from high altitude airplanes and ground-based systems.

The advantage of using LIS data to produce GLM proxy data is the source is very similar to the GLM (both LIS and GLM are essentially the same instrument, with different FOVs, different resolution, different sensitivities, and processing capabilities).

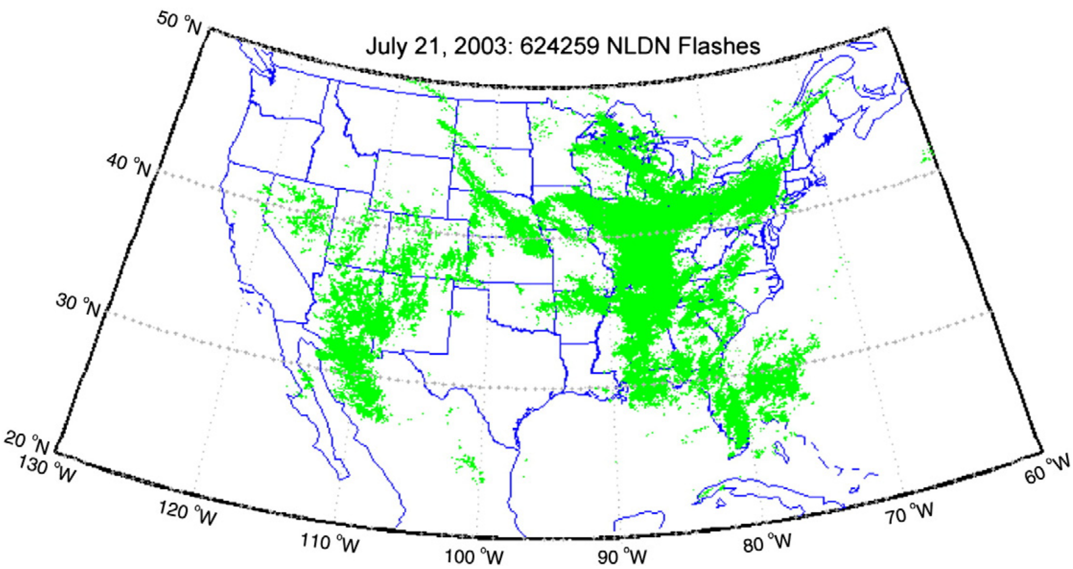


Fig. 6. NLDN proxy data for July 21, 2003 used to test the required processing throughput for the expected maximum expected flash rate. A total of 624, 259 cloud-to-ground flashes occurred in a 24 h period.

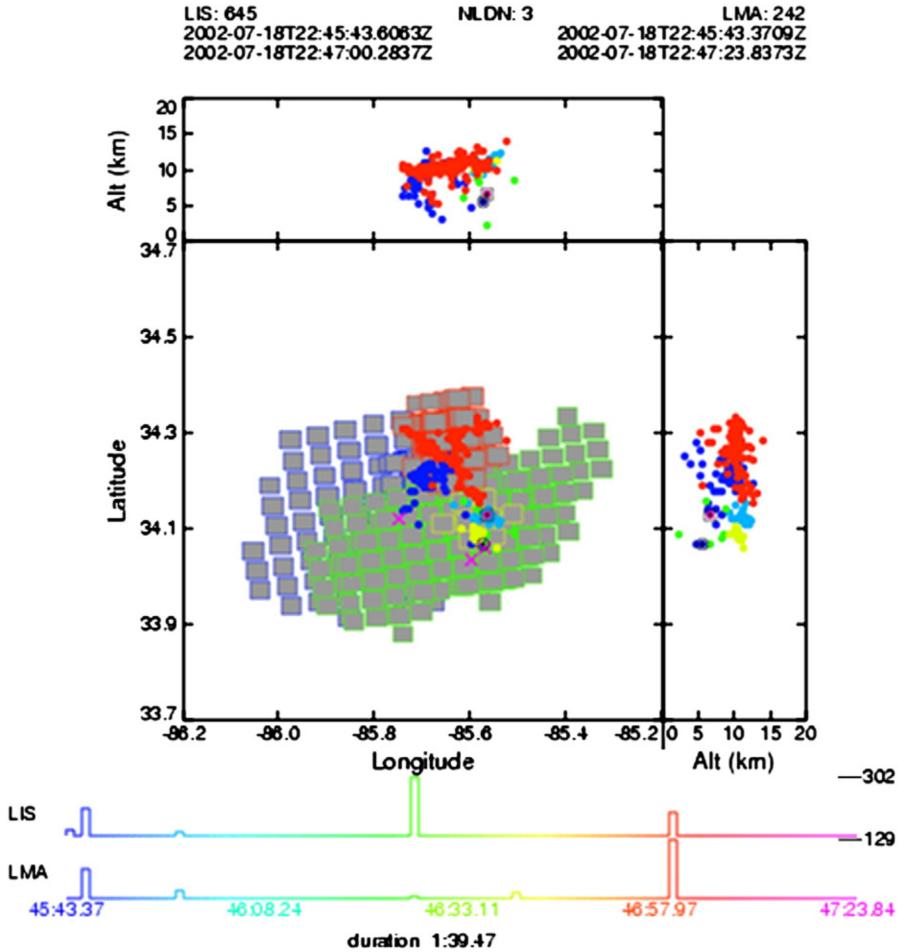


Fig. 7. LIS overpass of the central Oklahoma LMA network. The OKLMA VHF sources are depicted in a horizontal east–west plane and in vertical projection as a function of height and time. The plot contains 2 LIS flashes with 645 events (squares), OKLMA with 242 VHF sources (dots), and NLDN with 3 CG strike points (Xs).

The disadvantage of using LIS data is the FOV for LIS is very limited compared to the GLM. The LIS observes lightning at a higher pixel resolution (4 km at nadir) than the GLM, so a "re-sampled" LIS dataset will allow performance modeling of GLM characteristics over its entire FOV and diversity of background scene viewing conditions. It is relatively easy to resample LIS data at a lower spatial resolution, and the resulting proxy is adequate for completing tests that only require "snapshots" of lightning. In addition, we will also use heritage OTD data near boresight, since this is already ~8 km resolution.

The advantage of using artificially produced proxy data is that any characteristics of the proxy data can be set by the user. This includes the production of datasets that are quite different than might be expected from a real GLM dataset, but they can be tailored to test specific sections of the LCFA.

4.2. Cal/val field campaigns

Field campaigns provide valuable opportunities to collect more comprehensive data sets than are usually affordable or achievable by one investigator or even a single mission or agency. Inter-agency and international field campaigns have a long history of providing these opportunities to leverage resources. For GOES-R, and GLM in particular, we expect a number of pre- and post-launch experiments that can augment the GLM Testbed super site data sets, for developing more robust and realistic proxy data as well as for algorithm validation. The challenge for GLM is that there is no current geostationary lightning mapper to serve as a source of proxy data, unlike the case for the GOES-R ABI where quite extensive and representative proxy data sets can be developed from the geostationary GOES, MTSAT (Japan), or Meteosat Second Generation (MSG) 12-channel SEVIRI (Spinning Enhanced Visible and Infrared Imager), or the NASA 32-channel Moderate Resolution Imaging Spectroradiometer (MODIS) and recently launched 22-channel Visible Infrared Imager Radiometer Suite (VIIRS) with high spectral and spatial resolution in low Earth orbit. Thus, the OTD and LIS overpasses of instrumented ground sites present one of the better opportunities to develop and validate the pre-launch algorithms for GLM.

A recent opportunity to collect more comprehensive lightning and ancillary meteorological data took place between November 2011 and March 2012 in southeast Brazil during the

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)) Vale do Paraíba field campaign. The CHUVA experiment domain of southeastern Brazil is one of the more active thunderstorm regions in the Americas (Pinto et al., 2007; De Souza et al., 2009).

The primary science objective for the GLM-CHUVA lightning mapping campaign is to combine measurements of total lightning activity, lightning channel mapping, storm microphysics, and meteorological data to improve our understanding of thunderstorms. The measurements from the 3D total lightning mapping networks include a NASA-deployed São Paulo Lightning Mapping Array (SPLMA) and a number of regional and global ground-based lightning networks provided by government and commercial data providers (Fig. 8). These measurements were collected during LIS overpasses coincident with electric field mills, field change sensors, high speed cameras and other lightning sensors, dual-polarimetric radars, and meteorological data, which will allow for excellent cross-network inter-comparisons and performance assessments, and construction of a well characterized proxy data set for both GLM and the MTG-LI to advance algorithm development (Fig. 9). Finally, the diverse set of total lightning data coincident with SEVIRI (and MODIS, VIIRS) offers a unique opportunity to develop entirely new applications combining the imager and lightning (e.g., convective precipitation, aviation weather hazards, severe storms, nowcasting) so that they will be ready for operational use soon after the planned launch of GOES-R and MTG.

5. Risk reduction science

The GOES-R science program supports the development of new or enhanced concepts, products and services that more fully utilize and extend the full capabilities of GOES-R well into the next decade. These include innovative ideas for multi-instrument blended satellite products such as combining the information from the ABI and GLM (and radar where available) to detect, diagnose, and forecast convective initiation, evolution and potential storm severity (McCaul et al., 2009; Schultz et al., 2011; Mecikalski et al., 2013); improving forecasts of rapid intensification and weakening of tropical cyclones (DeMaria et al., 2012); identifying aviation weather hazards in the terminal area and data sparse oceanic regions (Harris et al., 2010); discriminating convective from stratiform rain areas (Xu et al., 2013) and better characterization of potential flash-flood producing storms in complex terrain, or using the ABI and GLM information combined with the Global Precipitation Mission dual frequency radar and microwave radiometer constellation to improve quantitative precipitation

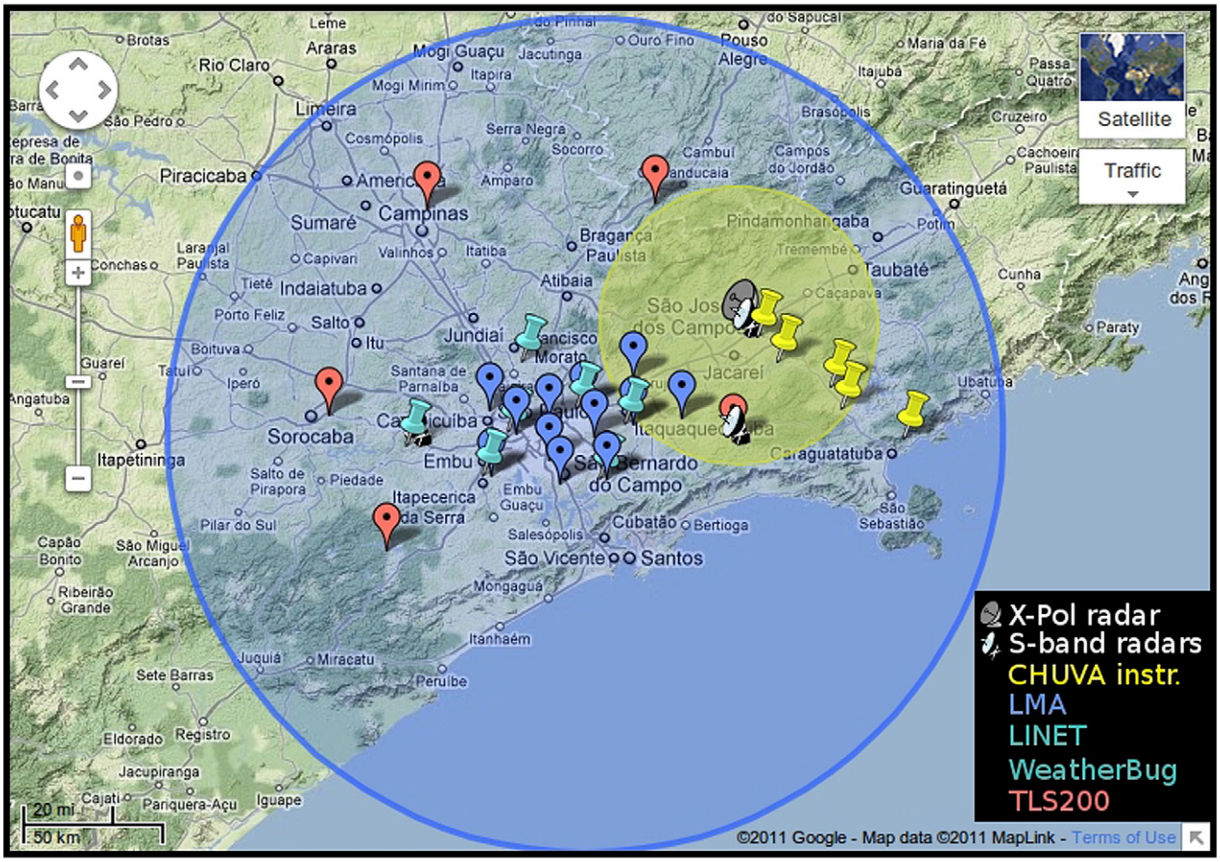


Fig. 8. Balloons and pushpins show the configuration of select lightning networks deployed in the vicinity of São Paulo for the CHUVA Vale do Paraíba campaign from November 2011–February 2012. The x-band polarimetric radar sits atop a building at the Univap — University of Vale do Paraíba Technological Park in São José dos Campos dos Campos (courtesy of Rachel Albrecht).

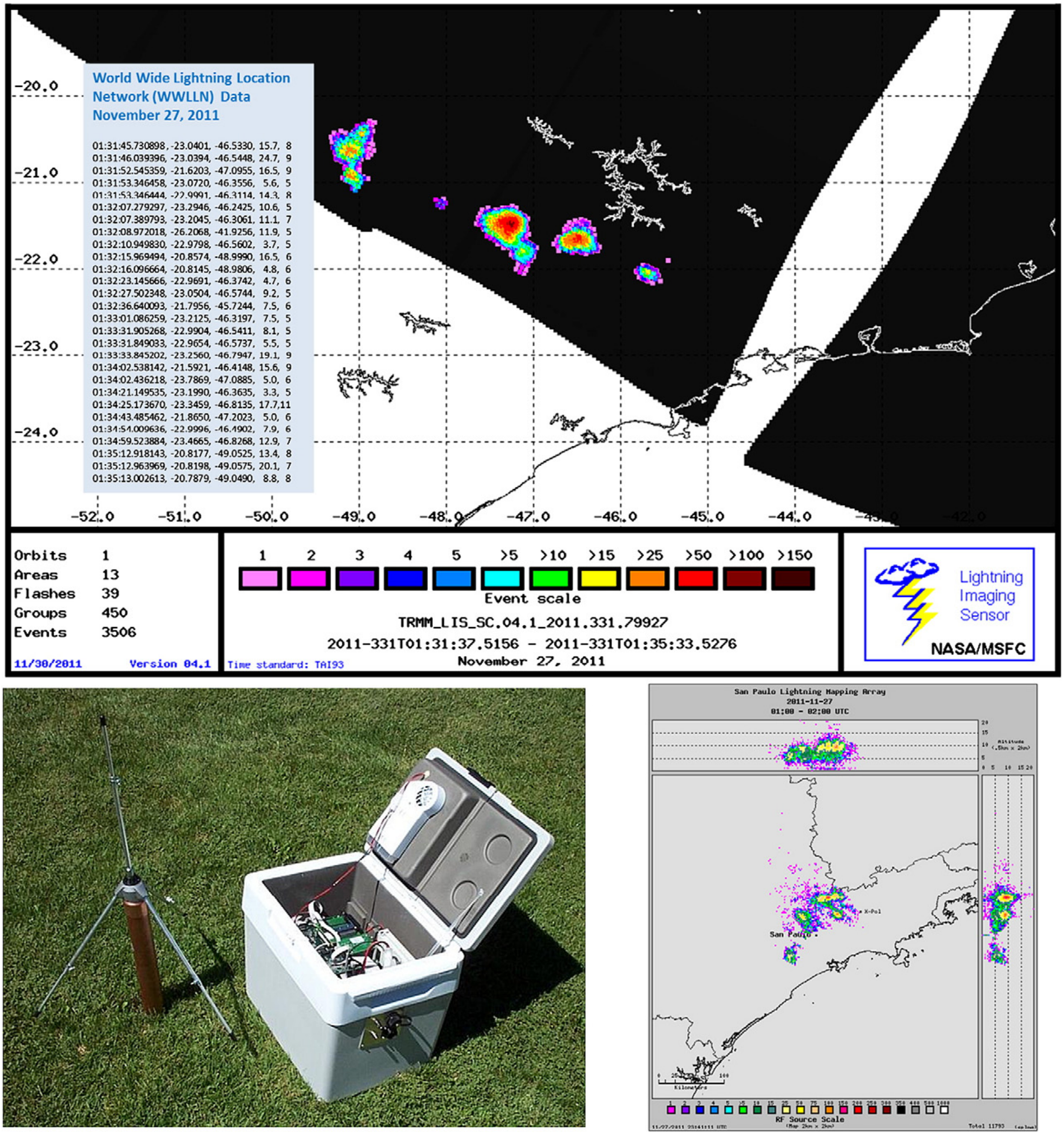


Fig. 9. São Paulo Lightning Mapping Array (SPLMA) station showing the VHF (Channel 8, 162 MHz) ground plane antenna, sensor electronics and computer package (lower left). Plot with horizontal and vertical projections of 1-hour source density for 0100–0200 UTC on 27-Nov-2011 (lower right) encompassing the LIS overpass 0131–0135 UTC and WWLLN observations (above).

forecasts (QPF); and the assimilation of total lightning data as a proxy for strong convection into cloud-resolving numerical weather prediction models (Fierro et al., 2012).

5.1. Lightning data assimilation and numerical weather prediction

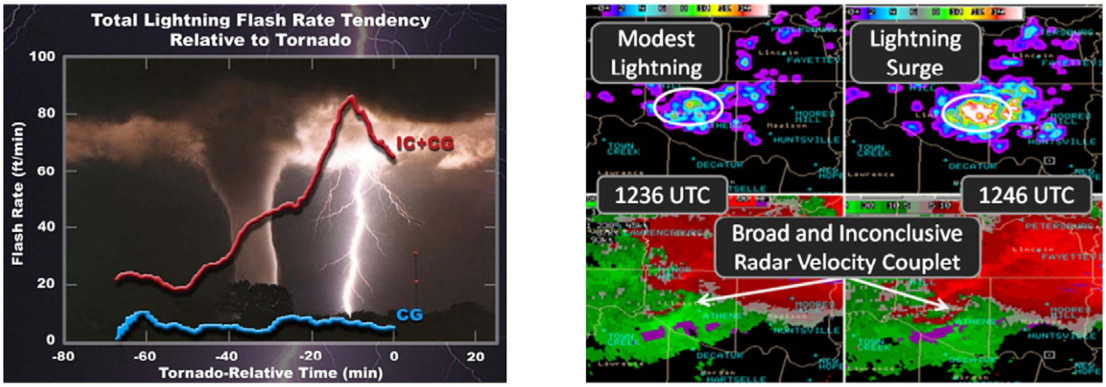
With higher resolution global and regional cloud-resolving numerical weather prediction models (e.g., Weather Research and Forecast, High Resolution Rapid Refresh) and advanced 3DVAR, 4DVAR, Ensemble Kalman Filter (EnKF), and hybrid data assimilation methodologies in widespread use this decade, there will be ever expanding possibilities for GLM lightning data assimilation to have a positive impact on the model forecast, especially in data sparse regions (Chang et al., 2001; Papadopoulos et al., 2005; Mansell et al., 2007; Pessi and Businger, 2009; McCaul et al., 2009; Barthe et al., 2010; Yair et al., 2010; Fierro et al., 2012; Lynn et al., 2012). These methodologies owe their success to the high degree of correlation widely observed between lightning and the cloud microphysical parameters and updraft intensity. Total lightning data provides improved initial conditions with a better constrained physical background and can limit spurious convection at model analysis time. Current research (e.g., Fierro et al., in press) is exploring the potential of 1-dimensional charging/discharge physics to alleviate or supplement the use of microphysical proxies. Not only might GLM data be assimilated into the model forecast analysis, but in the same way that the WRF simulated satellite cloud and moisture imagery is validated by GOES satellite observations, one can envision that the GLM will be used to validate NWP forecasts of lightning (Goodman et al., 2012a,b).

5.2. Severe weather warnings

A recent study of over 700 storms by Schultz et al. (2011) further supports the potential value of monitoring total lightning activity applicable to the GLM to increase tornado and severe storm warning lead-time and reduce the false alarm rate (Williams et al., 1999; Schultz et al., 2009; Gatlin and Goodman, 2010). The current operational warning approach relies heavily on weather radar signatures and visual cues from storm spotters, resulting in a national average tornado warning lead-time of 13 min with a false alarm rate of nearly 0.8 (Stensrud et al., 2009). A rapid increase or "jump" signature in total lightning rates, and which is dominated by the in-cloud lightning activity, is closely coupled to updraft intensification that produces both effective charging in the mixed phase region of the storm and enhances vortex stretching, occurs in advance of the tornado and severe storm damage at the ground. Their result suggests the warning lead-time can be increased to 21 min on average with a reduced false alarm rate of less than 40% (Fig. 10). While big supercells may produce clear Doppler radar gate-to-gate shear indications of rotation, there are still many storms that are less clear on radar. The total lightning provides a new indicator that can aid forecaster situational awareness and confidence that severe weather may be imminent, leading to earlier warnings. The lightning indicators are especially useful for detecting severe storms at night, in humid environments, and in complex terrain where storm spotters, radar beam blockage and visible satellite imagery are less effective.

6. GOES-R Proving Ground and forecaster training

The GOES-R Proving Ground is one of the primary means to accelerate user readiness for the new capabilities that will be provided by the GOES-R satellite series (Goodman et al., 2012b; Ralph et al., in press). To ensure user readiness, forecasters and other users must have access to prototype advanced products within their operational environment well before launch. Examples of the advanced products include improved volcanic ash detection, 1-min interval rapid scan imagery, convective initiation, synthetic cloud and moisture imagery, and lightning detection. A key component of the GOES-R Proving Ground is the two-way interaction between



Skill scores and average lead times using the sample set of 711 thunderstorms for both total lightning and CG lightning, correlating trends in lightning to severe weather.

	POD	FAR	CSI	HSS	lead time (all)	lead time (tornado)
Total lightning	79%	36%	55%	0.71	20.65 mins	21.32 mins

Fig. 10. Typical time series of total (in-cloud (IC) and cloud-to-ground (CG)) lightning and CG-only lightning flash rate trend relative to tornado touchdown (above left). This depiction shows the high flash rates dominated by the IC flashes in advance of the tornado touchdown. Total lightning flash density time rate-of-change over a ten minute interval showing VHF source density (upper panels on right) from the North Alabama Lightning Mapping Array (NALMA) and NWS WSR 88D Doppler radar velocity (lower panels on right) from the Hytop, AL NEXRAD during tornadogenesis. The "jump" increase in lightning activity is associated with updraft intensification which in turn results in increased electrification and lightning activity, and vortex stretching prior to tornado touchdown. These types of products, derived from the GLM, will be available to forecasters in their decision support system (Advanced Weather Interactive Processing System, AWIPS-II) to aid in the warning decision-making process. Skill score and lead-time are after Schultz et al. (2011).

the researchers who introduce new products and techniques and the forecasters who then provide feedback and ideas for improvements that can best be incorporated into NOAA's integrated observing and analysis operations. In the pre-launch timeframe, the GOES-R Proving Ground will test and validate display and visualization techniques, decision aids, future capabilities, training materials, and the data processing and product distribution systems to enable greater use of these products in operational settings.

Two higher order GLM-based lightning products described here, a pseudo GLM (PGLM) flash extent density product and NSSL-WRF simulated lightning threat forecast (McCaul et al., 2009), have been undergoing evaluation at the NOAA Hazardous Weather Testbed in Norman, OK (Fig. 11).

6.1. Lightning detection

The PGLM product utilizes total lightning data from three ground-based LMA networks (Central Oklahoma, Northern Alabama, and Washington DC) and the Lightning Detection and Ranging (LDAR) network at Kennedy Space Center, Florida (having recently updated their total lightning mapping capability with the addition of a LMA network). The real-time lightning data is resampled to the GLM nadir pixel resolution of 8 km and summed into 1- or 2-min intervals, depending on the network, and sorted into flashes using spatial–temporal clustering algorithms available through the Warning Decision Support System — Integrated Information (WDSS-II). Following flash sorting, a Flash Extent Density product which can be looped in AWIPS and trended with time is created at 8-km resolution to match the GOES-R GLM lightning detection event product. The PGLM product is a prototype nowcasting and warning tool that aids forecaster situational awareness by identifying rapidly developing and intensifying thunderstorms with the potential to produce severe or high impact (e.g., microbursts) convective weather (Goodman et al., 2005; Gatlin and Goodman, 2010; Schultz et al., 2009; Schultz et al., 2011).

6.2. WRF lightning forecast algorithm

The WRF lightning threat forecast is a model-based method for making quantitative forecasts of lightning threat. The algorithm uses microphysical and dynamical output from high-resolution, explicit convection runs of the WRF model conducted daily during the Spring Experiment time period. The algorithm uses two separate proxy fields to assess lightning flash rate density and areal coverage, based on storms simulated by the WRF model. One field, based on the flux of large precipitating ice (graupel) in the mixed phase layer near −15 °C, has been shown to be proportional to lightning flash peak rate densities, while accurately representing the temporal variability of flash rates during updraft pulses (McCaul et al., 2009). The second field, based on vertically integrated ice hydrometeor content in the simulated storms, is proportional to peak flash rate densities, while also providing information on the spatial coverage of the lightning threat, including lightning in storm anvils. A composite gridded threat field is created by blending the two aforementioned ice and graupel fields, after making adjustments to account for differing sensitivities to specific configurations of the WRF model used in the forecast simulations. One chief advantage of a physically-based lightning threat forecast is that it predicts a much smaller region for strong–severe thunderstorm activity than would be suggested by more general indicators of potential instability such as CAPE. The regional LMA networks

Fig. 11. Forecasters and researchers discuss the merits of new forecast and warning products and decision aids at the NOAA Hazardous Weather testbed in Norman, OK. Forecasters and algorithm developers work side-by-side during a 5–6 week period each spring. The typical week begins with forecaster training on the products they will be evaluating, followed by three days of forecasts and warnings in an operational setting, and concluding with a debriefing and assessment of product utility.

are used to support the validation of the lightning threat forecasts.

6.3. Training

The GOES-R Proving Ground is both a user and developer of satellite related training. The participants in the Proving Ground activities need to understand the characteristics of the proxy GOES-R products and their utility within NOAA's operational environment. The knowledge user's gain in applying these products is then passed back to product developers, GOES-R and other NOAA program managers, and to the broader user communities outside of NOAA. Forecasters participating in the GOES-R Proving Ground at the NOAA Hazardous Weather Testbed are already finding the total lightning data useful in the warning decision-making process, quoting from forecasters as follows:

- In terms of operational utility, forecasters noted that the Pseudo Geostationary Lightning Mapper (PGLM) total lightning proxy (as viewed from the 1-minute flash extent density) showed "good correlation" with "updraft intensity" and was typically seen "well ahead of the first CG" (cloud-to-ground) flash. Additionally, the total lightning data "pulled focus to individual storms" of interest. This was particularly useful during days that the weather was marginally severe with numerous storms across the county warning area of operations.
- The PGLM provides a preview of the future value of the GLM for air traffic flow management, since aircraft should be routed away from in-cloud lightning as well as cloud to ground lightning.
- "The total lightning data is an excellent tool for monitoring convection, I see much promise for such data in the future…"
- "I utilized it as a situational awareness product …. The PGLM data gave me more confidence in my warning …"
- "We saw several instances where the total lightning was picking up on storms before the AWIPS lightning [NLDN ground strikes] program picked up on them. One could see the utility of this in the future, bringing with it a potential for lightning statements and potentially lightning based warnings."
- "Total lightning data preceded the CG network anywhere from 10–40 minutes. I was able to quickly determine when flash rate was significantly increasing, and then compare with satellite and updraft/downdraft parameters for a nice big picture."
- "I really think it has a lot of functionality and is useful in warning operations. I look forward to it as a product from the GOES-R."

There are numerous sources of training for Proving Ground participants including the GOES-R website, the Cooperative Program for Meteorology Education and Training (COMET), the Virtual Institute for Satellite Integration Training (VISIT), Satellite Hydrometeorology Course (SHyMet) Courses, the Environmental Satellite Resources Center (ESRC), NASA's Short-term Prediction Research and Transition (SPoRT) Center, and Warning Event Simulator (WES) cases. Modules developed for the Proving Ground demonstrations and evaluations provide training material that forecasters can use to best understand how to apply the total lightning data to address their forecast problems. The training modules used in the HWT Spring Program describe total lightning, the GLM, and the PGLM product. Forecasters are provided operational examples, which are available on-line from SPoRT and from the NOAA Learning Management System.

7. Summary and conclusions

The GLM represents the next step in the global observing system for continuous operational high fidelity measurements of lightning on Earth. The GLM flight model #1 is scheduled for delivery in 2013 for integration onto the GOES-R spacecraft for a planned launch aboard an Atlas-V 541 rocket at the end of 2015. The ground processing algorithms are an extension of the algorithms developed for the earlier OTD and LIS research instruments in low Earth orbit. Concepts for the GLM have been explored since the early 1980s culminating with the single telescope design having high detection efficiency for total lightning approaching 90% with near uniform storm-scale spatial resolution owing to the variable pitch pixel detector design. The high detection efficiency is made possible by the data telemetry bandwidth of 7.7 mbps that allows the GLM to be set at a more sensitive (lower) detection threshold and transmit 100,000 events per second (nominally 40,000 lightning events and the remainder noise) to the ground where the ground processing algorithms filter out the non-lightning events.

GLM represents the first operational mission in this family and is designed for 5 years of on-ground storage, 5 years of on-orbit storage, and 10 years of operations while meeting key performance requirements through the mission end-of-life. The initial check-out and post-launch testing will be a minimum of 6 months in duration at 90° W longitude, followed by planned on-orbit storage at 105 W until GOES-R is called into service as a replacement for the current GOES. Users will be able to access the GOES-R data through four primary pathways as follows:

- GOES-R Rebroadcast (GRB) — the primary low-latency satellite direct distribution for Level 1b products. For GLM the Level 1B and Level 2 Lightning Detection Product components (event, group, and flash) are broadcast as a streaming data set by the GRB.
- AWIPS II — primary access pathway for NWS.
- Product Distribution and Access (PDA) — primary internet access pathway to the Environmental Satellite Processing and Distribution System located at the NOAA Satellite Operations Facility (NSOF) in Suitland, MD.
- Comprehensive Large Array-data Stewardship System (CLASS) — NOAA retrospective archive for all users. The GLM science and background data will be archived in CLASS.

The calibration and validation efforts are critical and challenging because the GLM flight model #1 is the first instrument of this type to operate in geostationary orbit. Pre-launch and on-orbit checkout of the instrument performance and algorithms will employ a variety of space, airborne and ground-based instrumentation. The Airborne GLM Simulator package under development is critically important since it is deployable nearly anywhere within the GLM FOV.

International partnerships in field campaigns such as the GLM-CHUVA GPM campaign among others provide comprehensive data for continued proxy data set development, algorithm and applications development, and fundamental research on storms in a number of diverse environments. The methodologies, validation tools, and correlative data needed during on-orbit checkout as well as continued monitoring of GLM performance can be developed and tested well before launch.

The research and Proving Ground demonstrations will serve to accelerate the transition of research to operations to achieve maximum societal benefit from this new contribution to our observing system. A key challenge for application developers is the development of "fused" products, forecast decision aids, and service capabilities whereby the GLM data are integrated with other observations (satellite, radar, in-situ) and models to provide a high fidelity depiction of the current and future state of the atmosphere.

The ability to map total lightning over the western hemisphere continuously day and night will help to save lives. As such, the GOES-R constellation will provide a major contribution to the NOAA Weather Ready Nation initiative to move "new science and technology into weather service operations that will improve forecasts, increase warning lead time and ultimately increase weather-readiness."

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