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*Samantha Edgington*

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# Design, Calibration, and On-Orbit Testing of the Geostationary Lightning Mapper on the GOES-R Series Weather Satellite

Samantha Edgington, Clemens Tillier, Mark Anderson
Lockheed Martin Space, 3251 Hanover Street, Palo Alto, California 94304, U.S.A.

## ABSTRACT

The GOES-R series is the latest in a long line of American geostationary weather satellites operated by the National Oceanic and Atmospheric Administration (NOAA). The two Geostationary Lightning Mapper (GLM) instruments currently operating on the GOES-16 and GOES-17 satellites give NOAA a unique new capability to map in-cloud and cloud-to-ground lightning flashes across the entire hemisphere within seconds of their occurrence. GLM enables improved warning times for severe weather events, decreased false alarms, persistent coverage over wide geographical areas without sampling bias, and long-term monitoring of trends linked to the changing climate.

Viewed from space, emissions from lightning appear as a series of brief (~500 µs) optical pulses diffused through clouds over scales of tens to thousands of km$^2$. A significant portion of the emitted optical radiation is in the form of emission lines, including a prominent neutral atomic oxygen triplet whose emission lines are near 777 nm. GLM discriminates lightning flashes from the bright sunlit cloud background by taking advantage of the spatial, temporal, and spectral characteristics of the optical signature of lightning.

This paper describes key design drivers in the development of GLM, methods used to calibrate the instrument, and lessons learned from on-orbit testing. We discuss optimization of the entire signal chain, from the telescope optics to the ground processing algorithms.

**Keywords:** lightning, remote sensing, weather satellite, calibration, post-launch test

## 1. INTRODUCTION

The GOES-R series Geostationary Lightning Mapper, developed by Lockheed Martin under a contract from NASA Goddard Space Flight Center, provides hemisphere-wide coverage for the Americas and surrounding oceans. The first-of-its-kind GLM lightning data stream, available within seconds of occurrence, supports lightning science, climatology, and operational weather forecasting of fast evolving severe weather events. Scientists and forecasters use GLM data to monitor severe weather across the Western hemisphere, including prediction of the formation of tornadoes, aid in air traffic management, support of sea transportation logistics, and contribution to long-term climate trending over the coming decades.

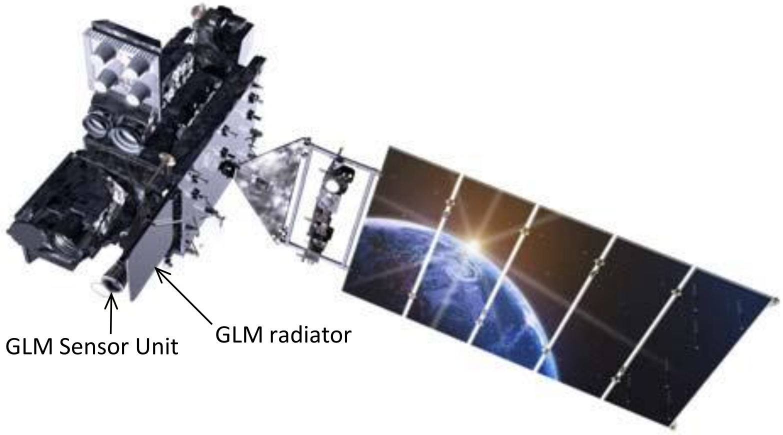

Figure 1: GOES-R series weather satellite, highlighting the location of GLM on the Earth Pointing Platform.

The first two of four identical GLM instruments were deployed on the GOES-16 satellite, launched November 19th, 2016 and now operating in the GOES-East position, and the GOES-17 satellite, launched March 1st, 2018 and undergoing post-launch testing as of this writing.

### 1.1 Lightning Phenomenology

A lightning discharge creates and excites atomic oxygen, which decays from its excited state by emitting photons at characteristic wavelengths. To detect a lightning flash, optical lightning mappers typically rely on a prominent oxygen triplet whose emission lines are near 777 nm. The transient optical signature of a lightning pulse diffuses through the surrounding cloud and illuminates a wide area of the cloud top, typically tens of km$^2$. The cloud medium is optically thick but absorbs very little at near-infrared wavelengths, so the resulting multiple scattering blurs the source geometry and delays and time-broadens the pulses. Observed on the cloud top, each lightning flash consists of a series of short (less than one millisecond) strokes separated by several milliseconds. An optical sensor positioned above the cloud top can thus sense the diffuse 777 nm glow from the individual optical pulses generated by the strokes without having a direct view of the lightning plasma channel itself.

## 2. INSTRUMENT OVERVIEW

GLM is a nadir-pointed staring video camera that covers a ~16° diameter field of view, clipped just inside the Earth limb as viewed from geostationary orbit (see Figure 2). The instrument has refractive telescope optics, a one nanometer wide interference filter, a focal plane operating at 500 frames per second, and ~10 km ground sample distance. These characteristics are tailored to the spectral, temporal and spectral phenomenology of lightning, maximizing the signal relative to the background arising from sunlight reflected from the tops of thunderclouds. The high volume of digital video data generated by the camera (12.5 Gbps) requires on-board processing by a Real Time Event Processor (RTEP) that performs thresholding of each camera frame against a running average of the background scene. Reporting of threshold exceedance events on an exception basis reduces downlink bandwidth by more than 3 orders of magnitude relative to the raw video stream. For an overview, refer to Goodman et al.[1]

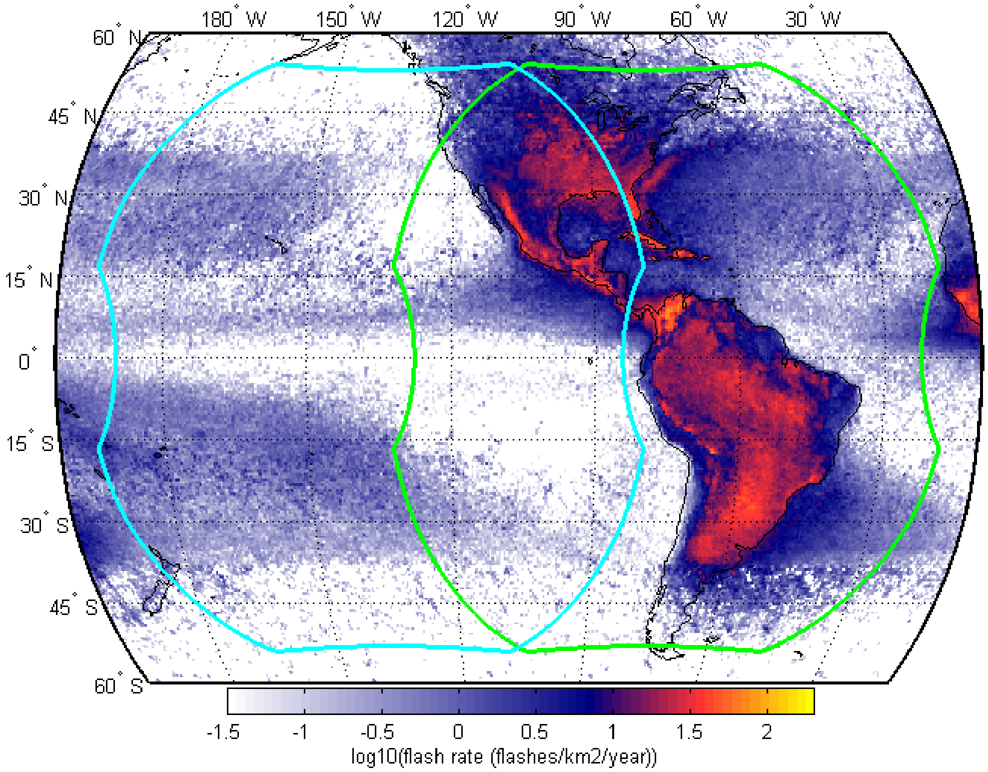

Figure 2: Required coverage footprint of the GOES-West GLM (cyan) and GOES-East GLM (green), overlaid on a map of lightning flash rate[2]. Actual coverage extends slightly beyond this specification requirement.

GLM consists of a Sensor Unit (SU) located on the Earth Pointing Platform of the satellite, and an Electronics Unit (EU) to perform on-board data processing as well as command and data handling, located inside the satellite bus. The former can be thought of as a digital video camera, and the latter as a digital signal processor. The instrument is succinctly described by the instrument characteristics listed in Table 1.

Table 1: Key design parameters of GLM

| **Design Parameter** | **Value** | **Unit** |
|---|---|---|
| Lens focal length | 134 | mm |
| Lens f number | 1.22 | - |
| Lens field of view | +/- 8 | deg |
| CCD imaging area size | 1372 x 1300 | pixels |
| Pixel size (variable, up to) | 30 x 30 | µm |
| Well depth (variable) | 2e6 | electrons |
| Ground sample distance | 8 – 14 | km |
| Frame rate | 503 | fps |
| Filter center wavelength | 777.4 | nm |
| Filter band pass | 1 | nm |
| ADC resolution | 14 | bits |
| Event rate | ≥1e5 | $sec^{-1}$ |
| Downlink rate | 7.7 | Mbps |
| Mass (total) | 125 | kg |
| Mass (Sensor Unit) | 67 | kg |
| Mass (Electronics Unit) | 41 | kg |
| Operational power | 290 | W |
| Flash detection efficiency (24 hr avg) | >80 | % |
| Operating life | ≥10 | years |

Figure 3: Photo of the GLM Electronics Unit (left) and Sensor Unit (right)

While the GLM Sensor Unit is a camera that can be described in the classical terms of imaging systems (resolution, spectral response, linearity, noise, clock rates, bit depth, etc.), the science data output of the GLM instrument consists primarily of event detections, not images. To understand how GLM detects lightning, it helps to think of it as an event detector, and set aside for a moment our usual thoughts about cameras.

As a digital image processing system, GLM is designed to detect any positive change in the image that exceeds a selected detection threshold. This detection process is performed on a frame-by-frame and pixel-by-pixel basis in the Real Time Event Processor (RTEP) by comparing each successive value of the pixel (sampled at 503 Hz in the incoming digital video stream) to a stored background value that represents the recent history of the value of that pixel. The background value is computed by an exponential moving average with an adjustable time constant.

An event is a 64-bit data structure describing the identity of the pixel, the camera frame (i.e. time) in which it occurred, its intensity above background, and the value of the background itself.

Performing on-board image processing in the RTEPs, and reporting changes in the Earth scene by exception only (when an event is triggered) reduces the downlink data bandwidth of the instrument to a reasonable level, from 14 bits/pixel * (1372 * 1300) pixels/frame * 500 frames/sec = 12.5 Gbps of raw video data to less than ~7 Mbps of processed event data, or approximately 1e5 events/sec. By design, most event detections arise from noise.

Additional detail on the physical and functional elements of the GLM instrument is available in the GOES-R Data Book[3].

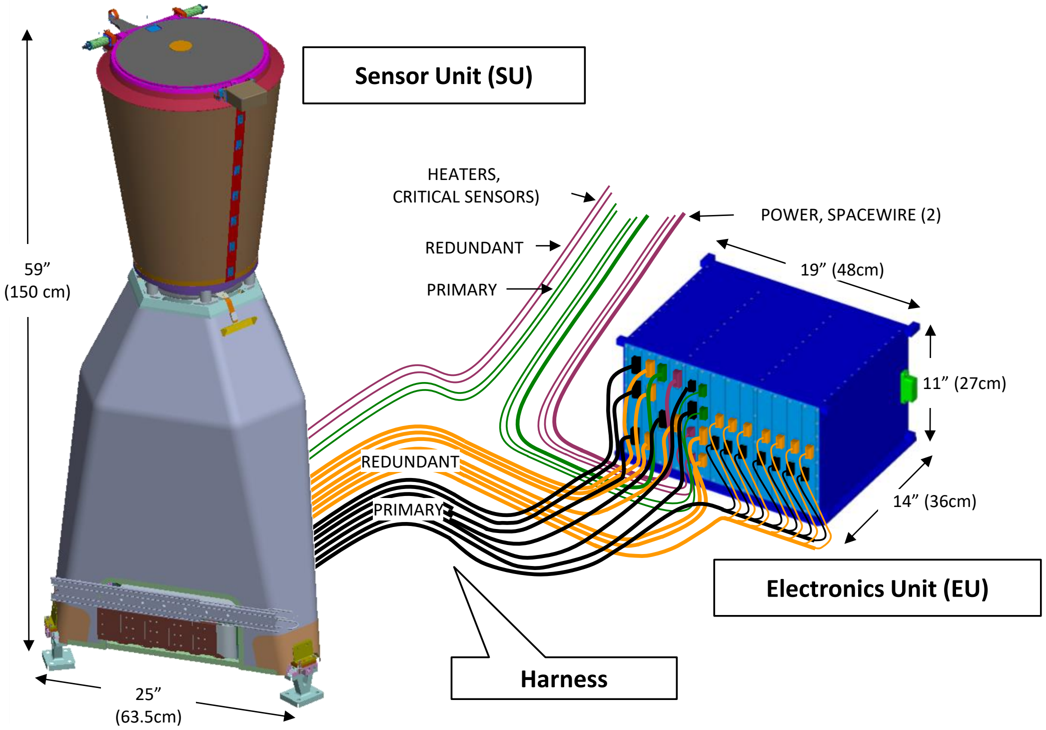

Figure 4: GLM Sensor Unit (SU), cable harness and Electronics Unit (EU), with approximate dimensions

### 2.1 Key Design Drivers

Lightning dissipates the very large quantities of energy in a convective storm cell. Only a small portion of this energy is converted to light that diffuses through the cloud and escapes to space, suffering $1/R^2$ losses along the ~4e7 m path to geosynchronous orbit (GEO). As seen by GLM, the radiant energy of a typical lightning pulse is on the order of 10 $\mu J\ sr^{-1} m^{-2}$. This pulse energy is what sizes the pupil area of the instrument, from which many other design parameters are derived.

Detection of lightning is complicated by the presence of bright sun light reflected from the cloud top. To distinguish the short, dim lightning signal at the top of the clouds from the relatively constant bright solar reflection, we apply temporal, spectral and spatial discrimination to extract the lightning signal. Achieving this discrimination, along with the wide field of view to cover the full disk, are the key design drivers for GLM.

### 2.2 Spatial Discrimination

The GLM CCD was designed such that the ground sample distance (GSD), i.e. the projected area of each pixel on the Earth's surface, is approximately constant with a target value of 8 km at nadir, and a limit of < 14 km across the Continental United States, matching the typical size of a storm cell. When following the development of severe thunderstorms, it is important to track the lightning flash rate of individual storm cells, and therefore constant ground sample distance over the Earth is preferred.

Near the edge of the field of view, the CCD design (patented under U.S. Patent 8063968) uses reduced pixel pitch to compensate for the foreshortening as the view shifts away from nadir. This ensures that the cloud background signal (and its associated photon noise) is minimized while the lightning signal is maximized, thus maintaining a good SNR near the Earth's limb.

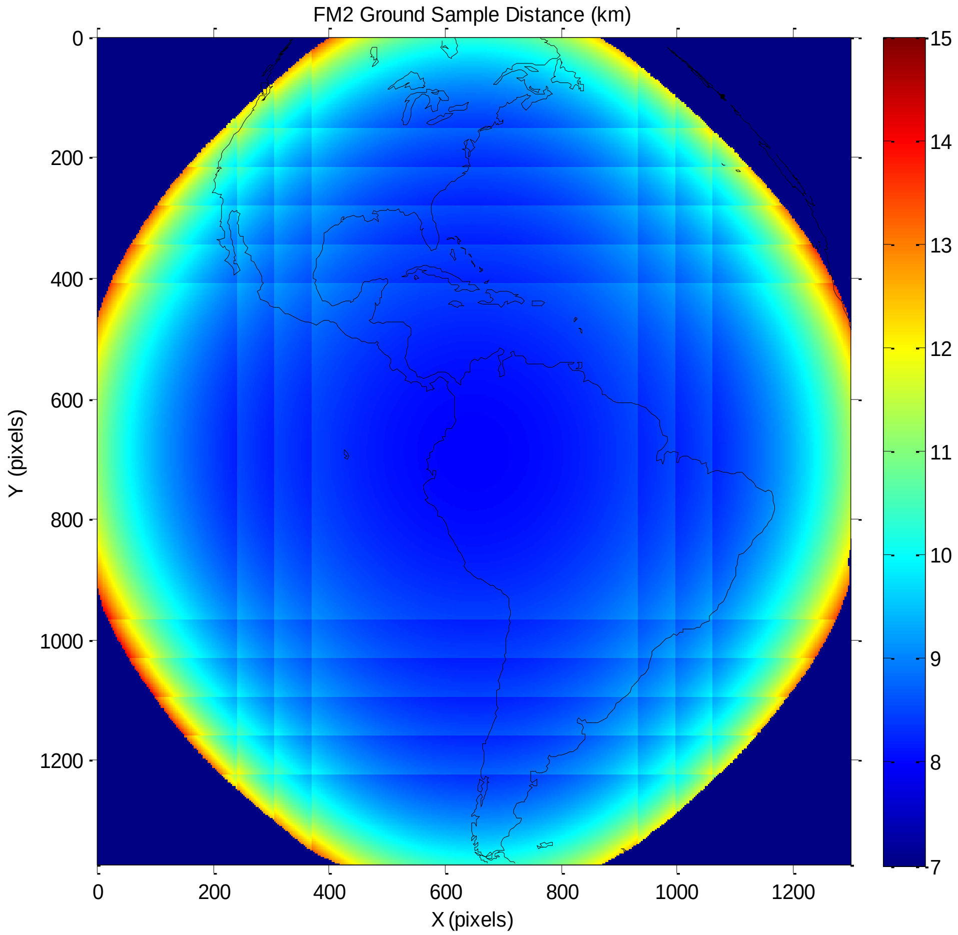

Figure 5: Measured ground sample distance (km) for GLM Flight Model 2 (on GOES-17). Pixel pitch boundaries are visible as vertical and horizontal discontinuities, at each of which the GSD steps down to compensate foreshortening of the pixel footprint. Black coast lines show a simulated view from 75°W longitude.

### 2.3 Temporal Discrimination

GLM detects the individual optical pulses caused by lightning, against a bright background of sunlit clouds. To detect these pulses with sufficient signal to noise, the frame rate is selected to be of the same order as the average duration of a typical pulse. If the frame rate is too low, then additional background is sensed, increasing photon noise without additional signal, thus lowering SNR. If the frame rate is too high, the signal can split into successive frames, again reducing SNR.

Considering only the phenomenology of lightning, the "sweet spot" is around 1500 fps. However, frame rate is strongly constrained by the performance of the analog readout chain and the data bandwidth of the digital processing. As a result, the frame rate selected for GLM was 503 Hz, resulting in a frame period ~4x longer than a typical lightning optical pulse.

### 2.4 Spectral Discrimination

While anyone can build a lightning detector that works well at night, the true test of a lightning mapper is how well it detects dim lightning events emanating from a bright, zenith-illuminated cloud top. Clouds are nearly Lambertian reflectors with an albedo that sometimes approaches unity, so a large amount of undesired reflected sun light is present in the spectral region of the oxygen triplet.

This background cloud radiance creates photon noise that can drown out dimmer lightning events. The background signal is reduced as much as possible by using optical filters that have the narrowest feasible band pass while still passing most of the lightning oxygen triplet. GLM contains three filters of increasingly narrow spectral width: a Solar Rejection Filter (SRF) at ~75 nm Full Width Half-Maximum (FWHM) that performs the task of rejecting the bulk of out-of-band radiation, a solar blocking filter (SBF) at ~3 nm FWHM, and the key narrow band filter (NBF) at ~1 nm FWHM. These filters are discussed in more detail below.

## 3. OPTICAL DESIGN

GLM features a refractive telescope with entrance pupil diameter of 110 mm and f/1.22. The field of view is clipped just inside the Earth limb as viewed from geosynchronous orbit, at slightly over 8° field angle. This strikes a balance between coverage and stray light rejection during eclipse seasons, when the sun passes the limb and comes closest to the optical axis.

### 3.1 Overall Optical Arrangement

The GLM optical assembly consists of seven powered lens elements subdivided into a front housing containing a two-element beam expander and a rear housing containing the five-element imaging optics, including one aspheric surface. The front and rear housing, both made of aluminum, can be separated to access the unpowered narrow band filter, which lies at the heart of the telescope and functions as the aperture stop. The central location of this filter also facilitates rigorous thermal control of this key component. Two additional unpowered filter elements are located at the front of the system. GLM has a total of 10 glass elements and 21 optical surfaces, including the focal plane. All elements are bonded in place with RTV566 and mechanically retained. Lens element 5 is a compensating element made of F2G12 glass (all other elements are fused silica). Its axial location is set to compensate for as-built variations and optimize image height and encircled energy performance of each assembly over temperature. The lens assembly weighs approximately 16 kg, and was fabricated and tested by II-VI Optical Systems (formerly LightWorks Optics) in Tustin, California.

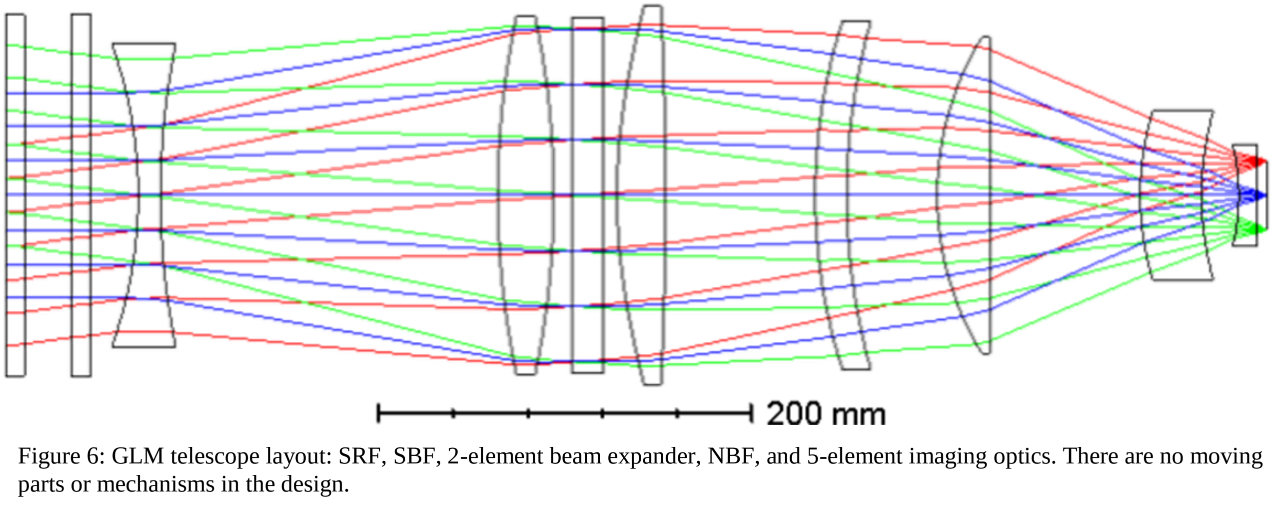

Figure 6: GLM telescope layout: SRF, SBF, 2-element beam expander, NBF, and 5-element imaging optics. There are no moving parts or mechanisms in the design.

### 3.2 Spectral Filters

GLM is a highly monochromatic design with a system band pass of 1.1 nm. The band pass must strike a delicate balance between passing enough of the oxygen triplet signal while blocking as much solar background radiation (and associated photon noise) as possible. The spectral filtering elements are therefore critical to achieving the desired SNR performance of the entire system. All spectral filtering elements of the telescope are unpowered, with interference coatings deposited on one or both surfaces of a fused silica substrate. Top manufacturing challenges included coating uniformity, center wavelength placement, and maintaining surface quality and cleanliness. Each filter has a similar mechanical arrangement, using an RTV566 bond to a flexure-mounted titanium ring mount. Each filter mount has a circumferential redundant patch heater to control its temperature.

The GLM instrument has three filters with progressively narrower band pass:

1. the Solar Rejection Filter (SRF), which performs the bulk of the solar out of band rejection, has a band pass of ~75 nm. The SRF serves as the first optical surface of the system and must therefore be designed to withstand the rigors of temperature, radiation and the micro-meteoroid environment of GEO. Its integrated solar reflectance from 200 – 4000 nm is required to be greater than 80%.
2. the Solar Blocking Filter (SBF) has a band pass of 3.4 nm, controlled to a nominal temperature of 30°C. This filter is located directly behind the SRF but is thermally connected to the lens assembly, which functions as a thermal sink to damp the influence of the temperature swings of the SRF.
3. the Narrow Band Filter (NBF) has a band pass of 1.0 nm. The center wavelength of the NBF is specified at 777.65 nm at zero angle of incidence and 33°C, the temperature to which this filter is rigorously controlled over all on-orbit conditions. With such a narrow band pass, there is no single wavelength that can adequately be described as the center wavelength of the entire filter element; the CWL inevitably varies across the aperture by several tenths of a nanometer. The manufacturing challenge of repeatably controlling filter coating characteristics over such a large aperture (180 mm for the NBF) required careful and repeated sampling at numerous locations. The spectral effects of coating non-uniformity, temperature shifts, and angle-of-incidence (AOI) shifts combine to determine the overall transmission of the NBF in the GLM system. Spectral measurements taken during manufacturing were carefully calibrated to ensure correct absolute placement of the CWL; as an additional verification measure, one filter specimen was designated as a calibration verification standard and shipped between Lockheed Martin and the filter supplier (Northrop Grumman, formerly Sonoma Photonics, of Santa Rosa, California) to frequently cross-check the relative calibration errors of our spectrophotometers. Spectral measurements included in-band transmittance, spectral uniformity, angular acceptance, temperature coefficient, transition slopes, out of band blocking, anti-reflection coating characterization, solar response, and thermal response. With a full data set in hand, the spectral shifts arising from coating non-uniformity, temperature and AOI were analytically combined to predict the integrated transmission of the lightning signal for each filter specimen, a measurement that is difficult to perform in the laboratory at the system level.

A key requirement for the telescope configuration was to limit the angle of incidence impinging on the narrow band filter to 5° or less. Beyond 5°, the center wavelength of the narrow band filter shifts too far away from the oxygen triplet and begins to cut off the lightning signal. Because the telescope was designed to cover the full Earth disk, a beam expander with expansion factor of 8/5 was required to reduce the angle of incidence at the narrow band filter to an acceptable range.

As a beneficial result of this arrangement, the differential spectral shifts of the SBF and NBF (varying at a 5:8 ratio with field angle) cut each other off beyond an angle of ~12°, which serves as a “virtual baffle” to reject off-axis stray light. While the virtual baffle is useful, it does not remove the need for a physical baffle to reduce access for out-of-band leakage at very high incidence angles, sunlight, and other sources of glint.

### 3.3 Focal Length Athermalization

The lens assembly image plane shifts with temperature due to thermal expansion of the aluminum housings and lens elements, and small thermal shifts in the index of refraction. The resulting image plane motion is about 6 µm/°C, a shift that is almost compensated by housing expansion. The focal plane is positioned by a composite metering tube with a layup designed for near zero CTE, ensuring that the image plane remains within 12.5 µm of the focal plane over all temperature environments. In practice, lens assembly temperature ranges by < 10°C, thanks to the strong thermal isolation between the telescope and the rest of the sensor unit.

### 3.4 CCD Focal Plane

The focal plane is an STA3900A backside-thinned 1372 x 2624-pixel split frame transfer CCD with an image area of 1372 x 1300 pixels and an image diameter of ~36 mm. The device, with the previously discussed variable pixel pitch, was designed by Semiconductor Technology Associates of San Clemente, California. The progressively clocked frame transfer architecture enables shutterless operation at 503 fps, with 56 parallel analog outputs operating at 2e7 pixels/s. The CCD has been described in a conference paper[4].

The well depth of the CCD is matched to the frame rate and spectral bandwidth of the optical filters. For the focal plane designer, an unfortunate feature of lightning is that it most often occurs in optically thick and very reflective clouds, in the afternoon when the clouds are well illuminated by the Sun. The CCD well depth must accommodate the background spectral radiance of bright clouds (~35 mW $sr^{-1}cm^{-2}\mu m^{-1}$ at 777 nm) integrated over the pupil area, over the frame period, and over the spectral band pass, before the lightning signal is added. While most lightning pulses as sensed by GLM produce only 5 to 10 thousand photoelectrons, the CCD requires a well depth of ~2 million electrons to swallow the cloud background signal while leaving sufficient head room to measure the radiance of the brightest lightning events. Under noon time cloud illumination, the photon noise from the background is of the same order as the read noise of the camera.

The focal plane is sub-divided into 56 physical regions, each 49 pixels tall by 650 pixels wide, known as subarrays. Each subarray is read out in parallel and is associated with an independent signal chain consisting of amplifier, ADC, and RTEP event detection logic.

### 3.5 Stray Light Control

The solar disk has ~5e4 times greater spectral radiance than the brightest background clouds that GLM ever sees. Keeping sunlight out of the image is the primary concern of the stray light mitigation measures in the GLM optics, since the viewing geometry from GEO makes it unavoidable that the sun will intrude near the edge of the field of view. The first line of defense against stray light is the baffle assembly, a 50 cm long cone seen in Figure 3 with 11 internal vanes achieving a solar exclusion angle of 24.5°. Inside of this angle, some sunlight begins to enter the optics. The second line of defense is the virtual baffle formed by the cutoff of the spectral filters, effective up to ~12°. The third line of defense consists of numerous internal features (such as steps and vanes) and black coatings to absorb light that (by design) enters the lens barrel. At a field angle of 8.7°, which corresponds to the Earth limb, sunlight reaches all the way back to the rear end of the lens assembly where a knife edge masks off the Earth limb before light can continue to the focal plane.

This layered approach to stray light rejection reduces the stray light by several orders of magnitude and allows GLM to continue operating through eclipse sunrise / sunset events. The system requirements allow for two 5° radius Zones of Reduced Data Quality (ZRDQ) centered on the sun and on its ghost image symmetrically opposite the optical axis, where the instrument is temporarily not required to meet performance requirements.

So far, the discussion of stray light has centered on undesired ray paths that bounce from some feature of the optics onto the focal plane, for which the traditional methods of stray light control are effective. Unfortunately, the viewing geometry of GEO features a second source of unwanted light where the ray bounce occurs on the Earth, which can be an excellent specular reflector. The resulting glint is an unavoidable feature of full-disk imaging from GEO and may occur anywhere in the image area. Excessive glint causes blooming of the CCD (despite anti-blooming features) resulting in undesired image artifacts. For an event detector like GLM, the moving edges of a bloomed area are the source of very high rates of false events that must be accommodated in the downlink and removed in ground processing.

The last line of defense for rejection of stray light is the ground processing algorithm that removes blooming events. This algorithm is based on a state machine formulation where each pixel in the image may have one of four states: not bloomed, flooding, bloomed, or ebbing. Flooding is characterized by a rapid increase in the background radiance to a level that is unusually high; bloomed state occurs when the pixel is saturated, therefore causing successive samples to be equal, a condition that results in zero event detections; and ebbing is characterized by a rapid decrease of the background radiance back to a normal level. The transitions between states are derived entirely from event data and may occur on timescales from a few seconds (e.g. for a brief river glint) to over an hour (e.g. sunrise glare from a calm cloud-free ocean). The blooming filter was designed and implemented after GLM was deployed on orbit, as the detailed event signature of solar glare would have been extremely difficult to simulate or test on the ground.

# 4. CALIBRATION METHODS

## 4.1 Focus and Alignment

When the focal plane assembly is mated to the optics, it must be aligned and focused to produce good imagery. The GLM instrument does not include any focus mechanisms; therefore, the correct focus must be achieved by shimming during assembly of the instrument. Three shims placed around the circumference of the aft end of the metering tube set the focus piston, tip, and tilt. Centration is achieved using three push/pull screws. Once the alignment and focus are set, the shims are staked, and the push/pull screws are removed.

The fast optics of the GLM lens assembly mean that the detector sits approximately 6 mm behind the last optic, and the allowable focus error is ±12.5 µm across the entire 36 mm image diameter. This makes the focus difficult to set properly; the procedure must account for air-to-vacuum shift as well as for non-flight-like temperatures and temperature gradients that can displace the image plane.

We measure the focus of the GLM instrument by filling the pupil with a steerable collimated infrared laser beam; the laser is tuned to pass through the filters. We then adjust the input beam from slightly converging, through collimation, to slightly diverging, while monitoring the spot size on the CCD at 16 points around the field of view. We analyze the data to generate a shim prescription to best fit the position error between the focal plane and the telescope image plane, neither of which are planar on such small scales. Each of the three shims is hand lapped and precision cleaned. We then iterate the process until the shim prescription converges. Once the focus is set and the instrument fully assembled, the focus is verified during thermal vacuum testing to ensure that the instrument remains in focus under flight-like conditions over the temperature environments expected on orbit.

## 4.2 Static Calibration

The static response of GLM is measured using a calibrated, NIST-traceable integrating sphere with a diameter of 50 cm and an aperture diameter of 20 cm. The integrating sphere is used to fully illuminate the GLM aperture and provides a flat field at illumination levels from 0 to 30 mW $sr^{-1}cm^{-2}\mu m^{-1}$ per the calibrated monitoring photodiode. We collect background images at 33 illumination levels, which provides an absolute static response of each pixel. Due to out-of-band leakage at very high angles of incidence, the large integrating sphere must be placed at 150±10 mm from the first optic. This distance places the sphere at the furthest distance from the instrument while still filling the pupil at all angles in the FOV. With the sphere at the largest distance possible from the instrument, we minimize the impact of out of band light on the measurement.

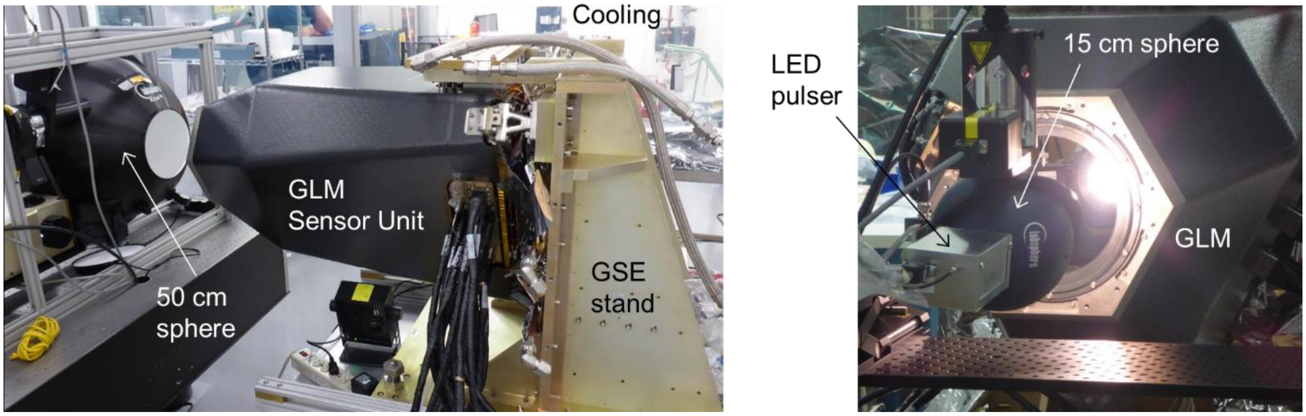

Figure 7: views of the Static calibration setup (left) and Transient calibration setup (right)

The GLM data product consists of calibrated, geolocated lightning events. To calibrate transient events, we generated a look up table that consists of the lightning signal gain (J/DN) for each pixel at each of 32 levels of background illumination. The calibration factor already accounts for optics transmission, filter cut-off, pupil area and pixel solid angle; it represents the time-integrated energy of the pulse just before it enters the optics. The gain is calculated using the slope of the response curve measured for each pixel during static calibration. Because the response curves are not perfectly linear, higher radiometric accuracy is achieved by determining the gain against a 32-segment piece-wise linear curve. In this way, the static calibration data set (acquired using the simplest of methods using the minimal amount of processing) is the only data used to calibrate the GLM data product. The next section describes the transient calibration, which checks the calibration for pulses imparted to a small number of pixels across the field of view.

### 4.3 Transient Calibration

The goal of transient calibration is to "test like you fly" by measuring the performance of GLM in detecting lightning-like optical pulses. In practice, it is extremely difficult to recreate a controlled, high-fidelity lightning signal in the lab, with the same spatial, spectral and temporal characteristics as the real phenomenology. The transient calibration uses pulsed infrared LED light to simulate lightning events to the extent possible with standard calibrated lab equipment. A significant portion of the final lightning event calibration is calculated analytically using the static and transient calibration data along with sub-assembly level data, most importantly filter bandpass measurements.

Transient calibration verifies event detection capability of the GLM instrument and provides event intensity calibration data to compare to the values derived from the static calibration data. The transient calibration is accomplished using small integrating sphere to simulate cloud background illumination, and a pulsing LED to inject calibrated events, both of which are mounted on a gimbal system to point the calibrated optical pulses to the required locations across the field of view, ensuring that all 56 readout channels are exercised. The LED is pulsed with constant amplitude and a pulse width that is varied over two orders of magnitude. Pulse width ranges from ~10 µs to ~1.5 ms and is synchronized with the GLM frame time to prevent frame splitting of the pulse energy.

During the test, three parameters are varied: the cloud background radiance simulated by the small sphere, the position of the pulser, and the width of the pulses. For each small sphere illumination setting, the pulser is steered to a variety of positions on the CCD, covering at least one position in each of the 56 subarrays; at each position, the width of the pulse is varied from sub-threshold to saturation. During event testing, the energy input is known from the measured amplitude and width of the LED pulse.

During static calibration, we evaluate the radiometric response of every pixel in the array. We calibrate the transient response of a selected subset of pixels (several hundred) within each subarray and evaluate the consistency of their transient response to their static radiometric response.

## 5. ON-ORBIT TESTING

After the satellite arrives on station in geosynchronous orbit, there are thousands of parameters that require tuning on board the instrument and in the ground processing system before the GLM system can reach its optimal performance, during a process known as Post Launch Test (PLT). A logical sequence of test modules was established to tune each section of the signal chain, from photons to lightning events, as summarized in Figure 8. On-orbit calibration was limited to a cross check of the ground-based calibration results and showed good agreement. Outside of the PLT process a cross-calibration was performed against the scene radiances reported by the Advanced Baseline Imager (ABI), which is co-located with GLM on the satellite's Earth Pointing Platform.

The two most important and complex phases of PLT are the tuning of the RTEPs and the tuning of the Ground Processing Algorithms (GPA).

RTEP tuning is where the 1792 on-board detection thresholds are selected by measuring the demonstrated Threshold to Noise Ratio (TNR) observed across a variety of diurnal and seasonal illumination conditions on orbit. The detection thresholds must be lowered as far as possible without saturating the downlink with false events. An extensive suite of analysis tools was developed in MATLAB to automate this process, using a large data sample consisting of ~billions of events. The analysis confirmed that the noise was well-behaved, i.e. Gaussian and repeatable across all illumination conditions.

GPA tuning is where the ground processing false event filter parameters are optimized. The filters operate in real time in the ground processing system, discarding events from the event data stream when they meet spatial or temporal criteria that indicate they likely arise from other phenomena than lightning. GLM operates as a system, where the instrument and ground processing function together. The science data downlink can be thought of as an intermediate processing stage, where by design the data consists primarily of false event detections with a few (5 to 10%) lightning events interspersed. The GPAs operate successively on each frame's worth of events, at the same 503 fps rate as the instrument, and tag events for deletion. There is no "lightning filter" in the ground processing algorithms; instead, any event that survives through all the false event filters is automatically deemed to be a lightning event and is passed along to the geolocation and radiance calibration algorithms.

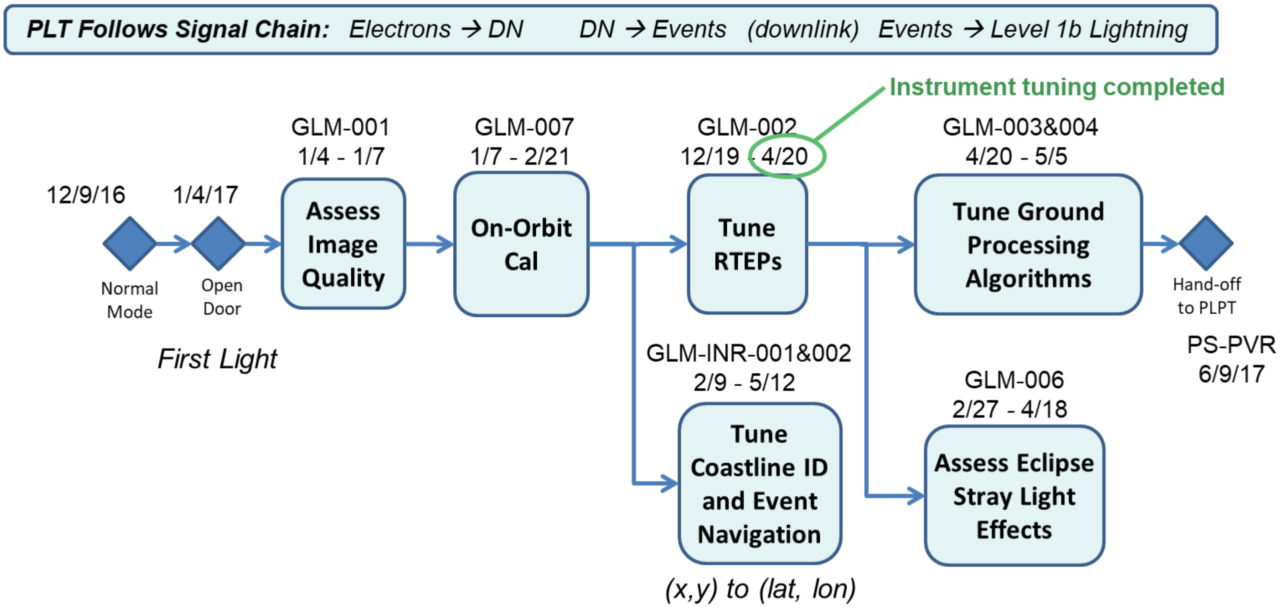

Figure 8: Timeline of GOES-16 GLM Post-Launch Test. The final milestone was the Peer-Stakeholder Product Validation Review (PS-PVR), a NOAA review that declared initial beta maturity of the GLM lightning data product and marked the start of the Post Launch Product Test (PLPT) phase.

Not all the GPA filters have the same importance; most remove only a small portion of the raw events and will not be further discussed here. The most important algorithm by far is the coherency filter, which exploits the spatial and temporal correlation of lightning events to discard false events arising from instrument noise and other sources.

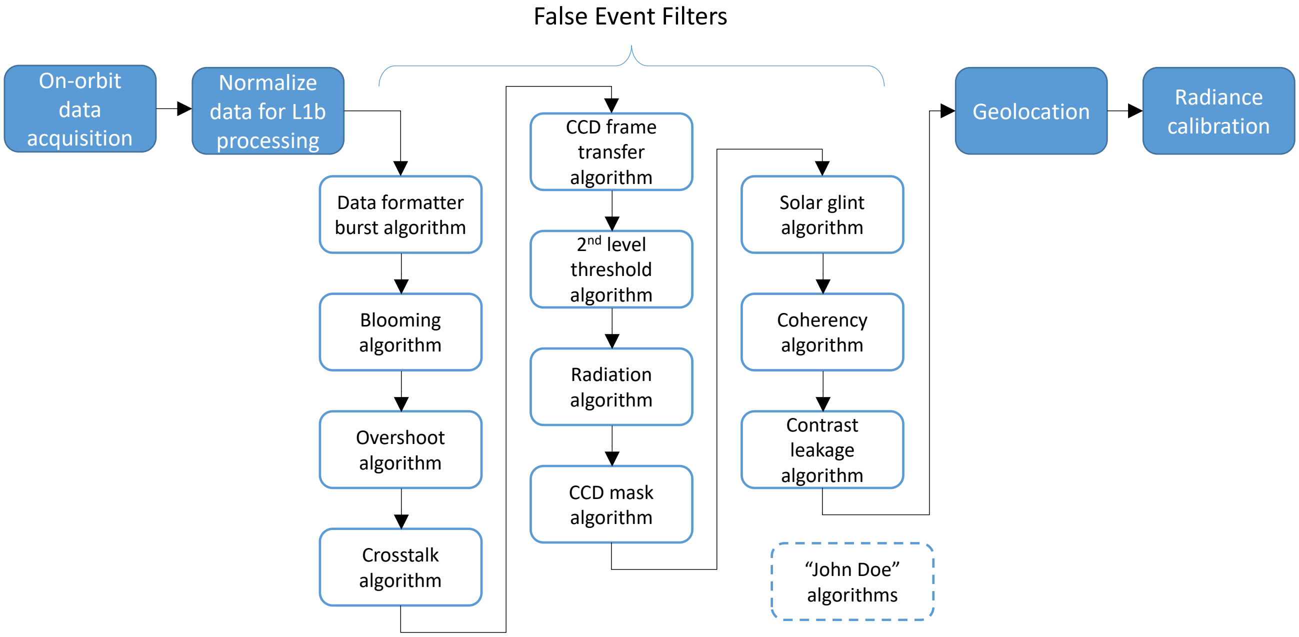

Figure 9: Flow diagram of false event filtering of GLM event data. It is anticipated that heretofore unknown algorithms may be developed in the future to improve performance, as symbolized by the box with the dotted outline.

The coherency filter relies on the fact that true lightning events are coherent in time and space, whereas noise events are not. This is the filter that enables GLM to operate at the edge of the noise, sending many noise events to the ground and detecting fainter lightning events embedded therein. As viewed from space, any given lightning flash will generate several to several tens of optical pulses. Flashes can be up to several seconds long, and contain multiple optical pulses detected in the same pixel or adjacent pixels. A noise event will not have this coherent behavior. Although many noise events may be triggered over the course of several seconds, they are unlikely to be in the same or adjacent pixels. The coherency filter calculates the probability that any given event is a noise event, based on the event intensity, the electronics noise, and the photon noise of the background. When another event occurs in this same pixel or an adjacent pixel, the filter calculates the probability that both of these events are noise events, based on the new event intensity, the instrument and photon noise, and the time elapsed between the two events. When two events have a sufficiently low probability of both being noise, the events are reported as lightning events. This probability threshold is adjustable to allow more or less stringent filtering of the data as desired by the user community, striking the appropriate balance between detection efficiency and false alarm rate.

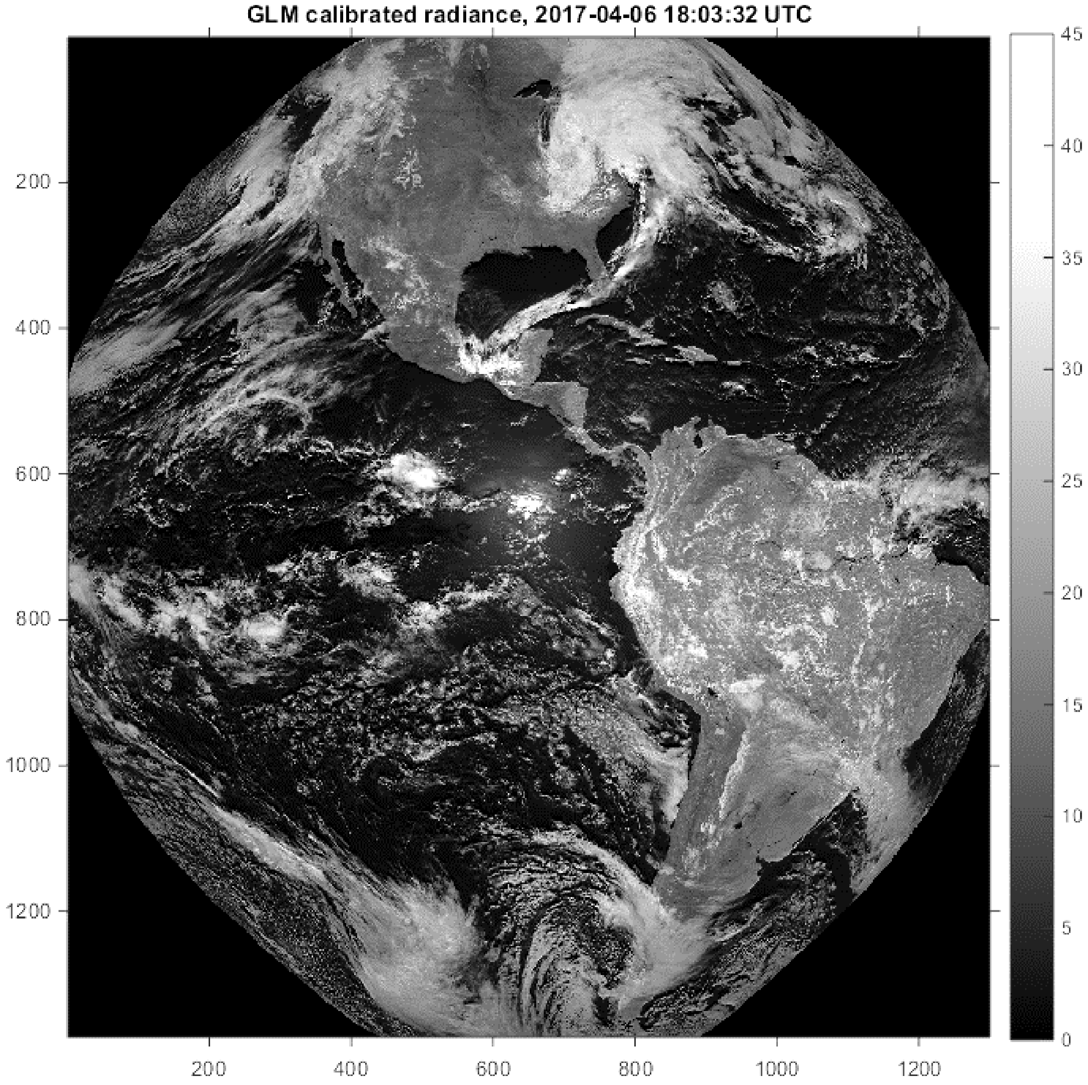

Figure 10: View of the Earth acquired from 89.5°W longitude by GOES-16, during PLT. Calibrated GLM background images are only used for tuning of the GPAs; they are not an output data product. Color bar unit is spectral radiance in mW $sr^{-1}cm^{-2}\mu m^{-1}$. This image is displayed at fixed pitch, which effectively stretches the edges of the scene. Note the strong contrast between land and water, which is characteristic of the near infrared.

## 6. LESSONS LEARNED

We provide lessons learned during our experience with on-orbit operation of the two GLM instruments currently deployed.

Items we learned or re-confirmed:

- Our ground calibration program was robust and was confirmed by on-orbit calibration.
- It was important to use the same data formats and data analysis tool suite for ground test and for on-orbit test.
- Tuning a system like GLM is a coupled problem where the ground processing must be tuned in concert with the on-board processing. Adjusting a knob in the instrument may require adjusting another knob on the ground, so thinking of the space segment and ground segment as separate elements is counter-productive.
- The on-board processing settings can be tuned to take full advantage of the pointing performance margin of the platform. A more stable platform enables tighter detection thresholds and better detection efficiency. However, there should be thorough testing during occasional small disturbances to pointing (from thruster firings or mechanism motion elsewhere on the satellite) that are fully within the platform specification but may nevertheless trigger bursts of false events. An event detector like GLM can be exquisitely sensitive to jitter if tuned too tightly.
- Seeing the real data from orbit always provokes new thoughts on how the ground processing could be changed, but change is a challenging process to undertake in an operational system of national importance. Doing it successfully requires creativity, teamwork and diplomacy.
- No amount of stray light analysis is worth a single good stray light test using the sun as a light source. Ground based testing in a heliostat provided good agreement with observed on-orbit performance during eclipse season.

Items we resolved, but wish we had known or anticipated better:

- The thresholds achieved on orbit were significantly lower than predicted from ground testing, due to a combination of conservatism in the analysis and excess noise in certain ground measurements (in comparison, the Earth is a remarkably stable light source.)
- Single-pixel radiation hits that are indistinguishable from instrument noise can conspire with regular noise false events to sneak past the coherency filter, because they violate the statistical assumptions built into the algorithm. This issue was addressed in ground processing through the addition of a new post-processing filter.
- In the operation of a geosynchronous satellite, the daily phasing of platform disturbances such as thruster firings varies with season. Disturbances that were tolerable during sub-satellite night during post-launch test turned out to be more annoying during the day, six months later, requiring a minor re-adjustment of the on-board detection parameters.
- Glint blooming can have large spatial extent (e.g. sunset) and very high intensity, causing image readout artifacts that may occur far away from the location where one can calculate the glint should occur. Therefore, a location-agnostic blooming filter is necessary on the ground.
- It is important to work closely with end users (meteorologists) to understand their needs in the context of their day-to-day forecasting tools and processes. When you've built a good instrument and generated an accurate scientific data product, your job isn't finished: you still need to package and present it in a way that is useful and intuitive from the perspective of an end user working under intense time pressure with numerous data streams to issue a hazardous weather forecast.

Items that were surprising:

- The Earth and the lightning that constantly dances across it can make for stunningly beautiful imagery. The team was well-prepared with data analysis tools for the detailed post-launch test activities, but the very different tools needed for creating cinematic time lapse animations to convey the beauty of nature to the general public were only developed after launch, during a very busy time.
- Besides lightning, GLM is an excellent detector of bolides[5].
- If your instrument is popular, Twitter may provide important feedback during post launch test.

# 7. CONCLUSION

This paper described key considerations in the development of the GOES-R series Geostationary Lightning Mapper, reviewed the optical design and the methods used to calibrate the instrument, and reviewed the lessons learned from on-orbit testing to date. We discussed optimization of the entire signal chain, from the telescope optics to the ground processing algorithms.

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