

Post Launch Calibration and Testing of The Geostationary Lightning Mapper on GOES-R Satellite

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ABSTRACT

The Geostationary Operational Environmental Satellite R (GOES-R) series is the planned next generation of operational weather satellites for the United States National Oceanic and Atmospheric Administration (NOAA). The National Aeronautics and Space Administration (NASA) is procuring the GOES-R spacecraft and instruments with the first launch of the GOES-R series planned for October 2016. Included in the GOES-R Instrument suite is the Geostationary Lightning Mapper (GLM). GLM is a single-channel, near-infrared optical detector that can sense extremely brief (800 μ s) transient changes in the atmosphere, indicating the presence of lightning. GLM will measure total lightning activity continuously over the Americas and adjacent ocean regions with near-uniform spatial resolution of approximately 10 km.

Due to its large CCD (1372x1300 pixels), high frame rate, sensitivity and onboard event filtering, GLM will require extensive post launch characterization and calibration. Daytime and nighttime images will be used to characterize both image quality criteria inherent to GLM as a space-based optic system (focus, stray light, crosstalk, solar glint) and programmable image processing criteria (dark offsets, gain, noise, linearity, dynamic range). In addition ground data filtering will be adjusted based on lightning-specific phenomenology (coherence) to isolate real from false transients with their own characteristics. These parameters will be updated, as needed, on orbit in an iterative process guided by pre-launch testing. This paper discusses the planned tests to be performed on GLM over the six-month Post Launch Test period to optimize and demonstrate GLM performance.

Keywords: lightning, remote sensing, geosynchronous, space-based

1. BACKGROUND AND SYSTEM NEED

The United States weather and climate communities established a need for a lightning mapper at geosynchronous orbit following the tremendous success of the Lightning Imaging Sensor (LIS) flown aboard the Tropical Rainfall Mapping Mission (TRMM). Launched in 1997, TRMM was conceived as joint NASA / Japan Aerospace Exploration Agency (JAXA) mission to study rainfall volumes and the water cycle—especially over oceans and tropics. TRMM included the LIS among its instrumentation suite which itself was a descendent of airborne optical sensor experiments (Optical Transient Detector—OTD) flown aboard a U-2 airframe [1]. Over the course of its 17-year lifetime, LIS delivered data that allowed for strong correlations between lightning activity and other measures of storm intensity (see Figure 1). It also validated the utility of sensing lightning's distinctive narrow band Oxygen emission at 777.4 nm [3]. The meteorological community also realized that reliable data on the increasing rate of lightning events, groups and flashes allowed for greater advance warning of storm intensification than other data which was more indicative of real-time activity.

With that success, early concept planning to develop an operational version of the sensor began in early 2000s. As an operational sensor, it would be characterized by high reliability and availability but stable performance over time. Due to the transient nature of lightning and the rapid development of severe storm activity, NOAA chose its operational geosynchronous platform to provide a synoptic, hemisphere-wide field of view for this instrument—GOES [2]. The instrument that eventually became GLM was manifested for the GOES-R series, which was in the formulation phase of development at that time. By 2008, the GOES-R Flight Project Office selected Lockheed-Martin Advanced Technology Center (LMATC) in Palo Alto, CA to develop the sensor, building on their experience with the LIS heritage instrument.

The GOES Program is jointly operated by NASA and NOAA. NOAA operates multiple constellations of weather monitoring spacecraft on behalf of its line offices (including the National Weather Service) in pursuit of its mission to protect life and property, in that order. NOAA defines the mission requirements and is the end user of the system; it partners with NASA, which provides systems engineering, spacecraft, launch vehicle and instrument expertise needed to successfully procure a capable observatory. The first spacecraft in the GOES-R series (R/S/T/U, flying Flight Models (FMs) 1-4, respectively) is planned for an October 2016 launch.

TRMM Lightning Imaging Sensor (LIS) vs. VIRS IR Image Along U.S. Gulf Coast 0412 UTC 22 Jan 1998

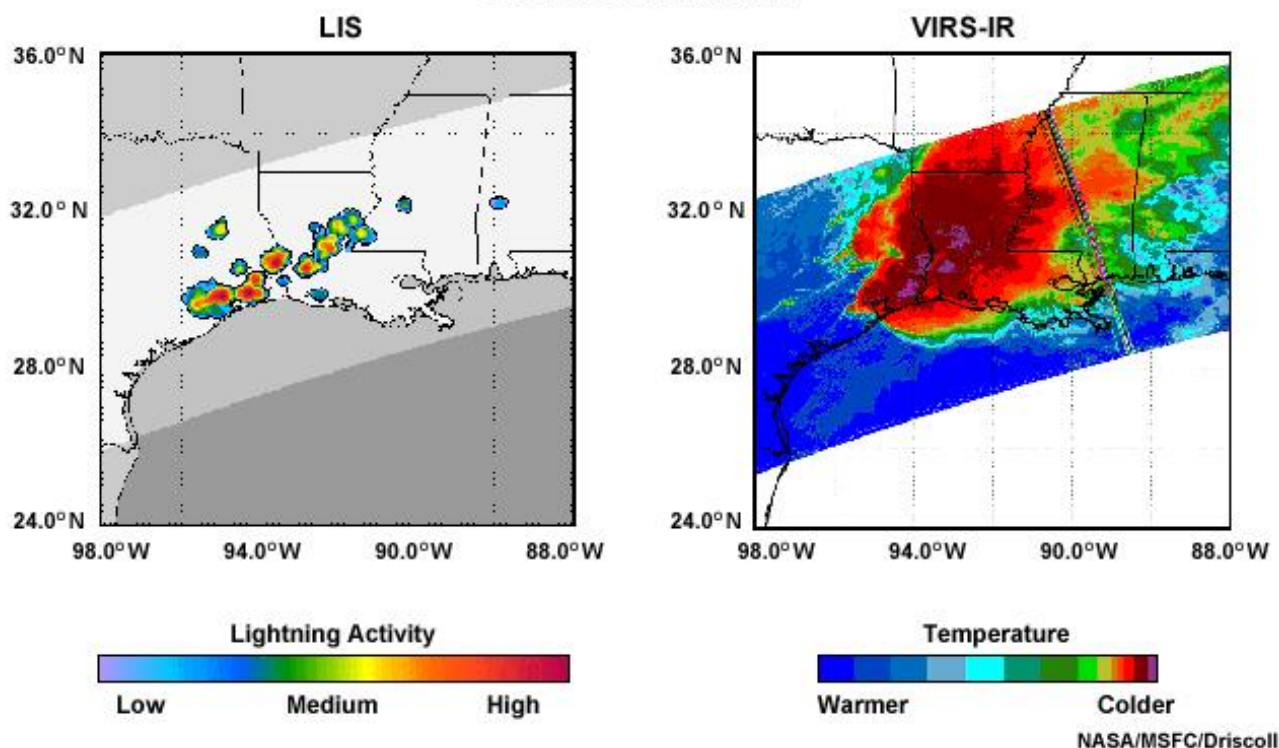


Figure 1. Correlation between IR-induced storm phenomenology and lightning activity.

1.1 Required Performance

The GLM is required to correctly identify 70% of real lightning flashes, with fewer than 5% as false-positives. Lightning events, groups and flashes must be correctly navigated to within 5.0 km at the sub-satellite point (SSP) or 140 μ radian across the field-of-view. Based on ground test and analysis conducted by the vendor with the support of NASA, the GLM is expected to meet or exceed these performance requirements in flight.

1.2 GLM Functional Architecture

The GLM system architecture, shown in Figure 2, consists of a Sensor Unit (SU), Electronics Unit (EU) and Ground Processing Algorithms (GPAs). The GLM SU is a single channel narrow-band infrared event detector, with solar filters, a 1.0 nm band pass filter, optics and CCD optimized for the O emission line at 777.4 nm. Because of the pulsed nature (2 ms) of the lightning optical transient, the CCD frame rate is a fixed, nominal 500 frames per second. The SU performs Analog / Digital conversion and passes digital data to the EU. Onboard lightning “event” detection is based on a reprogrammable radiance / Digital Number (DN) threshold table. Within a suite of Real-Time Event Processors

(RTEPs), GLM maintains a moving average of background illumination for each pixel of the CCD. During each readout cycle, that background level is subtracted from the observed DN in each pixel; if the remaining DN exceeds the defined threshold, that event is time tagged and downlinked for ground processing.

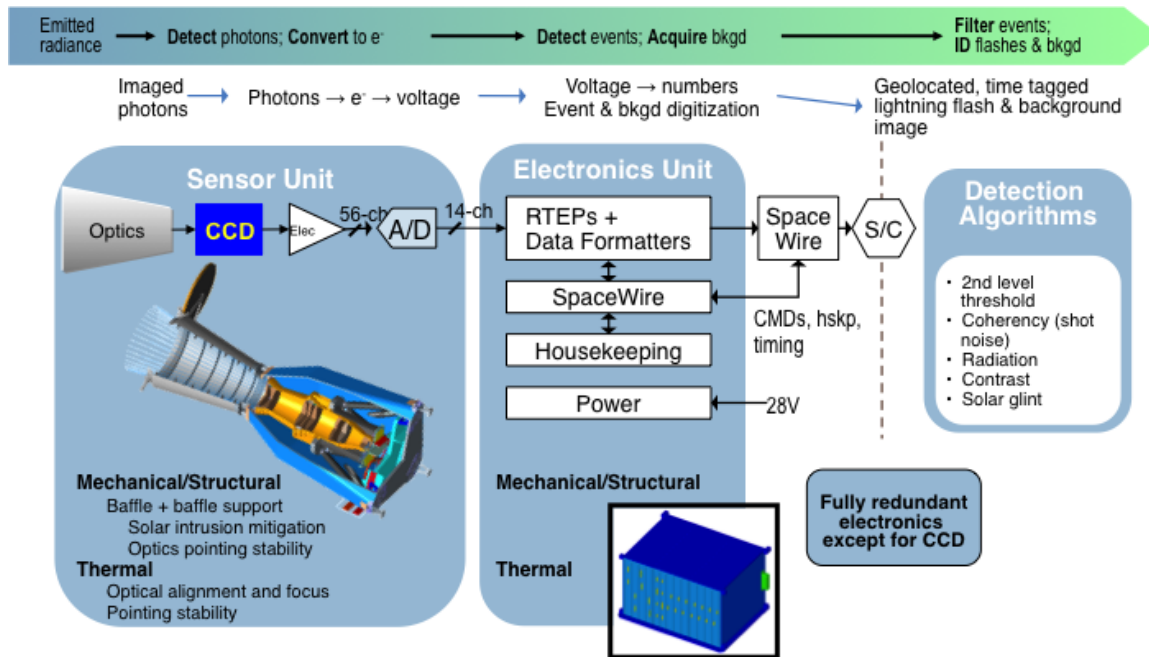


Figure 2. GLM Instrument System Architecture.

The GPAs filter downlinked events for false events based on lightning phenomenology as well as specific noise characteristics observed on both OTD and LIS.

- **2nd Level Threshold:** Applies additional thresholding to certain “hot” pixels that have been identified to have abnormally high response due to manufacturing defects or radiation damage.
- **Coherency (shot noise):** Screens CCD read-out noise by filtering out events which are not correlated in pixel location or time to other events (which is characteristic of lightning, but not characteristic of shot noise).
- **Radiation:** The radiation path for high-energy particles impacts to the CCD is a highly acute angle, resulting in linear “tracks;” this filter screens out these characteristic tracks.
- **Contrast Leakage:** High contrast boundaries (bright cloud, dark land) in the presence of high-frequency mechanical disturbances (jitter) can produce false events as those bright regions cross between pixels—they appear to break the threshold with respect to the average background. This filter looks for a characteristic spatial structure to remove these events.
- **Solar glint:** Similar to contrast leakage, solar glint can produce false events but with a physical appearance of specular reflection. This filter removes any glint.

2. GROUND TEST AND CHARACTERIZATION OVERVIEW

Lockheed Martin subjects each GLM to an extensive ground test program both for verification and characterization purposes. The details of this test program are beyond the scope of this paper. This overview will instead focus on the impact of ground testing to observable performance on-orbit, leading to the Post Launch Test (PLT) approach selected by NASA. While much of this test program relates to on orbit performance in some critical way, we will instead focus on the subset of that testing applicable to the most unique features of the instrument and therefore the greatest risk of mismatch between ground and on-orbit test conditions. That is: the large CCD, high frame rate, sensitivity and onboard event filtering.

2.1 Electronics Noise

Electronics noise directly relates to instrument sensitivity (gain and dynamic range) as well as overall shot noise. GLM electronics noise is tested according to two criteria, each tested with the fully integrated instrument with zero light input to the optics during an initial characterization and as part of a Comprehensive Performance Test (CPT) dark frame:

- The standard deviation for each pixel in a given sub-array, averaged over a large number of dark frames is small.
- The calculated noise figure for each sub-array never varied significantly.

Thus far, each GLM FM has passed both these criteria, which represented a design challenge given the size of the CCD and the complexity of the analog signal chain. The stability of the noise is also a key component in tuning the Coherency GPA which is why it was tracked across instrument CPTs. During PLT, as the more aggressively we require events to be correlated (dictated by higher electronics noise), the more likely we are to reject real lightning flashes consisting of fewer events.

2.2 Static Response

The GLM static response testing used an un-collimated fiber source as well as an integrating sphere at the instrument aperture. The primary objectives were to verify the gain of each sub-array as well as the instrument linearity with input brightness. This ties directly to instrument dynamic range and the functional capacity of the RTEPs' background subtraction functionality on orbit. The static response characterization also provides inputs for the 2nd level threshold filter, based on each pixel's response.

2.3 Transient Response

The transient response testing builds on the electronics noise measurements and static response and the static response by directly testing the ability of the instrument to detect light pulses similar to lightning. During instrument characterization, this was done using an integrating sphere, to provide fixed background levels, fitted with an LED pulser to emulate the 2 ms lightning pulse width. This LED was steered into each sub-array and modulated at various frequencies and the data assessed for fraction correctly detected. In general, performance was excellent with all instances of the instrument so far testing greater than 80% detection probability, across modulation frequencies.

Transient response directly maps to instrument threshold settings, which are both tested on orbit and are the most operational configuration parameter in that we expect it to change over instrument life, based on CCD aging effects on responsiveness. By design definition, the threshold setting is defined as the DN (mapped to radiance) at which a light pulse has a 50% probability of detection. This becomes the primary fulcrum around which post launch testing and instrument configuration turn—by lowering the detection threshold we can detect more events, however this must be traded against electronics noise and the resolution of background subtraction. The more events, the greater reliance we have on the Coherency GPA to filter out shot noise events, which will also be downlinked by GLM in greater numbers.

3. POST LAUNCH TESTING

The post launch test period for GOES-R follows roughly a 6-month timeline. For GLM, these tests largely consist of GPA parameter modification and GLM instrument / camera parameter setting followed by a period of protracted data collection. This data is analyzed in aggregate, primarily because instrument performance is quantified in terms of statistical features (false alarm percentage, percent correctly detected, i.e. "detection efficiency"). Following this analysis, the NASA operations team will make modifications as needed to GPA parameters, GLM settings and repeat data collections as needed.

3.1 Navigation Characterization

GLM image navigation is based on two fundamental principles: precision alignment of the instrument boresight with respect to the spacecraft control reference frame; and automated coastline identification in background images to track and process out diurnal variations in pointing from that control frame. The latter process we refer to as "Coastline ID." The GLM precision alignment to the spacecraft accounts for the majority of the budget to meet the navigation requirement; diurnal variation (due to thermal alignment deflection, orbital perturbation) additionally would exceed the requirement if un-corrected.

Generally, the approach is initially to leave alignment un-corrected, using Coastline ID to trend boresight alignment over several days. Based on this trend, the static (constant order) offsets are separated from the dynamic trend (in roll, pitch and yaw, respectively). In a nominal case, where the instrument alignment is stable, the dynamic (diurnal) trend will oscillate in a sinusoid-like envelope. To aid in this trending, the GOES-R Program plans to use laser beacons stationed at Monument Peak, CA and at NASA Goddard Space Flight Center in Greenbelt, MD. This will generate artificial control points in addition to coastline measurements allowing more accurate alignment knowledge than coastlines alone provide and at the same time allowing improvements in the coastline detection process itself to occur asynchronously. Once the alignment is measured, the diurnal envelope is characterized. The objective of Coastline ID is to fit a center to that envelope for each Euler angle. If successful, the static alignment knowledge, plus the daily diurnal correction will keep the extremes of the alignment variation below the 140 μ radian navigation requirement.

3.2 RTEP Thresholds

The basis for setting RTEP thresholds is determining an optimal Threshold to Noise Ratio (TNR). If the threshold is too high, no shot noise false events will be observed, but lower energy lightning pulses will not be reported. Too low, and shot noise can dominate the population of reported events and objectively incoherent events can—simply by occurring in high frequency—defeat the Coherency GPA by seeming to be correlated.

Thresholds are set by iteratively screening though events *rejected* by the Coherency GPA with different threshold levels in DN to determine what the false event (noise) rate would have been with each of those threshold levels. The TNR is then computed for each of those cases. A threshold is then selected such that the GLM downlink is not saturated (false events with true events), corresponding to a TNR of approximately 4—but that the false event rates remain manageable in the Coherency GPA. These thresholds are then commanded to the instrument. Because GLM is the first of its kind in this orbit and in an operational setting, the true energy distribution of observable lightning pulses is uncertain. Together with the fact that electronics (shot) noise and the Coherency GPA may not interact linearly, this process is one that we expect to repeat iteratively throughout post launch testing.

3.3 2nd Level Threshold GPA

Once RTEP thresholds have converged, background images are passively analyzed on the ground and pixel-wise histograms are computed to determine if individual detectors consistently have out of family responses due to excessive shot noise. This type of response may be indicative of a “hot” pixel. In that case, a ground threshold can be set for this subset of pixels effectively applying an additional event threshold on a case-by-case basis. This prevents overactive detectors from saturating down stream GPAs with excessive false events. This analysis can be re-run periodically and is entirely ground-based.

3.4 Coherency GPA

Coherency is tuned for two key parameters—temporal correlation (latency for a recent valid lightning event nearby) and spatial correlation (adjacency distance over which two events are likely to be part of the same group or flash structure). In a given frame, an event breaking the threshold “activates” that pixel. If an event in a subsequent frame (within the temporal correlation) is sufficiently close to the original event (spatial correlation), that event is marked as valid. By its nature, the Coherency GPA discards the first event in a string of lightning pulses since there’s no a priori method for establishing its validity.

Coherency is less a feature of the GLM instrument than it is of lightning phenomenology. As such, the initial configuration is driven heavily by experience with the pathfinder instrument (LIS and OTD). It will be modified based in part, with feedback from Radio Frequency ground networks established to track lightning. However, this is only a useful guide for validation, not prescriptive—it is not our expectation that GLM will produce data products identical to RF networks; while a lightning pulse is a lightning pulse the RF and optical emission mechanisms are different and can be affected by the mix of cloud-to-cloud and cloud-to-ground lightning. In setting the precursor filters and instrument parameters which operate on the data prior to running Coherency, the objective is to drive down the volume of incoherent noise and repetitive event errors while detecting the weakest pulses—and therefore most real lightning—possible.

3.5 Validate CCD Timing and Gain

Based on the quality of background images (qualitative uniformity, dark offsets and apparent headroom), we will evaluate if the CCD timing / readout parameters are appropriate or require updates in collaboration with the manufacturer, Lockheed Martin ATC. The dark (DC) offsets, readout and reset gate clocking parameters are ground commandable and may be updated if they appear inappropriate—that is result in artifacts that interfere with event data collection and processing. This is a contingency test; we have every reason to believe that static response testing and flat field measurements performed on the ground are sufficient, however we allow for the fact that laboratory tests of even the highest fidelity are imperfect proxies for field-testing. If the CCD timing is modified, however, the ground calibration / radiometric characterization would not be applicable to the new timing settings.

Additionally, based on pre-launch analysis, there is the likelihood that GLM gain will exceed design expectation. While this makes the instrument more sensitive, it also reduces dynamic range in the presence of a bright background. Based on analysis of the CCD headroom on orbit, we may choose to modify CCD timing to artificially degrade instrument gain if this headroom proves insufficient for the principal mission function—lightning event and event rate of change detection.

3.6 Product Validation

The primary product for GLM is based on lightning count (and the instrument system is optimized to this end), however event radiometry also plays a role in lightning climatology and monitoring the long-term performance of GLM. By the end of the post launch test process, we expect that GLM will contribute a version of the LIS / OTD lightning averages, shown in Figure 3, over its own field of regard. Lightning event count will be validated with an extensive list of ground networks, each covering a limited terrestrial range. Event radiometry will be characterized through background images when bright, deep convective clouds (DCCs) are available as a Lambertian surface. While GLM is not calibrated to an absolute standard, its radiometric accuracy is known. By observing DCCs, in concert with GOES-R's Advanced Baseline Imager (ABI), GLM's radiometric response over time can be trended and the energy distribution of lightning measured. Once fully characterized, these validated data products will allow lightning event rate, rate of change and intensity to be included in numerical weather prediction models and to improve the accuracy of severe storm warning and forecasting.

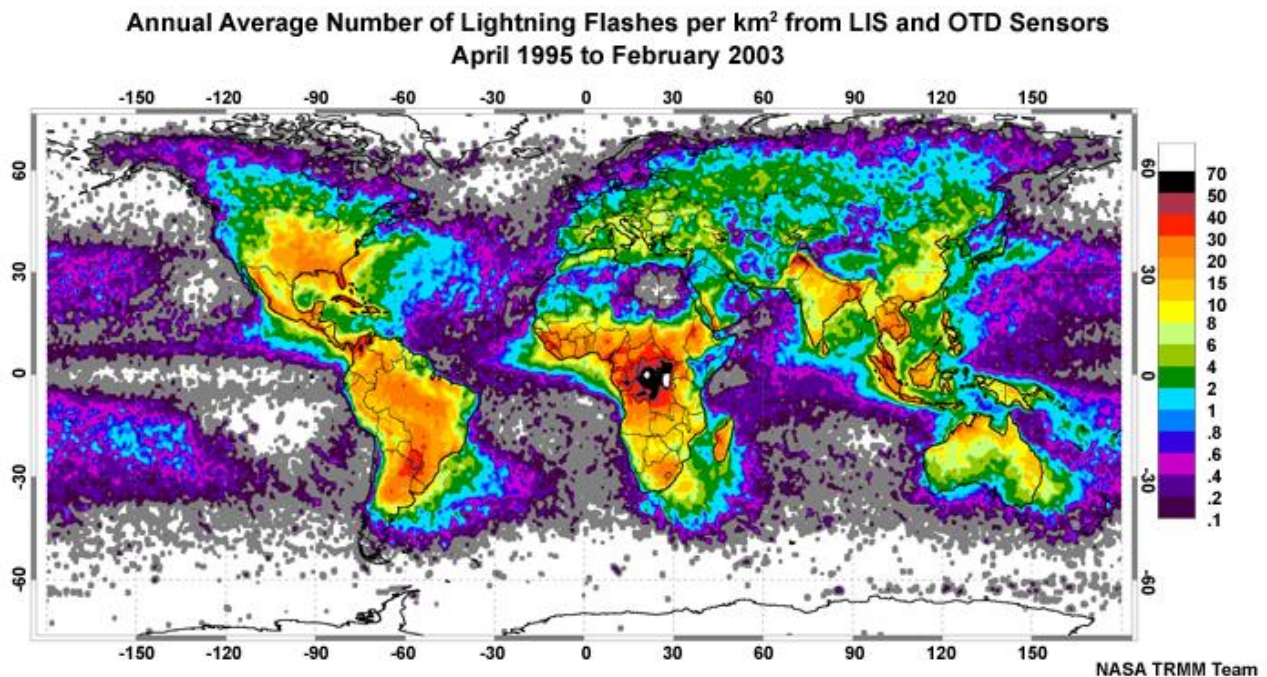


Figure 3. Estimated total lightning activity from GLM path finding instruments.

4. CONCLUSION

Lightning plays an important but still poorly understood role in severe storms. In addition to seasonal storms in the central North American plains (“Tornado Alley”), Figure 4 shows typical formation and transit regions for tropical cyclones visible to the GOES Constellation. By providing a reliable instrument that more perceptively indicates this relationship to storm intensity, we expect the accuracy of storm warnings to be greatly increased. Further, their increased precision will result in those warnings being focused on regions under direct threat rather than expanded in an abundance of caution. In both cases, we suspect that these alerts will be both credible to the public and with more advance notice to allow them to take credible action to protect their lives and livelihoods.

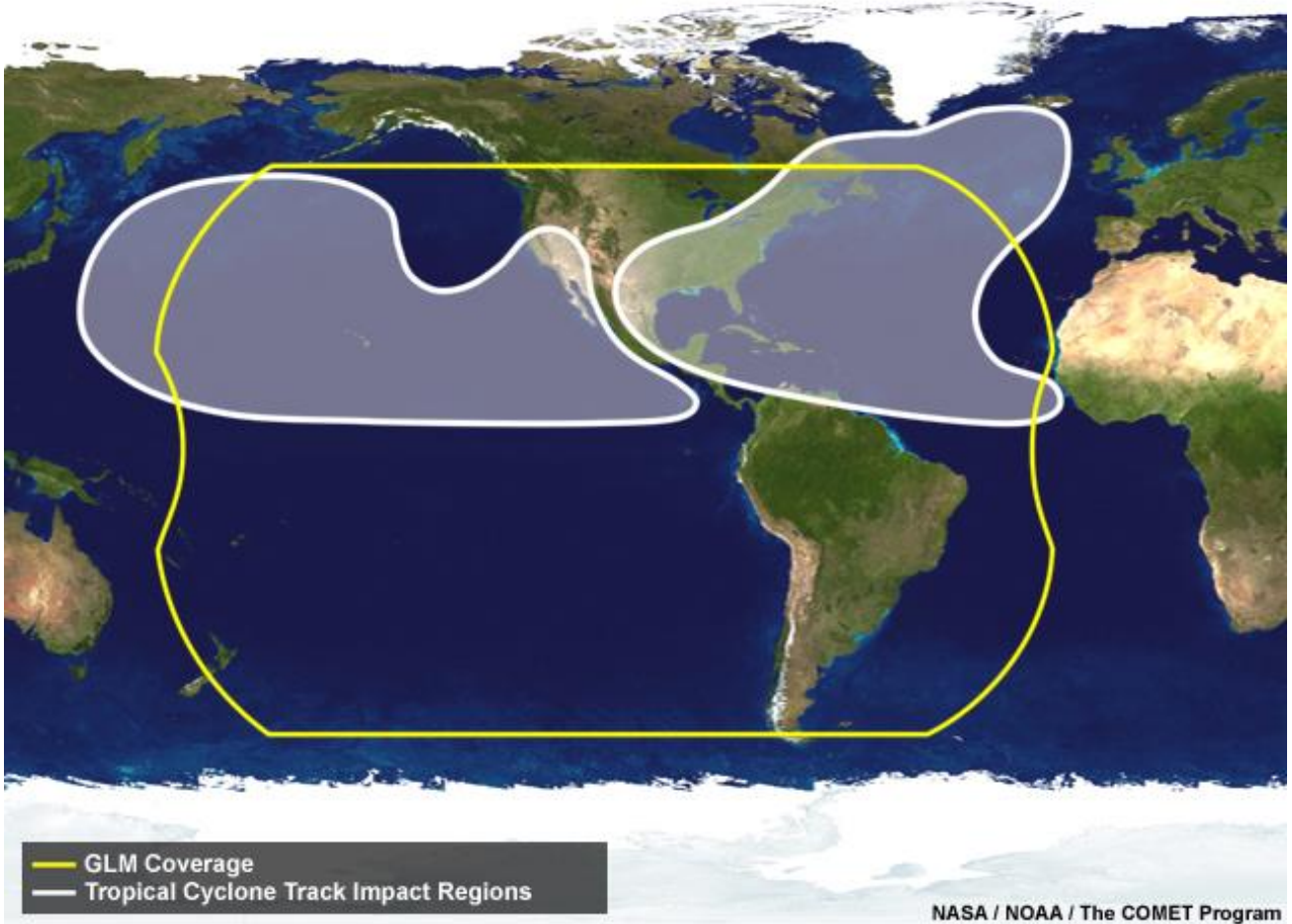


Figure 4. Tropical cyclone paths within the GLM field of regard (GOES-West and East combined)

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