On-orbit validation of the lightning location accuracy of the Geostationary Lightning Mappers (GLM) on GOES-16 and 17 using ground-based laser beacons

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GLM Overview

REQUIREMENTS:

- Provide continuous, full-disk lightning measurements for storm warning and nowcasting.
- Provide early warning of tornadic activity.
- Accumulate a long-term database to track decadal changes in lightning activity.

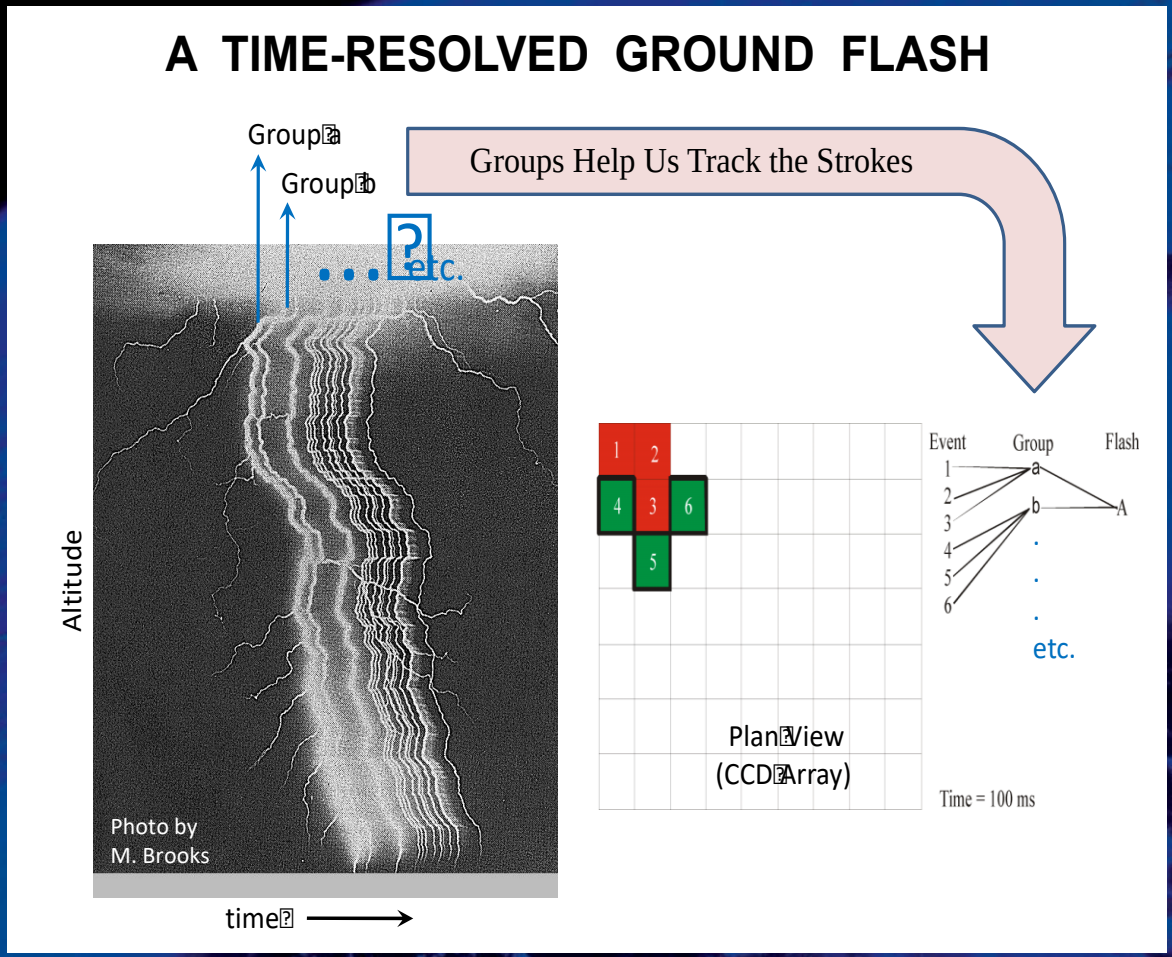
INSTRUMENT DETAILS:

- High-speed nadir-staring camera
- CCD imager (1372x1300 pixels)
- Near uniform spatial resolution
- 8 km nadir, 14 km edge of FOV
- Coverage: ±54 latitude
- Single band 777.4 nm
- 2 ms frame rate
- 7.7 Mbps downlink data rate
- 20 sec product latency

GLM is the first lightning mapper to be flown in geostationary orbit. Heritage LEO sensors include: Optical Transient Detector (1995-2000), and TRMM/LIS (1997-2015)

GLM Data Products Description

- Events: pixel-level optical detection in one frame.
- Groups: one or more (side/corner) adjacent pixel detections in one frame.
- Flashes: one or more groups within 330 ms (i.e. ~ interstroke duration), & within 16.5km.



GLM Performance Requirements

Parameter	Requirement Value
Production Mapping Accuracy [INR]	**5km** (= $\|\mu+3\sigma\|$ < 140 µrad)
Product Measurement Range	**0-600 flashes/s**
Product Measurement Accuracy	**70%** total flash detection efficiency (DE)
Flash False Alarm Rate (FAR)	**5%** flash false alarm rate (FAR)
Event Time Tag Accuracy	**1 ms**

Post Launch Product Tests (PLPT) were developed and performed by the GLM CAL/VAL Team:

- GOES-E GLM full validation attained on November 1, 2018
- GOES-W GLM in provisional mode - still undergoing PLPTs
- Cal/Val continues with ADRs/WR to refine performance

ADR: Algorithm Discrepancy Report
WR: Work Report

- References: GLM PORD (Performance and Operational Requirements Document) V2.21, 9 Oct 2018, GOES-R Series Mission Requirements Document (MRD) V3.28, May 22, 2019

GLM Cal/Val

GLM Timeline (1/2)

11/19/16 – GOES-16 Launch

4/24/17 – First usable GLM data from the GS

6/9/17 – GOES-16 Beta Maturity

6/28/17 – Updated Lookup Tables (CDRL079)

10/31/17 – Fixed “Charlie Brown” stripes

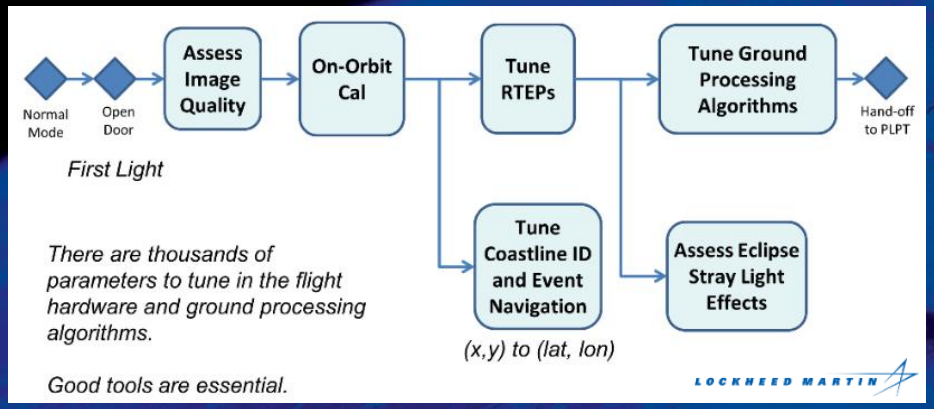
11/28/17 – Removed radiation + duplication “dots”

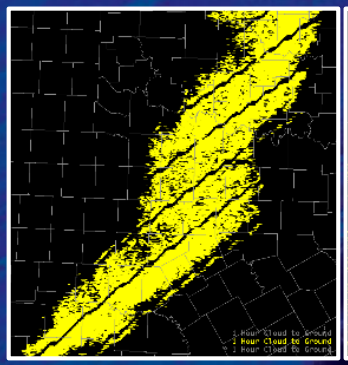
1/19/18 – GOES-16 Provisional Maturity

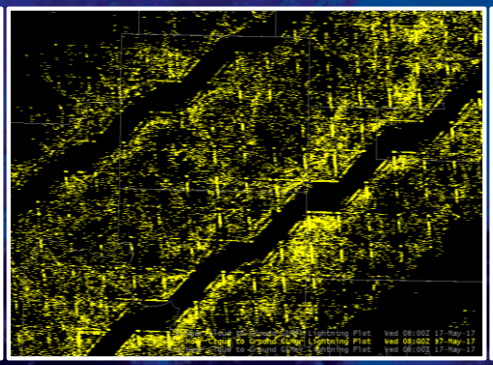
3/1/18 – GOES-17 Launch

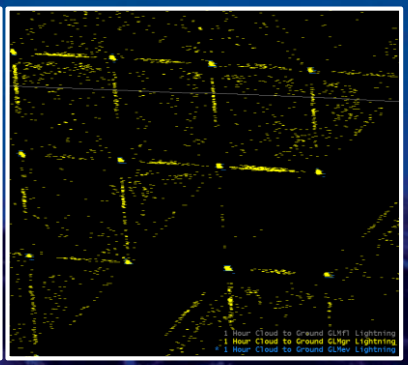
10/2/18 – GOES-17 Beta Maturity

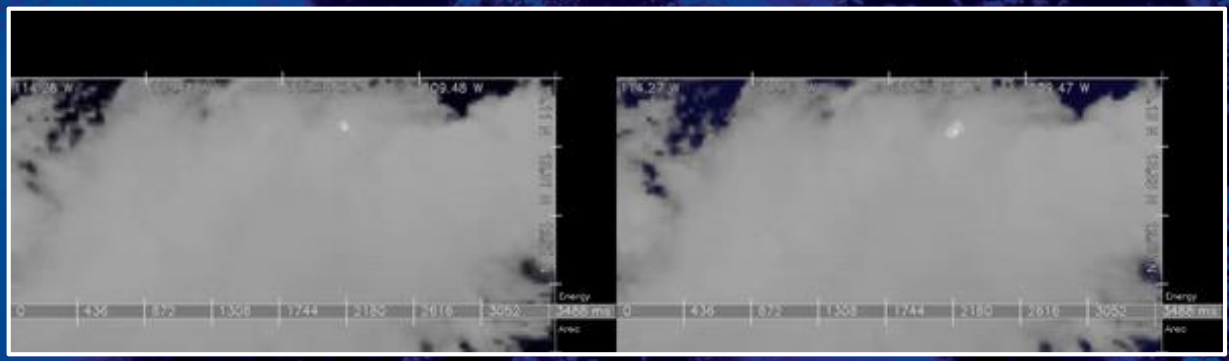
10/15/18 – Properly account for time of flight











GLM Cal/Val (Cont'd)

GLM Timeline (2/2)

10/29/18 – Updated lightning ellipsoid values

11/1/18 – GOES-16 Full Maturity

11/5/18 – Overflow valve for 'burst events'

11/15/18 – Updated 2nd level threshold

12/20/18 – GOES-17 Provisional Maturity

2/27/19 – 2nd-level threshold filter code change

4/30/19 – Updated the second level thresholds*

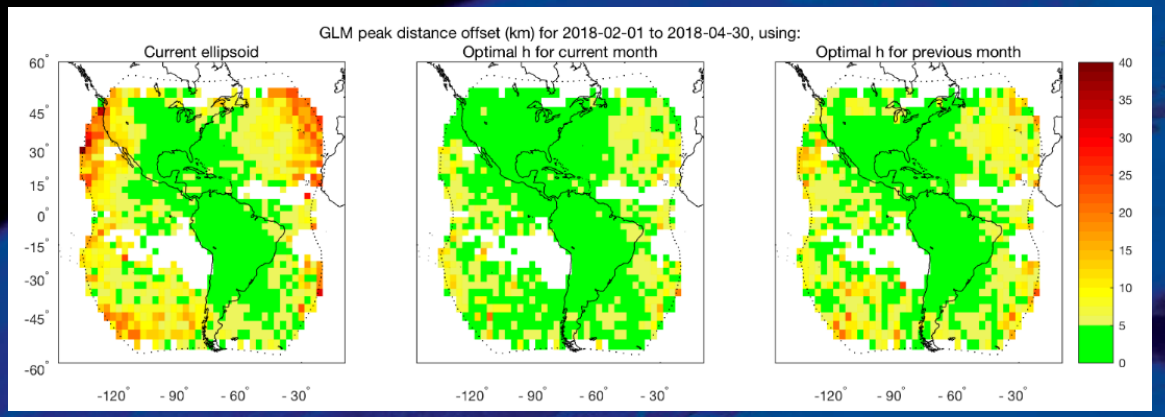
7/25/19 – GLM Blooming Filter

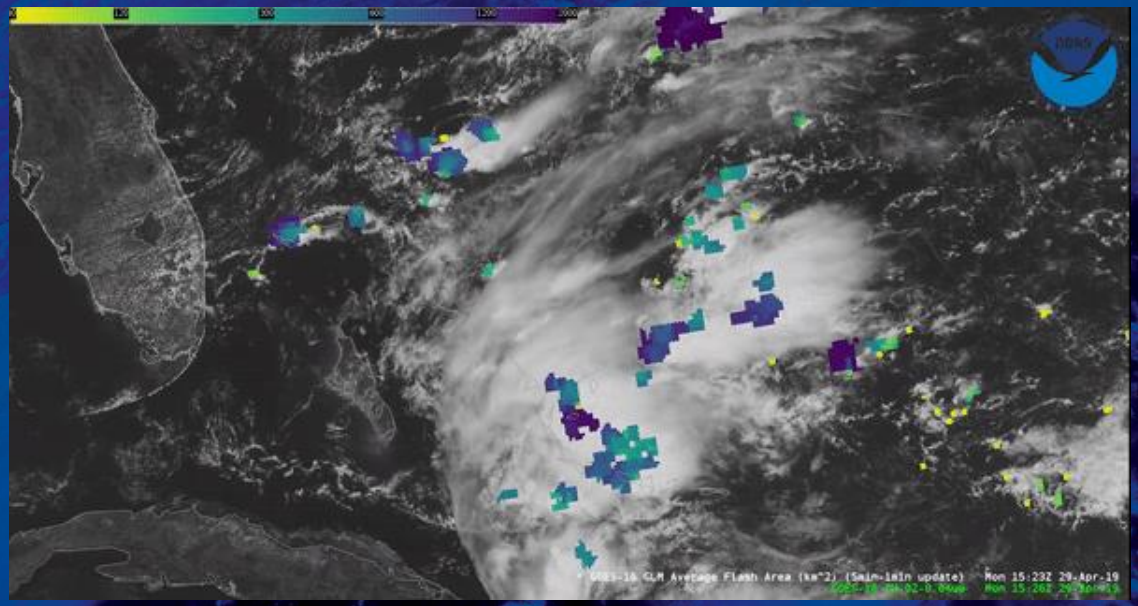
And still hope for…

GLM L2 Data Quality Product

GLM Full-Parallax Compensation

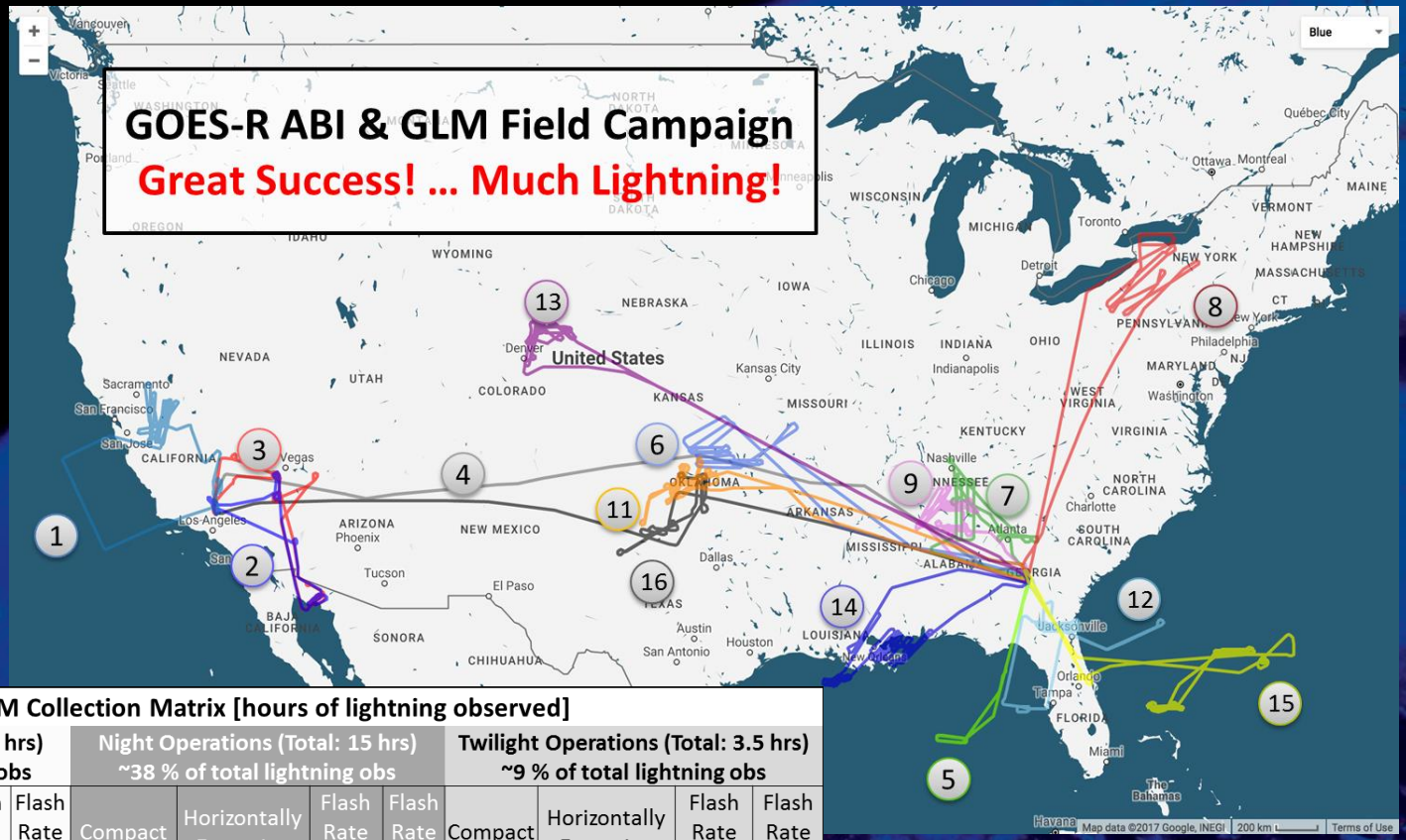
GLM Gridded Products





GOES-R Field Campaign

- GLM observations overlapping ground networks, ISS-LIS, and ER2



GLM Collection Matrix [hours of lightning observed]

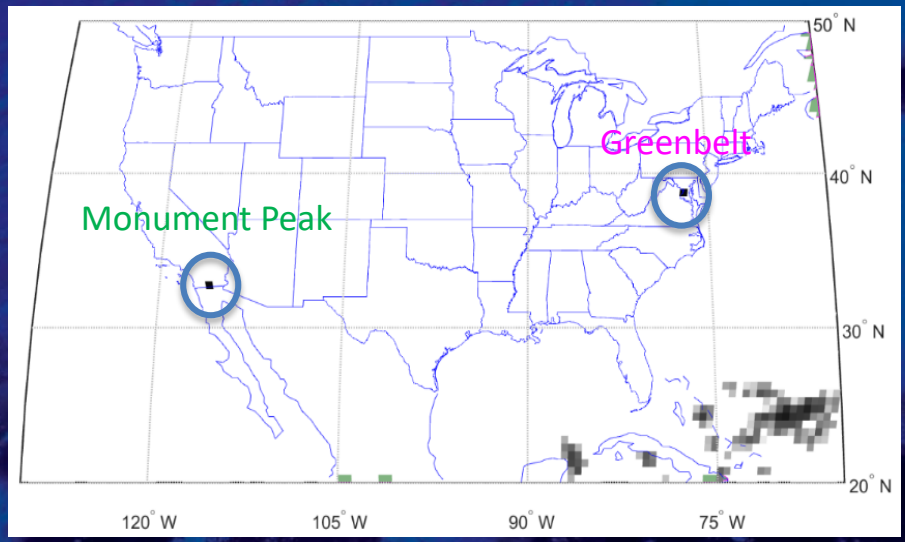
Location	Day Operations (Total: 21 hrs) ~53 % of total lightning obs				Night Operations (Total: 15 hrs) ~38 % of total lightning obs				Twilight Operations (Total: 3.5 hrs) ~9 % of total lightning obs			
	Compact	Horizontally Extensive	Flash Rate Low	Flash Rate High	Compact	Horizontally Extensive	Flash Rate Low	Flash Rate High	Compact	Horizontally Extensive	Flash Rate Low	Flash Rate High
Northern, AL	4.5		1	3.5		2.5	2.5		1.5			1.5
Norman, OK		0.5		0.5	0.5	8.5	1	8		1	0.5	0.5
Lubbock, TX						0.5		0.5				
KSC, FL	1		1									
Ft. Collins, CO	2	0.5		2.5						0.5		0.5
Atlanta, GA	1		1									
Toronto, Ca.						3	1.5	1.5		0.5		0.5
Land	1.5	4.5	3	3								
Ocean	3.5	2	5.5									

GLM Navigation

- The operational GLM navigation scheme uses GLM background images
  - Coastal boundaries from GLM background images are compared to a known high-resolution coastal database to determine navigation offsets
  - only useable from ~1000-1400 hours satellite time
  - GOES-W GLM coastlines limited to NE field of view
- Misalignments can occur due to thermal gradients from differential solar heating
- Thermal gradients are most severe at night when the satellite's nadir surface is sunlit.
- Ground and space based observations of lightning are not necessarily co-located
  - GLM detects cloud top optical signal
  - Specified cloud top height can affect GLM geolocation (parallax)
  - Ground sensors detect lightning electromagnetic signals

GLM Laser Beacons

- Laser beacon measurements provide unambiguous control points throughout the diurnal cycle that can be used to verify the image navigation algorithm
  - Laser locations are known to within a few mm
  - Lasers tuned to near 777.4 nm wavelength of GLM
  - Two lasers provide large baseline
    - Greenbelt, MD
    - Monument Peak, CA
  - The lasers are pulsed (50 Hz or 100 Hz) so GLM events are processed as lightning by the Ground Processing Algorithm (GPA)
    - The GPA geolocates the laser signal
- GLM geolocation requirement 5 km (MRD)
- No operational accommodation required
- No interference with other instruments

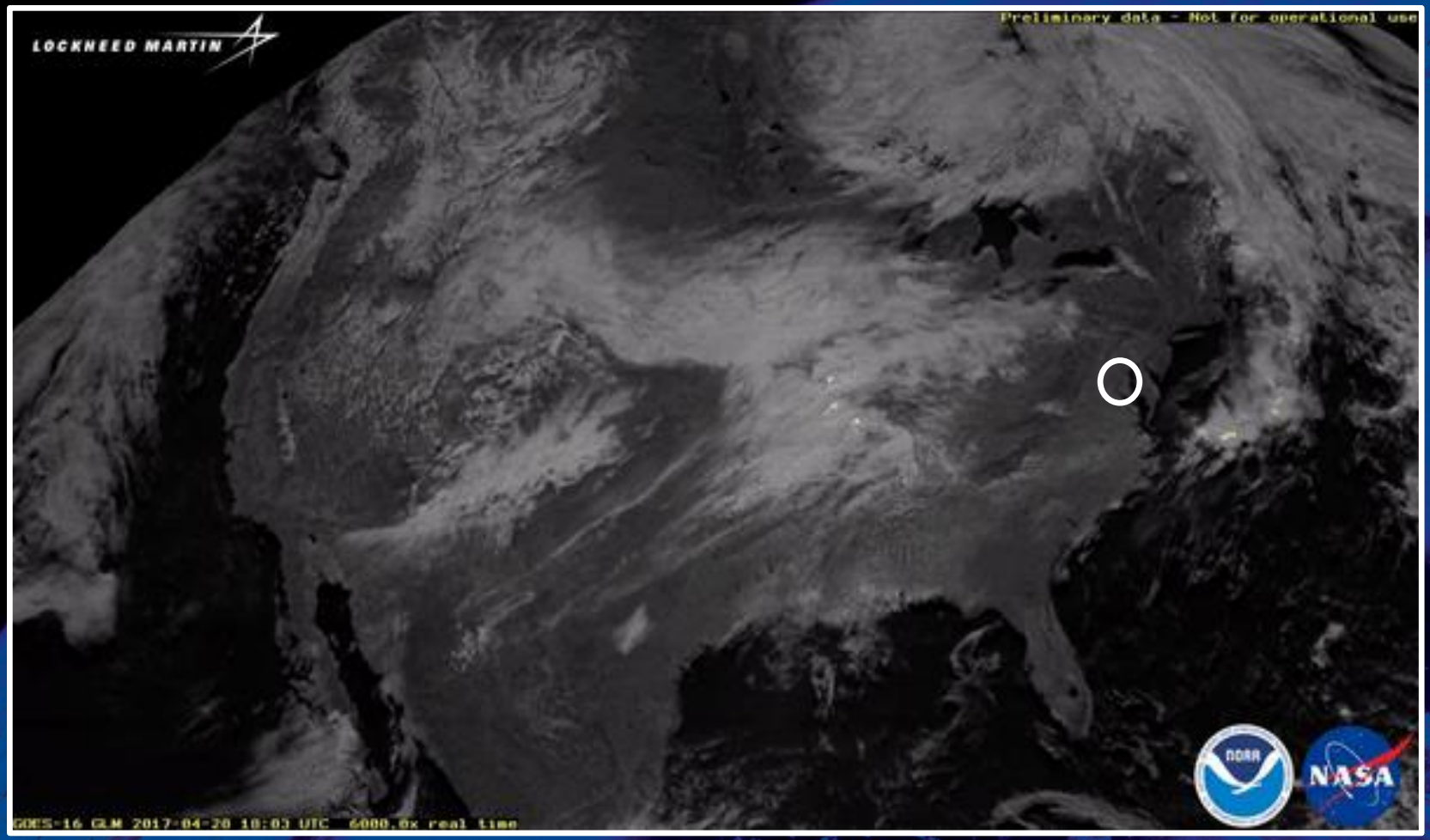


GLM Beacons use MOBLAS Satellite Laser Ranging (SRL) Facilities

The piggybacked beacon telescope-fiber optics assembly on top of the NASA SLR telescope at the MOBLAS facility.

- Advantages of SLR Laser Facilities:
  - Use existing staff
  - Staff trained in satellite pointing using ephemeris data
  - Ability to perform GLM beacon operations along with normal SLR operations
  - Cost effective
  - Greenbelt, MD (MOBLAS 7)
  - Monument Peak, CA (MOBLAS 4)

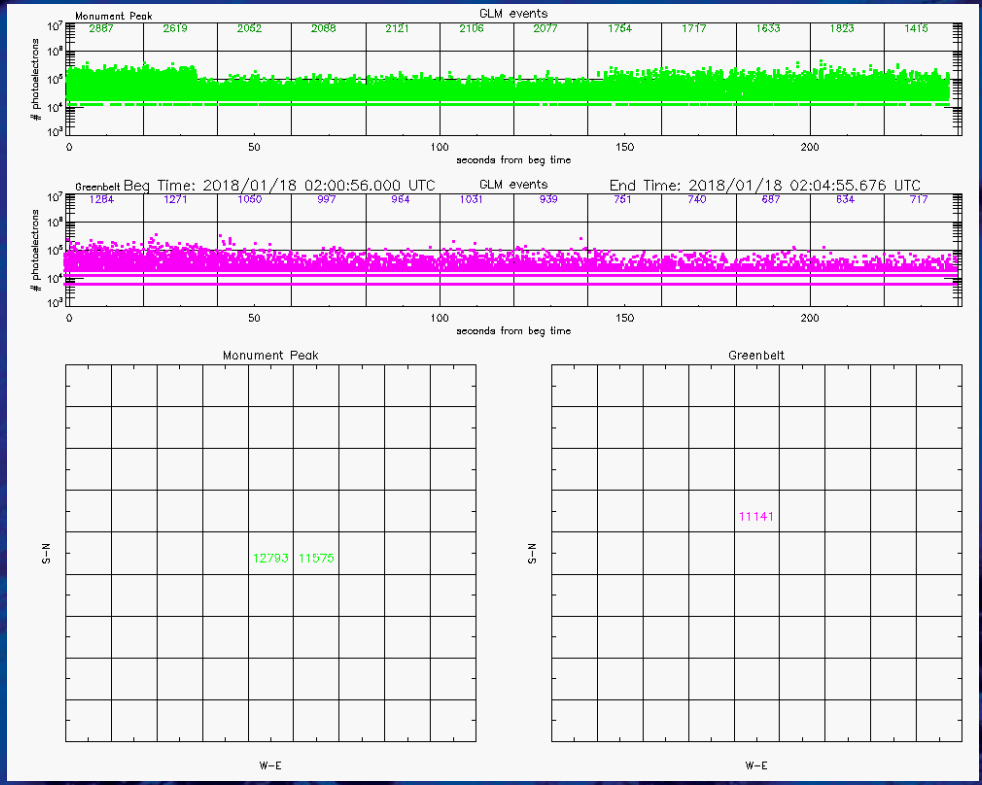
GLM Background Image Animation with Lightning



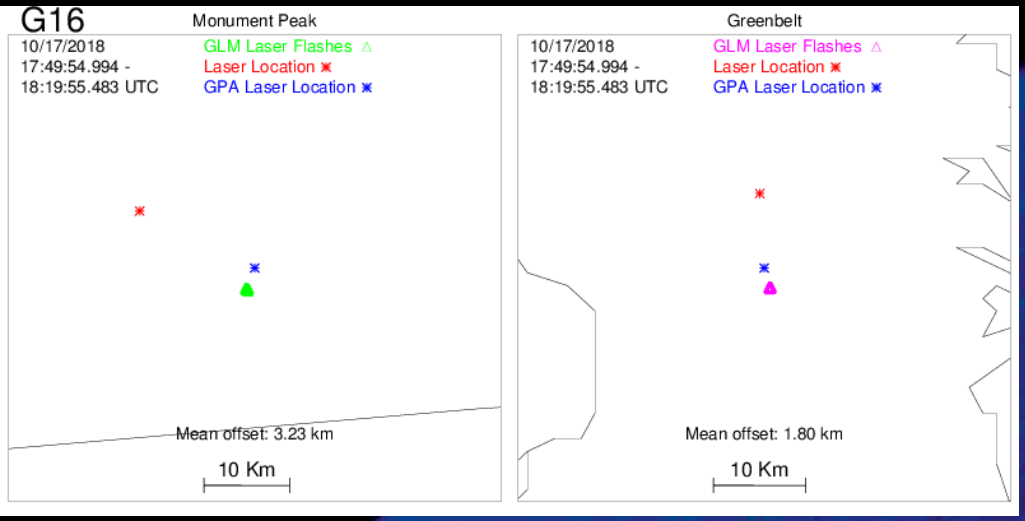
Circle denotes Greenbelt laser beacon location

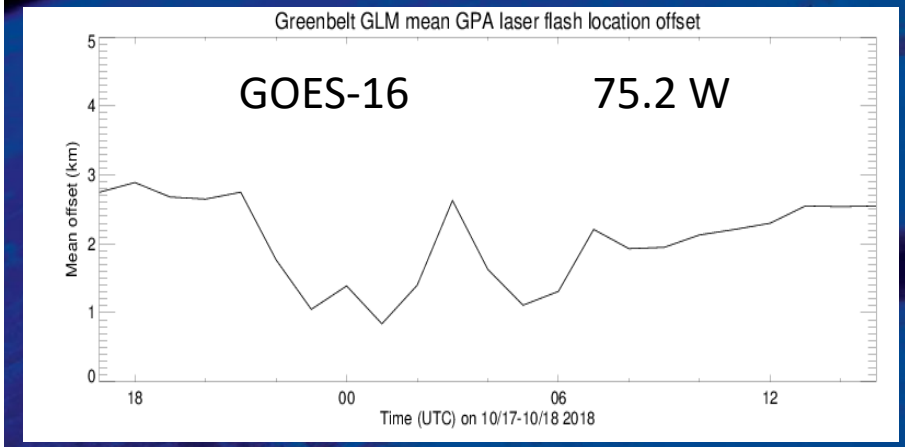
Real time Laser Beacon Web Page

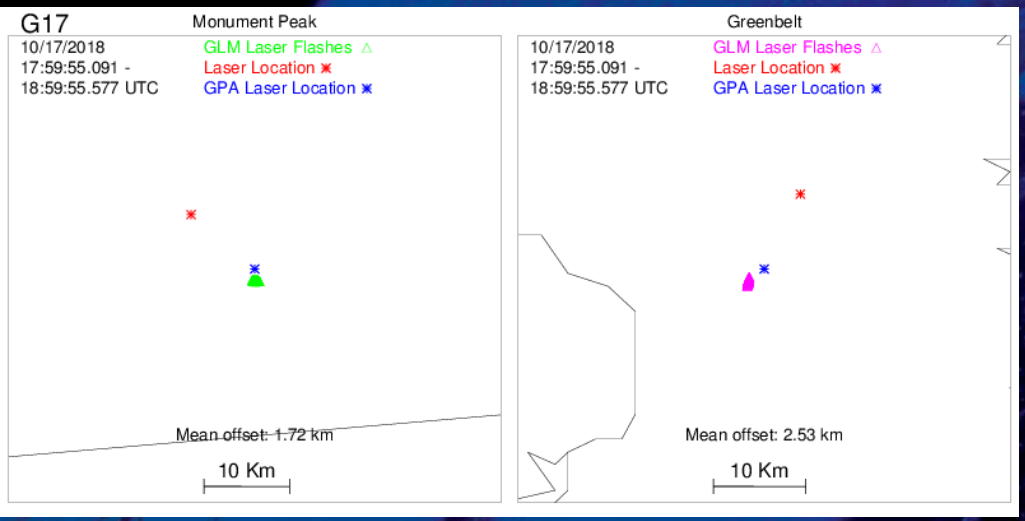
- GLM Laser Beacon Operations
  - Need ability to monitor GLM activity at laser beacon sites
  - Near Real time web display was developed
  - GLM L2 data obtained via NOAA PDA (Product Distribution and Access)
  - Display latency of 1-2 minutes

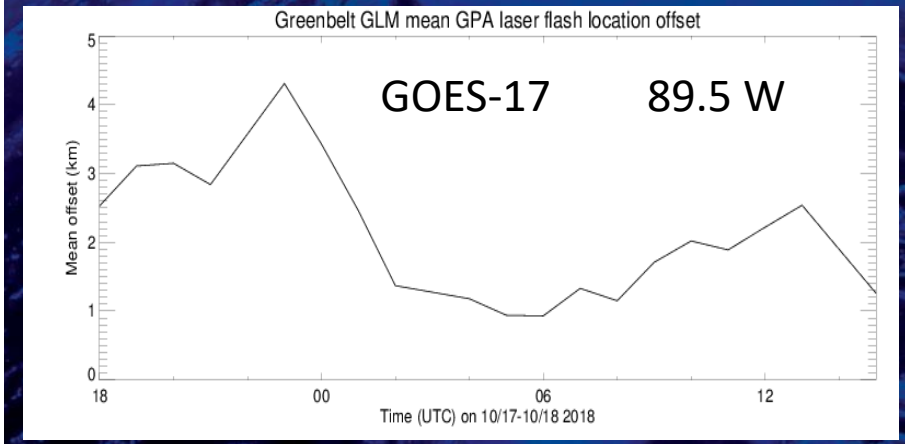


Real time Laser Beacon Results









Summary and Conclusions

- Demonstrated laser signal can be detected by GLM
- The laser signal detected by GLM passes through the GPA as lightning
- Developed a methodology for real time monitoring of GLM laser lightning
- Verified that the GLM “lightning” flashes achieved the MRD 5 km offset requirement over the diurnal cycle

GLM Forecaster Comments

The GLM products are nice for confirming that a storm is strong, or developing, but radar is still the best choice for monitoring storm evolution. It was nice though to observe that the AFA product identified a developing cell (in bright green at 23:47) and increasing lightning activity directly over the airport as we were hearing the first thunder, which was not picked up be the NLDN right away. Early detection of lightning is important because we are supposed to notify airport operations when lightning is within 5 miles."

"GLM highlighted areas of concern for lightning. At times, GLM picked up on lightning that ground-based networks failed to."

"It was useful showing the lightning activity within a storm cell being updated every one minute. In a data sparse area with poor radar coverage in many areas of the CWA, this certainly helps in providing greater temporal and spatial coverage where the radar may not pick up the full column of an updraft."

"As for using this for severe weather ops, the GLM is helpful on seeing where the stronger convection is, as you can observe the changes in GLM intensity with time."

"I need to stress that the GLM over the mtns is very helpful, especially for initiation and for wintertime ltg. Radar coverage in the mtns is poor to say the least and having the GLM and NLDN helps us know where the stronger convection is."

Backup Slides

Laser Specifications

Parameter	Requirement	Rationale
Wavelength (λ)	777.2 ± 0.3 nm	GLM's central λ at ~6.4° field angle
Pulse Repetition Frequency (PRF)	50 Hz	Min PRF > 3 Hz Coherency filter Max ~ 100-200 Hz for threshold relaxation
Pulse Duration (τ)	1.5 msec	Maximize power from CW laser & minimize frame splitting (1.8 msec exposures)
Received energy/pulse	> 50,000 photo-e's < 1,500,000 photo-e's	Exceed threshold by ~10x to permit centroiding Prevent saturation
Mode/ polarization	Mostly TEM00 Polarization not critical	Maximize received energy

Laser Design: Optically modulated CW laser, variable PRF but operated at 50 or 100 Hz

Laser Beacon Test Procedure

- The satellite ephemeris was obtained weekly from NOAA
  - Used to determine pointing angles
- Schedule dates 1-2 weeks in advance
- Notify NOAA so user notifications can be sent out
- Monitor weather conditions at sites
- Morning of test confirm go/no go based on:
  - Weather (clouds or high winds)
  - Personnel
  - Data availability
- Start web tool for monitoring test
  - Hosted on the GOES-R Field campaign web site

No Plausible Damage to GLM or ABI

Both GLM and ABI required to survive direct Sun in the FOV for > 2 min

Worst-case laser illumination of GOES-R (requiring major errors by beacon operators) won't damage the GLM or the ABI

1. GLM laser beacon operated in CW mode:
   890x weaker than direct sunlight in a single pixel
2. Wrong laser: Nd:YAGx2 @ 532 nm:
   Not focused on ABI's FPA (Blocked by spectral filters)

Laser Beacon Web Page: Real Lightning Example