

# On-orbit validation of the geolocation accuracy of GOES-16 Geostationary Lightning Mapper (GLM) flashes using ground-based laser beacons

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# Geostationary Lightning Mapper (GLM)

The GLM data shown in this presentation

# Geostationary Lightning Mapper (GLM)

New Instrument on GOES-R Series Satellites

Natural Hazards and Lightning

- Tornadoes
- Hailstorms
- Wind
- Thunderstorms
- Floods
- Hurricanes
- Volcanoes
- Forest Fires
- Air Quality/NOx

# GLM Overview

## Spaceborne Instrument parameters

Staring sensor with truncated  $8^\circ$  radius circular FOV

At nadir  $30 \times 30 \mu\text{m}$  pixel has  $8 \times 8 \text{ km}$  footprint

Pixel pitch decreases with increasing field angle

to minimize footprint growth

$1372 \times 1300$  pixel array, single spectral band:  $\lambda = 777.4 \text{ nm}$   $\Delta\lambda = 1 \text{ nm}$

503 Hz frame rate

## Onboard processing (Real Time Event Processor [RTEP])

Signal in each pixel compared to background (average of previous signals in same pixel)

Event detected when Pixel Signal  $>$  Threshold + Background

Background saved every 2.5 minutes and used for image navigation

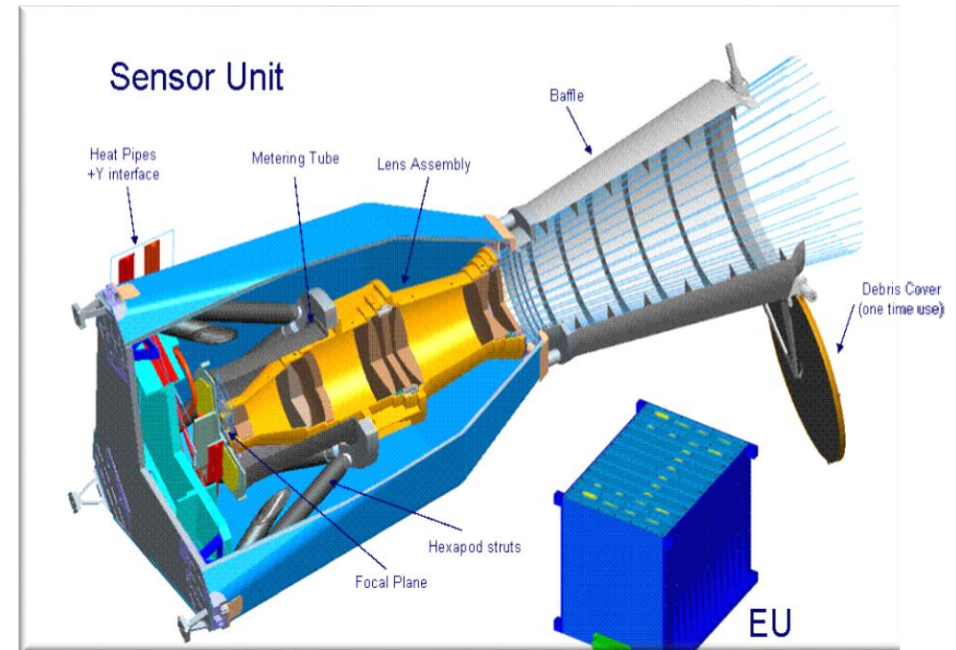
## Ground processing

Lightning flash declared when 2+ spatially overlapping groups are detected within  $1/3 \text{ sec}$

Flashes at same frame time & adjacent pixels grouped

SW filters eliminate cosmic ray streaks, contrast leakage, sun glints, etc.

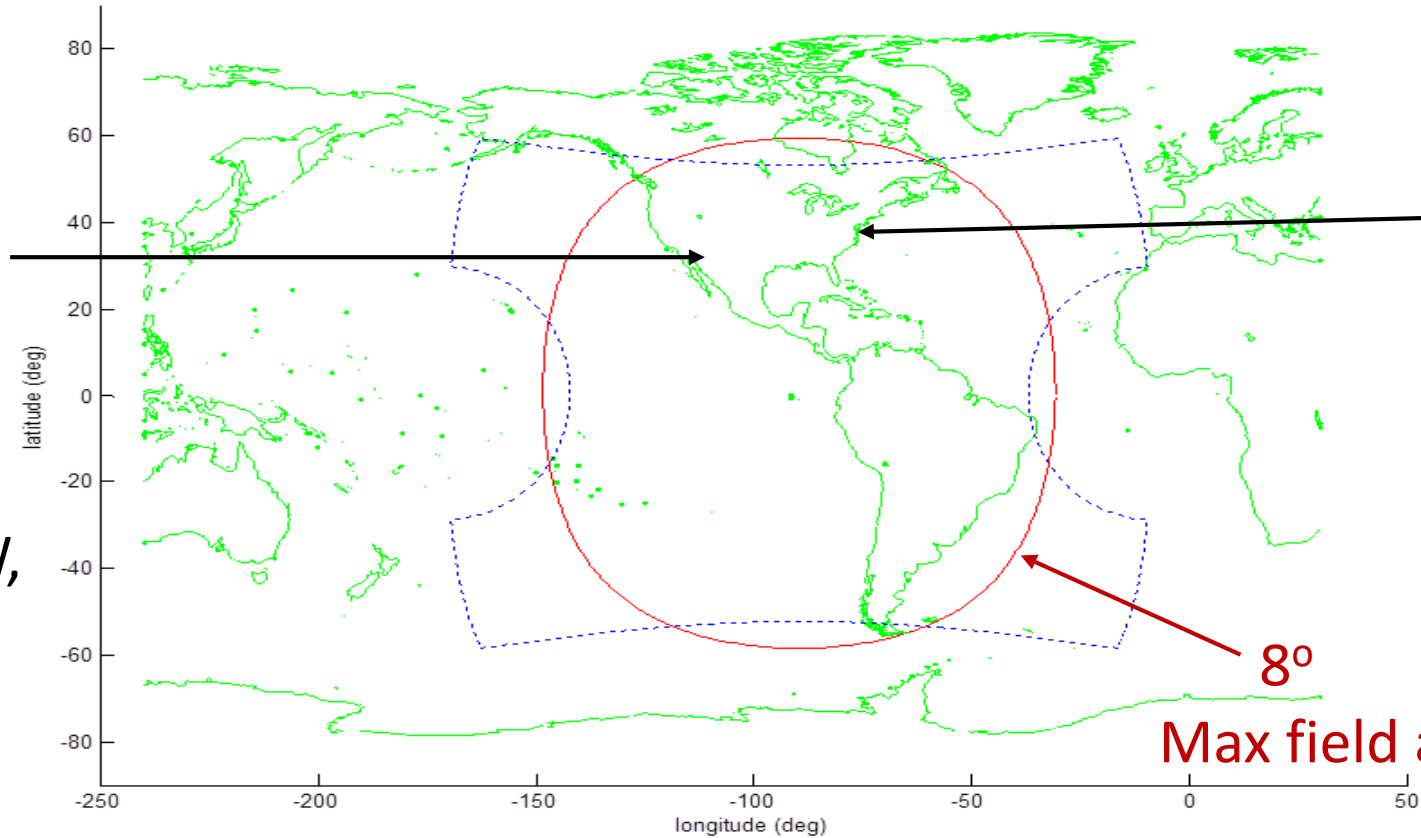
Can detect lightning against 100x brighter cloud background



# GLM's Coverage from GEO @ 89.5° W

(intersection of 2 curves)

Mon. Pk.  
116.4° W  
32.8° N  
GLM field  
angle  
 $\theta_x = 3.72^\circ$  W,  
 $\theta_y = 5.26^\circ$  N



GSFC  
76.5° W  
39.0° N  
GLM Field  
angle  
 $\theta_x = 1.67^\circ$  E,  
 $\theta_y = 6.11^\circ$  N

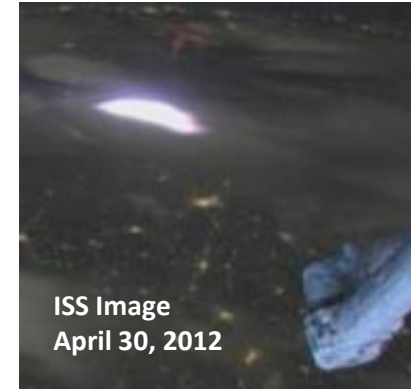
Using MOBILAS sites within the USA minimizes cost & requirements (e.g. ITAR)

# Optical Lightning Detection: How it works

**Lightning from Space:** Lightning appears like a pool of light on the top of the cloud as the discharge lights up the cloud.

**Daytime Challenge:** During day, sunlight reflected from cloud top dominates the lightning signal. Daytime lightning detection drove the design.

**Solution:** Special techniques are applied to extract the weak, transient lightning signal from the bright, background signal.



<p><b>Spatial</b></p> <p>Optimal sampling of lightning scene relative to background scene.</p> <p>Pixel field-of-view 4-10 km.</p>		<p><b>Spectral</b></p> <p>Optimal sampling of lightning signal relative to background signal.</p> <p>LIS uses 1nm filter at 777.4 nm.</p>		<p><b>Temporal</b></p> <p>Optimal sampling of lightning pulse relative to background signal.</p> <p>LIS uses 2 ms frame rate.</p>	
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- Even with spatial, spectral and temporal filters, background can exceed lightning signal by 100 to 1 at the focal plane.
- The final step is a frame-by-frame background subtraction to produce a lightning only signal
- Filtering results in  $10^5$  reduction in data rate requirements while maintaining high detection efficiency for lightning.

**Background Subtraction**

Optimal subtraction of background signal levels at each pixel.

Transient events selected for processing.

Input Signal: Background Scene + Optical Transients

Averaged Background

Optical Transients

Programmable Threshold

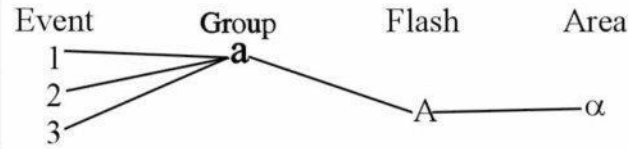
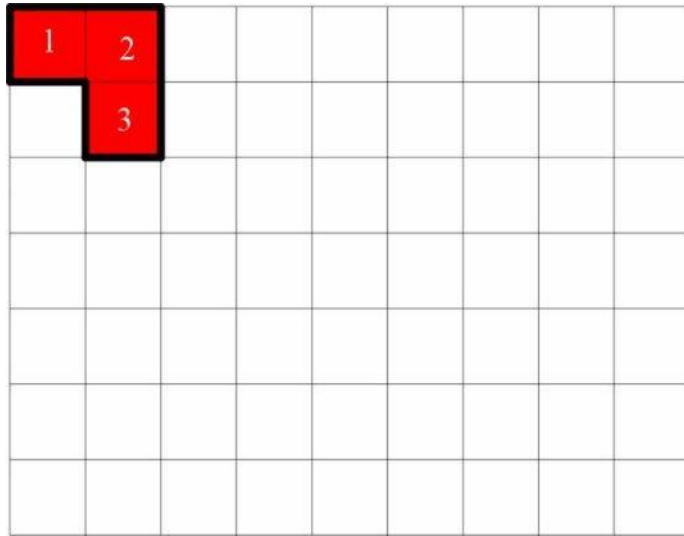
Optical Transients

COMPARATOR A > B

Qualified Lightning Events

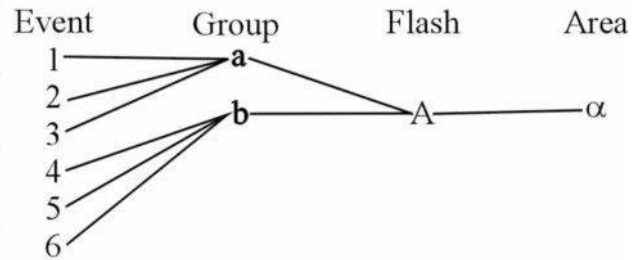
(a) (b)

# Events Clustered to Flashes



Time = 0 ms

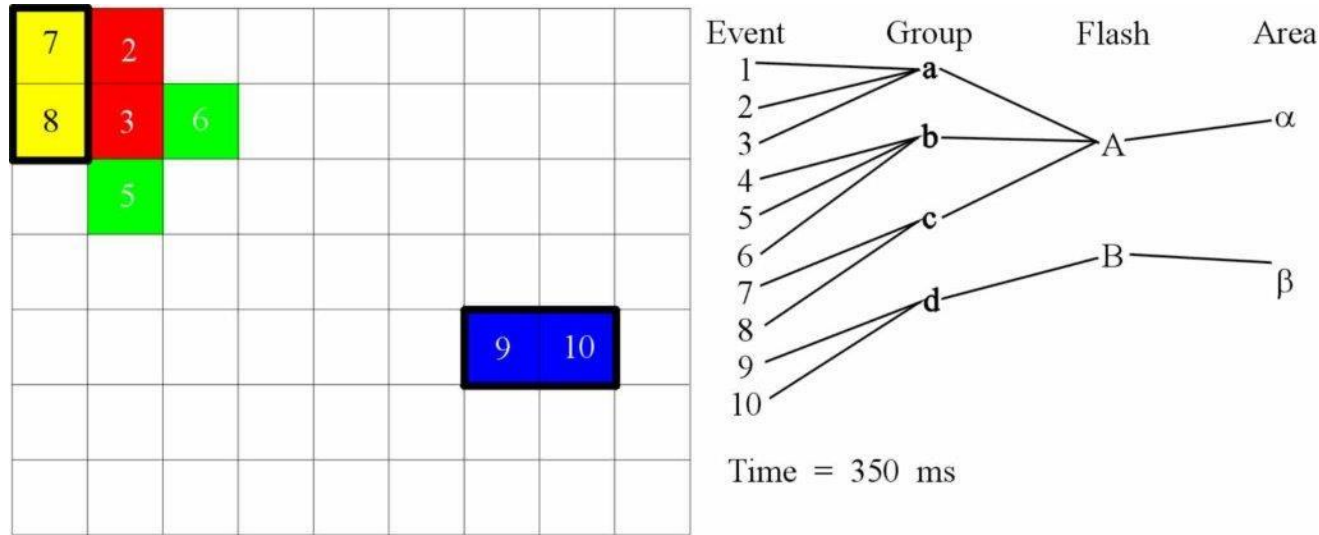
**Groups - Events  
that occur at same  
frame time in  
adjacent pixels**



Time = 100 ms

**Flashes – Groups  
that occur close  
together in space  
and time**

# Events Clustered to Flashes (cont'd)



**A flash is ended when no nearby groups occur for 1/3 s.**

**GLM products – Geolocated (latitude, longitude), calibrated (i.e., radiant energy) events, groups , and flashes**

**Event geolocation – pixel latitude, longitude adjusted to specified cloud top height**

**Group geolocation – Radiance weighted mean event location**

**Flash geolocation – Radiance weighted mean group location**



# Why are Laser Beacons Beneficial?

- The GLM's lightning detections must be navigated to  $140 \mu\text{rad}$  ( $3\sigma$ ) to provide geographically accurate severe weather warnings.
- The GLM's error budget allocation is  $112 \mu\text{rad}$  ( $3\sigma$ ).
- The primary image navigation with respect to land features in the background Earth imagery is only useable from  $\sim 1000$ - $1400$  hours satellite time
- Navigation is extrapolated for entire day assuming GLM's FOV is fixed with respect to GOES-16's attitude reference from startrackers
- Thermal gradients can change the boresight between the GLM & the startrackers. They are most severe at night when the satellite's nadir surface is sunlit.
- The GLM's wide-FOV lens assembly contains a large number of refractive elements. Misalignments among them can change boresight, focus & plate scale. Radiation can change indices of refraction over the lifetime of the mission.
- Ground and space based observations of lightning are not necessarily co-located
- The beacon measurements provide unambiguous control points throughout the diurnal cycle that can be used to verify the image navigation algorithm and the GLM optical model or, if necessary, modify them.

# Laser Requirements

Parameter	Requirement	Rationale
Wavelength ( $\lambda$ )	777.2 $\pm$ 0.3 nm	GLM's central $\lambda$ at $\sim$ 6.4° field angle
Pulse Repetition Frequency (PRF)	50 Hz	Min PRF > 3 Hz Coherency filter Max $\sim$ 100-200 Hz for threshold relaxation
Pulse Duration ( $\tau$ )	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 $\sim$ 10x to permit centroiding Prevent saturation
Mode/ polarization	Mostly TEM00 Polarization not critical	Maximize received energy

# GLM Beacons use MOBLAS Satellite Laser Ranging (SRL) Facilities

Beacons share existing MOBLAS pointing & tracking systems, and co-boresighted radar with shutter (Facilitates GSFC Code 350, FAA & LCH safety approval)

MOBLAS sites at Greenbelt, MD & Monument Peak, CA provide a long baseline within the GLM's FOV for GOES-16 & 17 during PLT (89.5° W) & for GOES-16 operating as GOES-E (75.2° W)

Laser beacon pulses transmits ~1.5 ms pulses @ 50 Hz & 777.2 nm (optimized for field angles)

Identical detection & processing for natural lightning & beacon pulses

No operational accommodation required for satellite nor interference with other instruments



## **MOBLAS Station (above)**

Laser located inside station laser room & fiber coupled to telescope (important for safety, T &  $\lambda$  control)

# GLM Beacons use MOBLAS Satellite Laser Ranging (SRL) Facilities

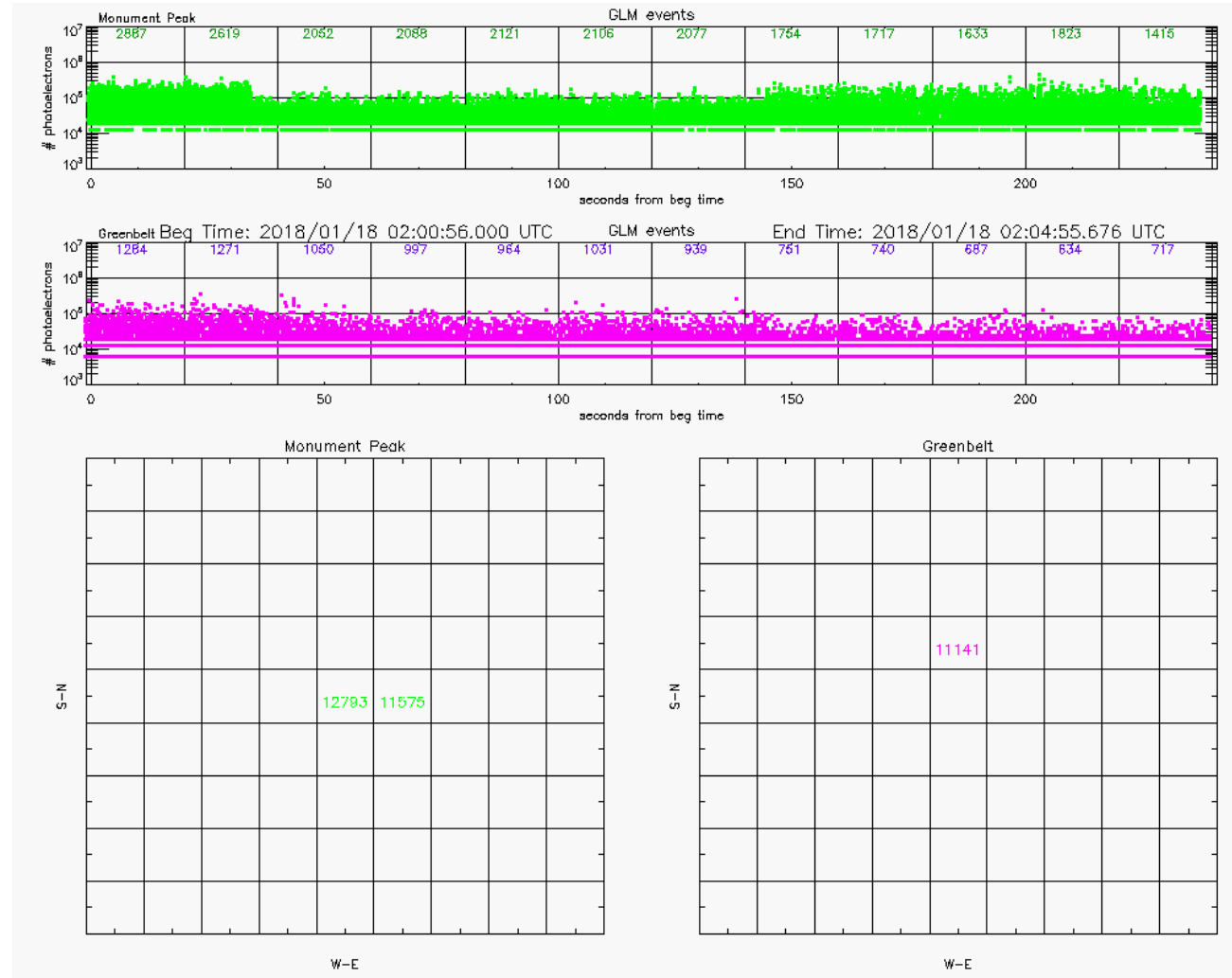


The piggybacked beacon telescope-fiber optics assembly on top of the NASA SLR telescope at the MOBLAS facility.

- Advantages of MOBLAS Laser Facilities:
  - Already staffed
  - 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)

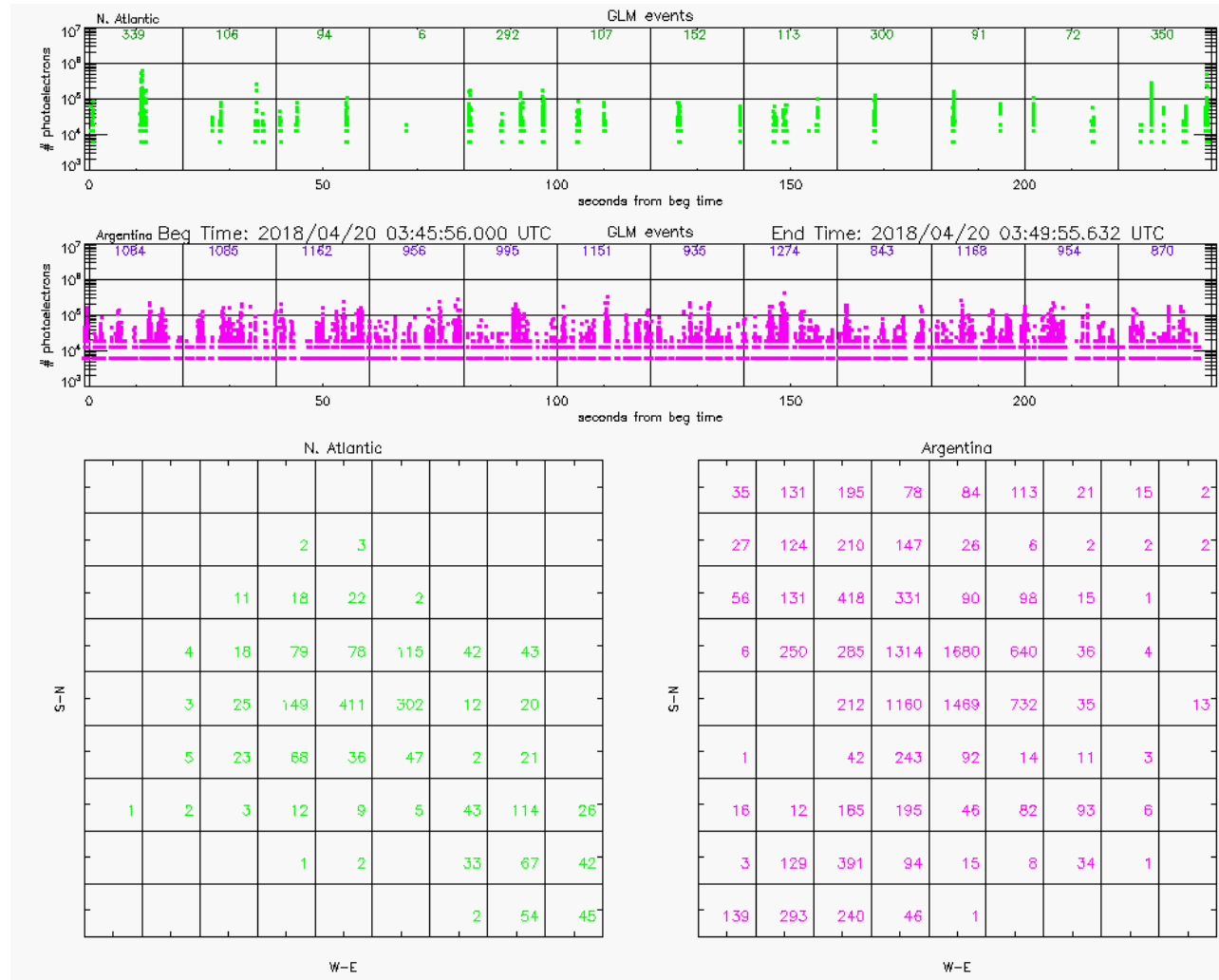
# Laser Beacon Web Page

- 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



These GOES-16 data are preliminary, non-operational data and are undergoing testing. Users bear all responsibility for inspecting the data prior to use and for the manner in which the data are utilized.

# Laser Beacon Web Page: Real Lightning Example



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# 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

# Laser Operations

Date	Time (UTC)	Location GB-Greenbelt MP-Monument Pk	Notes
April 19, 2017	0152-0352	GB	
April 29, 2017	0055-0200	GB	
May 3, 2017	1720-1850	GB	dither
May 8, 2017	1730-1840	GB	
June 9, 2017	1645-1710	GB	
June 11, 2017	0300-0340	GB	
June 13, 2017	1700-1712	GB	dither
June 24, 2017	0420-0510	MP	
June 28, 2017	1750-1754	GB	Very few events
July 13, 2017	0339-0715	GB & MP	
Aug 10, 2017	0225-0323 1440-1552	GB & MP GB & MP	Night Day
Sep 5, 2017	1405-1455	GB & MP	

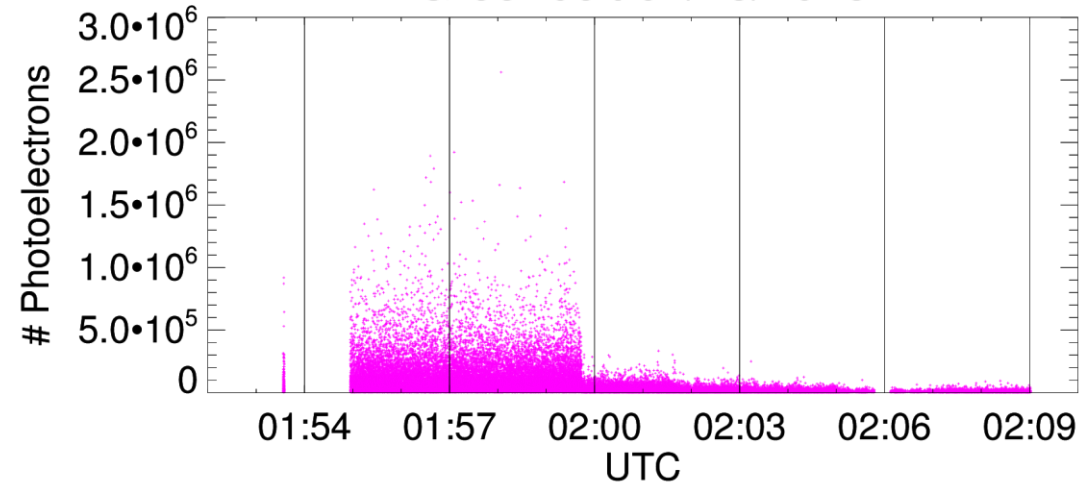


# Laser Operations (continued)

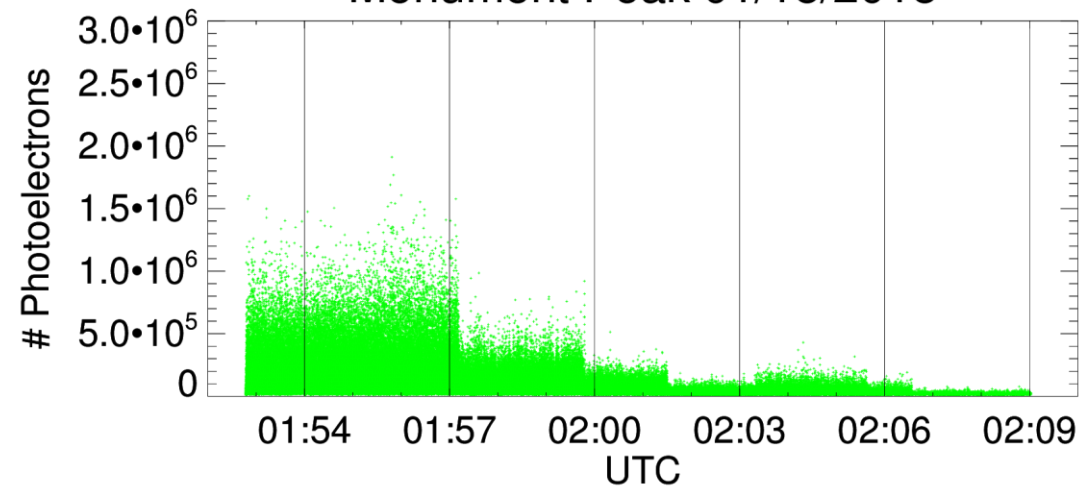
Date	Time (UTC)	Location GB-Greenbelt MP-Monument Pk	Notes
Sep 21, 2017	1450-1655 1850-1830	GB & MP GB & MP	
Oct 2-3, 2017	1020/2-1409/3	GB & MP	24 hr test (hourly obs)
Nov 28, 2017	0340-0425	GB	
Nov 29, 2017	0250-0320 2149-2215	GB & MP GB & MP	
Nov 30, 2017	0350-0415	GB & MP	
Dec 19, 2017	2115-2130 2200-2240	MP GB & MP	At 75.2° W
Dec 20 , 2017	0010-0045 0155-0225	GB & MP GB & MP	
Jan 5, 2018	0018-0040 2250-2328	GB GB & MP	
Jan 6, 2018	0210-0240	GB & MP	
Jan 17, 2018	2225-2255	MP	
Jan 18, 2018	0150-0210 0445-0515	GB & MP GB & MP	

# Results: Time Series

## Greenbelt 01/18/2018

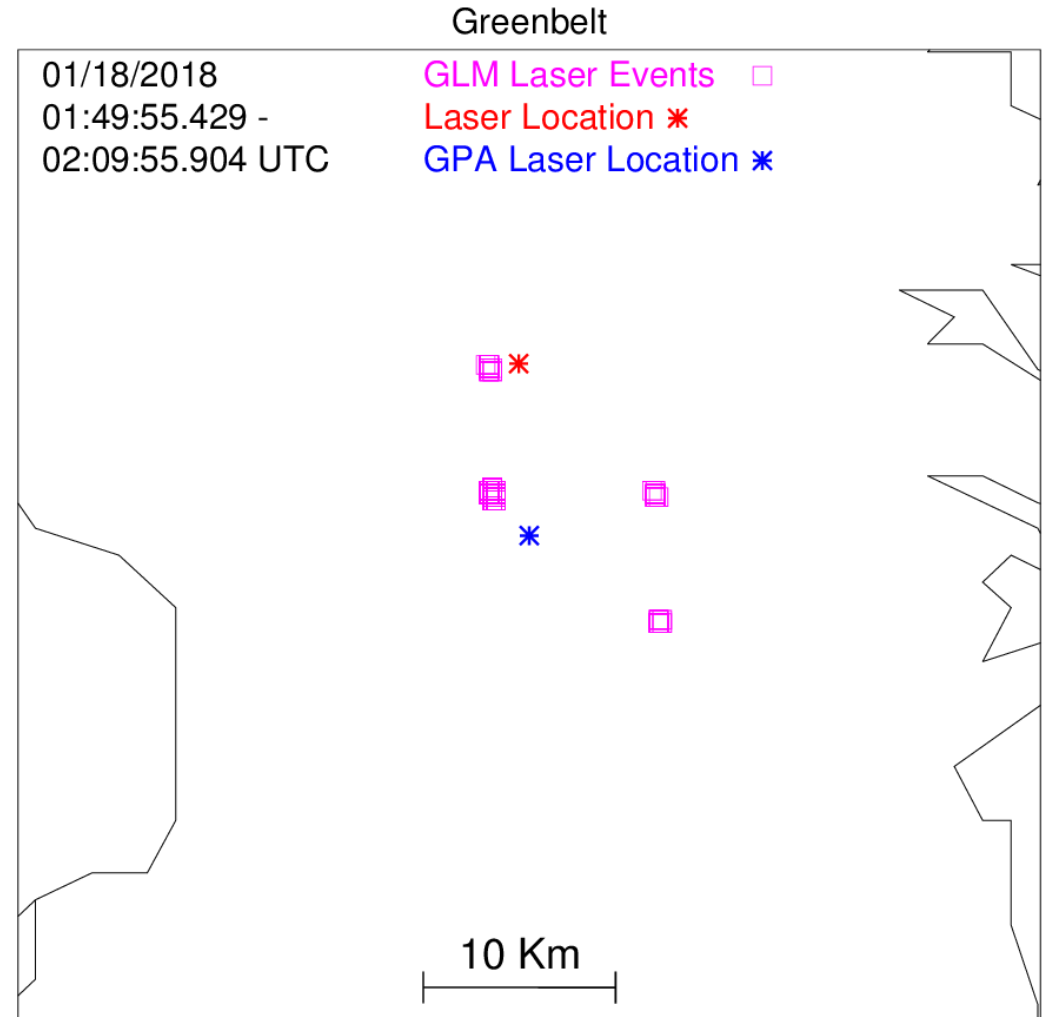
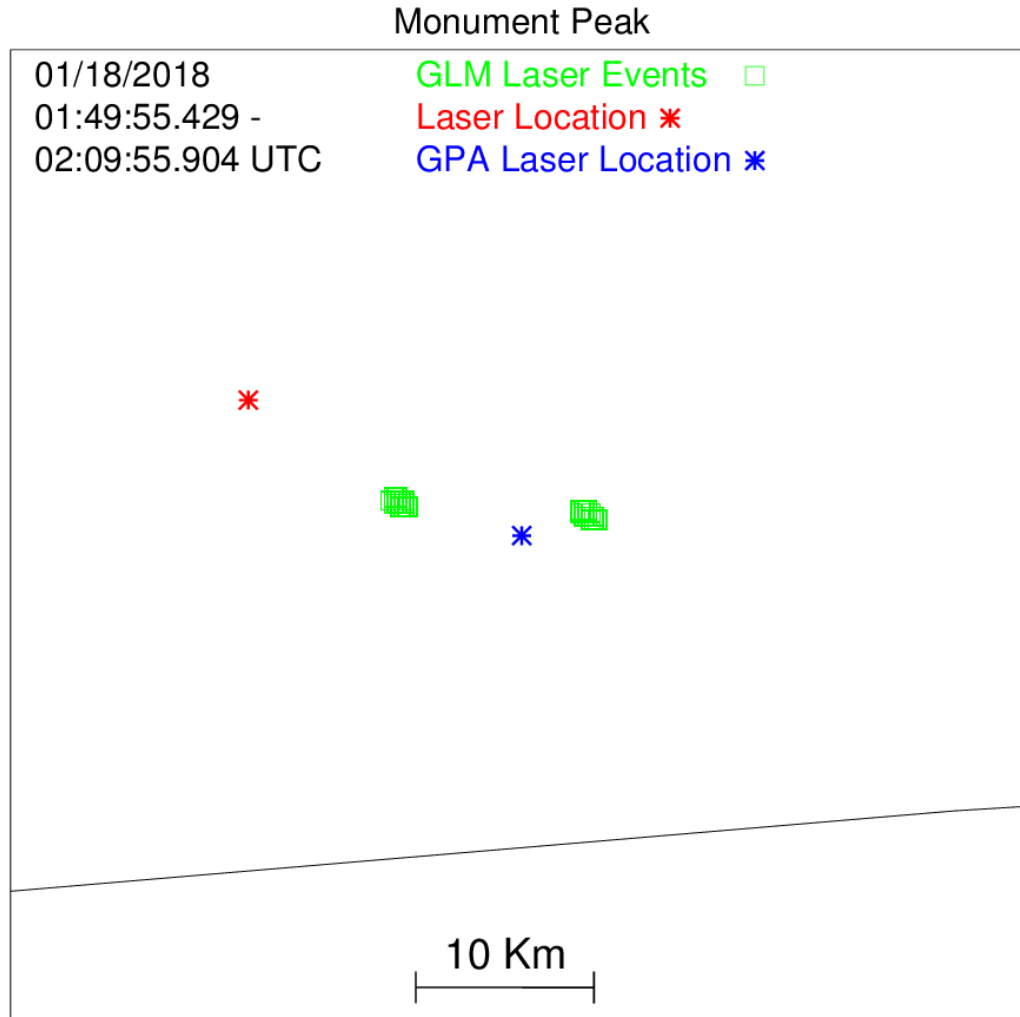


## Monument Peak 01/18/2018



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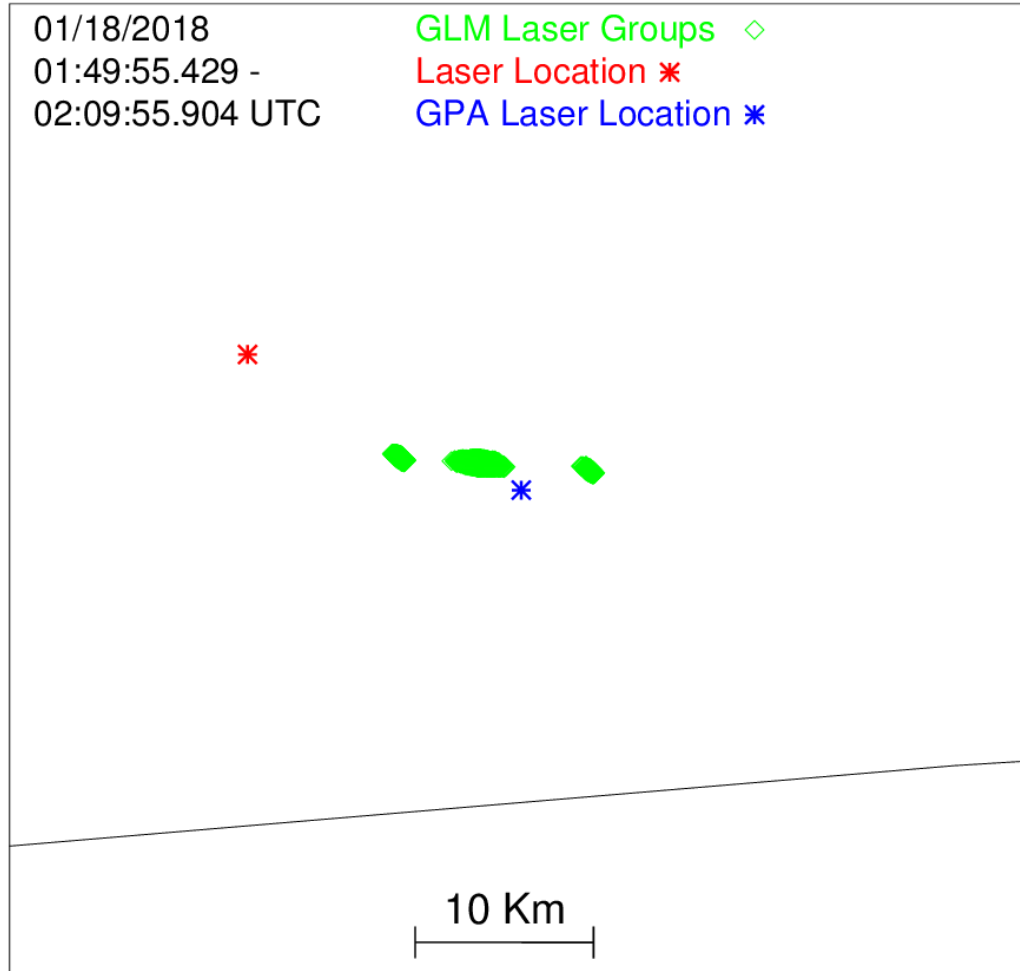
# Results: Events



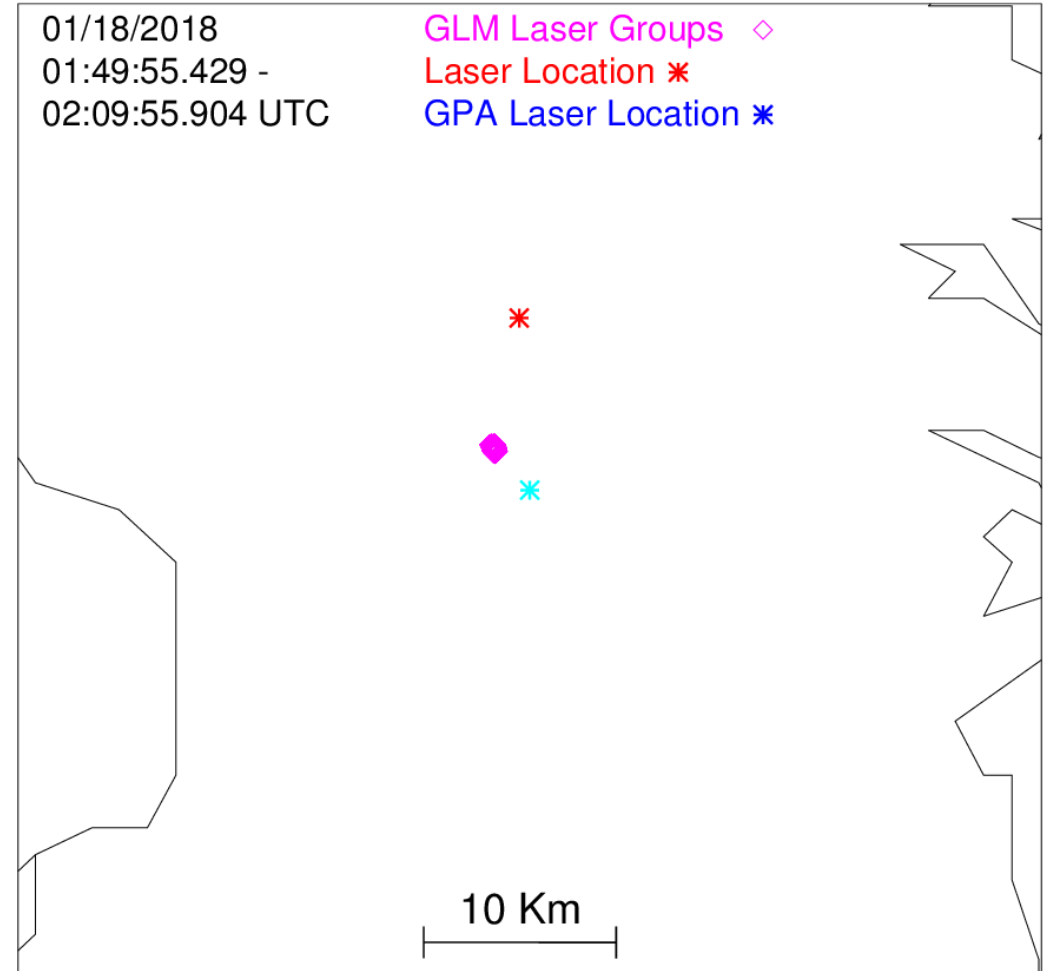
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# Results: Groups

Monument Peak

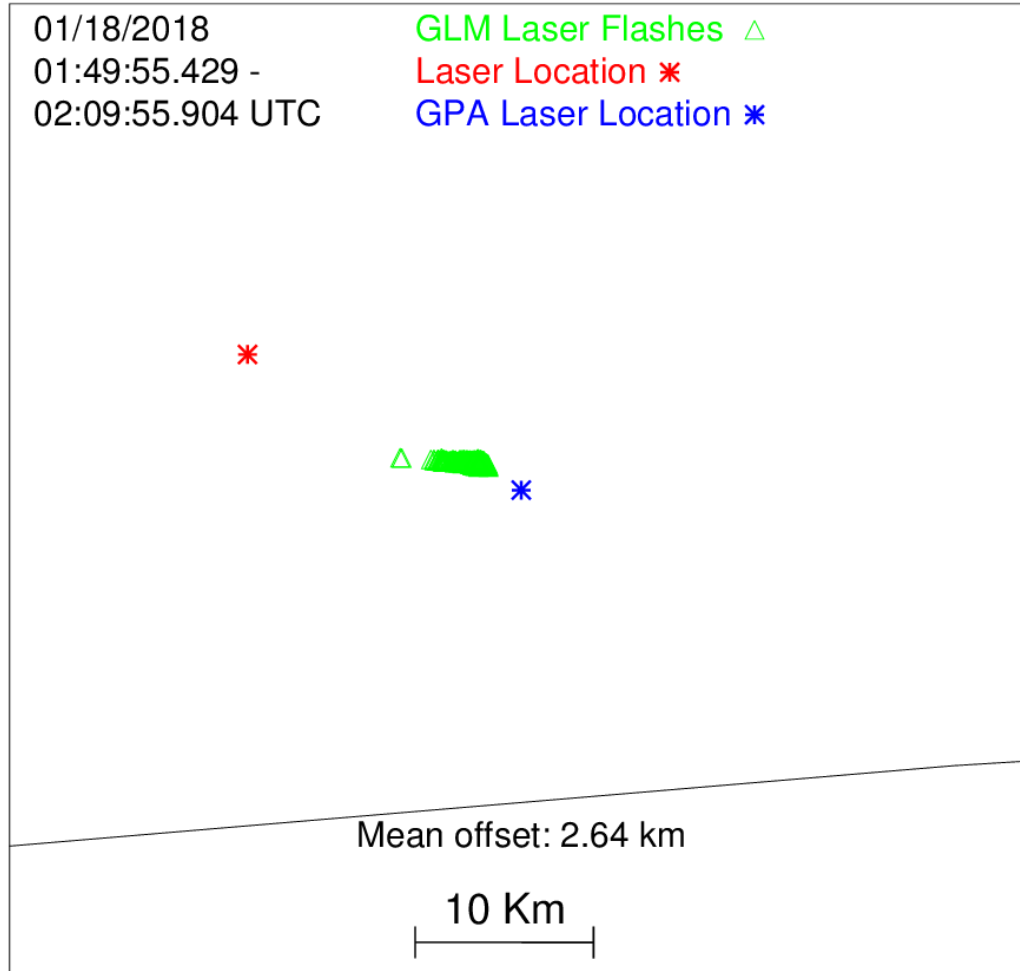


Greenbelt

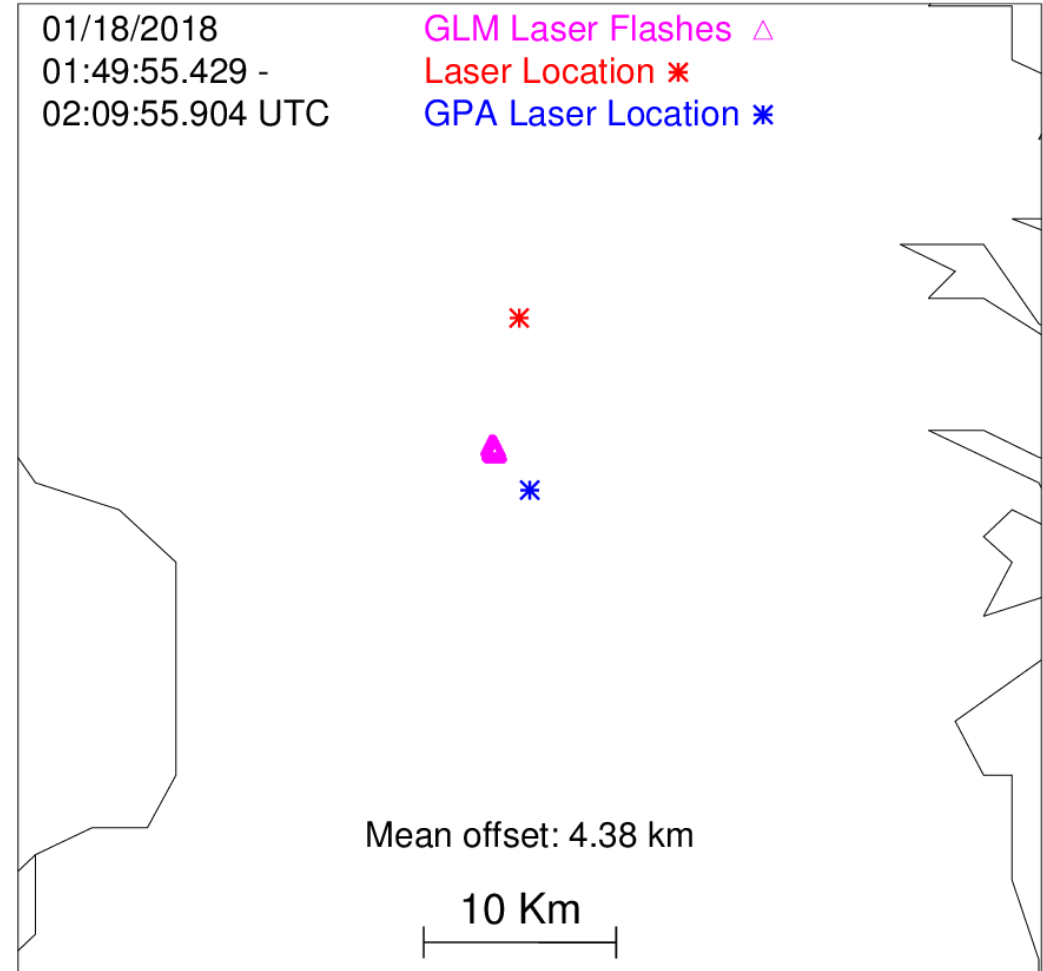


# Results: Flashes

Monument Peak



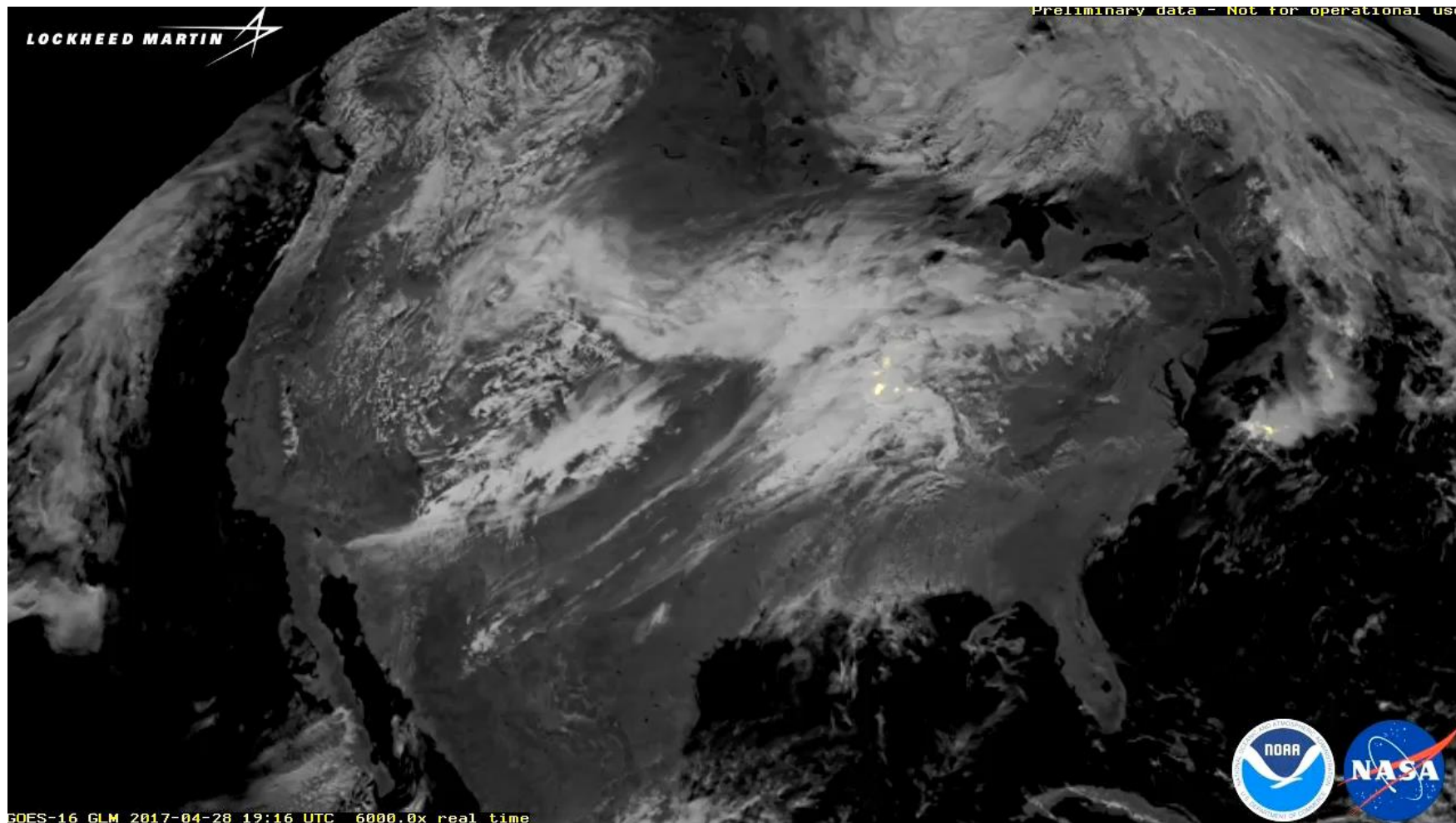
Greenbelt



# 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 were within 5 km
- The offset was also less than 5 km at 0500 UTC 01/18/2018 laser beacon period
- Laser operations now underway for GOES-17
- Further analysis of GOES-16 and GOES-17 datasets

# GLM backgrounds and lightning with laser beacon signal



<https://www.youtube.com/watch?v=Uf9C-yr9iaA>

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Thanks



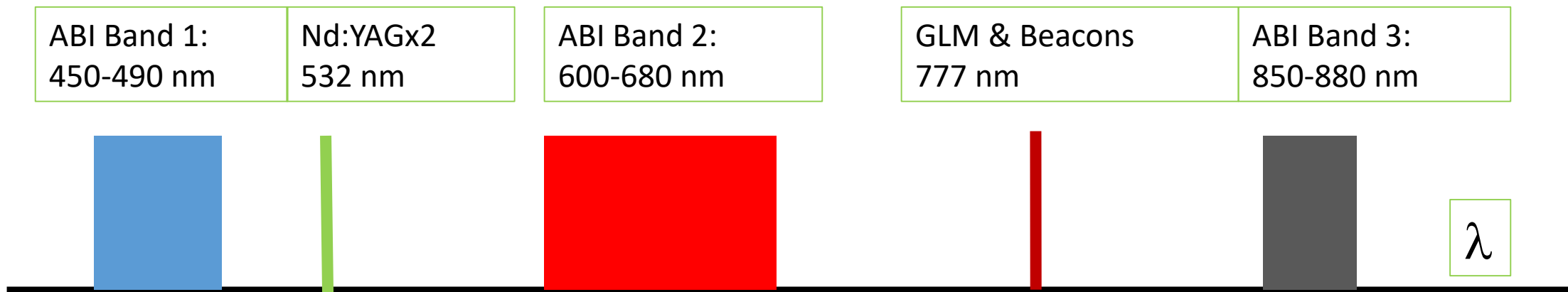
# Back-up Charts

# No Plausible Damage to the GLM or the 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)



# Beacon parameters for GOES-E

Parameter	GSFC to GOES-E	Mon. Pk. To GOES-E
Beacon Azimuth	177.09°	121.58°
Beacon Elevation	44.81°	31.64°
Range	37,422 km	38,466 km
GLM E/W field angle	0.24° W	5.31° W
GLM N/S field angle	6.13° N	5.16° N
GLM E/W pixel pitch	30 μm	24 μm
GLM N/S pixel pitch	22 μm	24 μm

# Beacon Parameters for GOES-W @ 137°W (GSFC lies outside the GLM's FOV)

Parameter	Mon. Pk./ GOES-W	Tahiti/ GOES-W	Mt. Haleakala/ GOES-W
Beacon Azimuth	214.68°	36.55°	135.31°
Beacon Elevation	45.79°	64.81°	57.34°
Range	37,355 km	36,307 km	36,652 km
GLM E/W field angle	2.90° E	2.10° W	3.09° W
GLM N/S field angle	5.30° N	3.02° S	3.51° N
GLM E/W pixel pitch	30 μm	30 μm	30 μm
GLM N/S pixel pitch	24 μm	30 μm	30 μm

# Beacon Telescope Mount

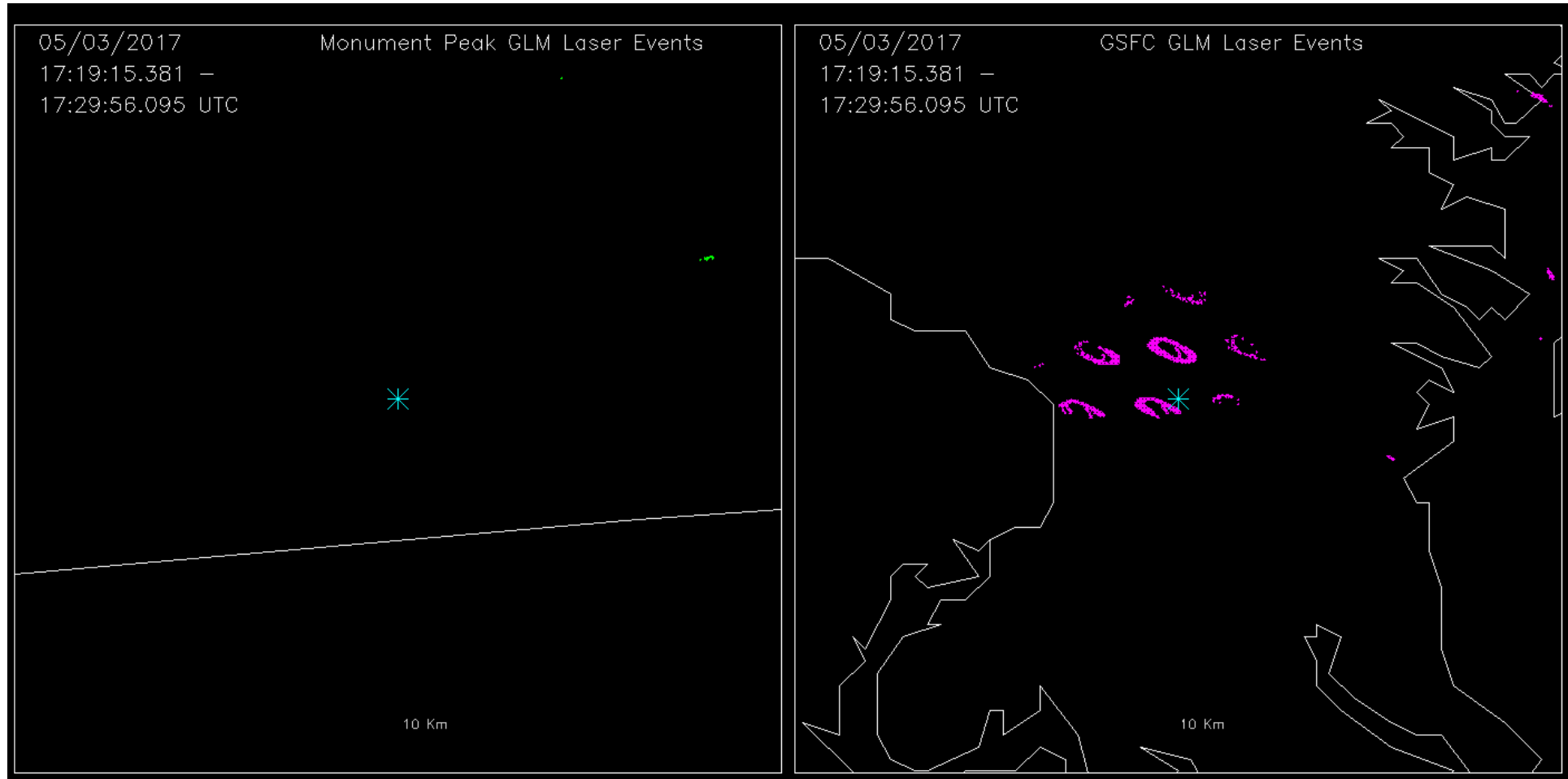


MOBLAS transmitters,  
optimized for Nd:YAGx2,  
transmit poorly @ 777.4 nm

Beacon telescopes  
“piggybacked” on MOBLAS  
telescopes uses their  
pointing system,  
co-boresighted radar,  
power, & enclosure

Inexpensive COTS telescopes  
have good transmission  
@ 777.4 nm

# Dither Events



# Results: Time Series

