GOES-18 GLM Level 2 Data
Full Validation Product Quality
17 November 2023

Product Performance Guide For Data Users

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1. INTRODUCTION

The Geostationary Lightning Mapper (GLM, see Figure 1) on the Geostationary Operational Environmental Satellite Series-R (GOES-R) is the first operational lightning detection system at geostationary orbit. The overarching objectives of GLM are to: (1) provide continuous, near full-disk lightning measurements for storm warning and nowcasting, (2) provide early warning of tornadic activity, and (3) accumulate a long-term database to track decadal changes of lightning.

GLM is a high-speed nadir-staring optical (near-IR, 777.4 nm) camera Charge Coupled Device (CCD) imager (1372 x 1300 pixels) with near uniform spatial resolution (8 km at nadir, 14 km at the edge of its field-of-view, FOV). Its coverage is approximately ± 54 degrees in latitude, and it monitors lightning activity 24/7 with a 2 ms frame time across the Americas and adjacent oceanic regions. Total GLM downlink data rate is 7.7 Mbps, with a product latency requirement of under 20 s.

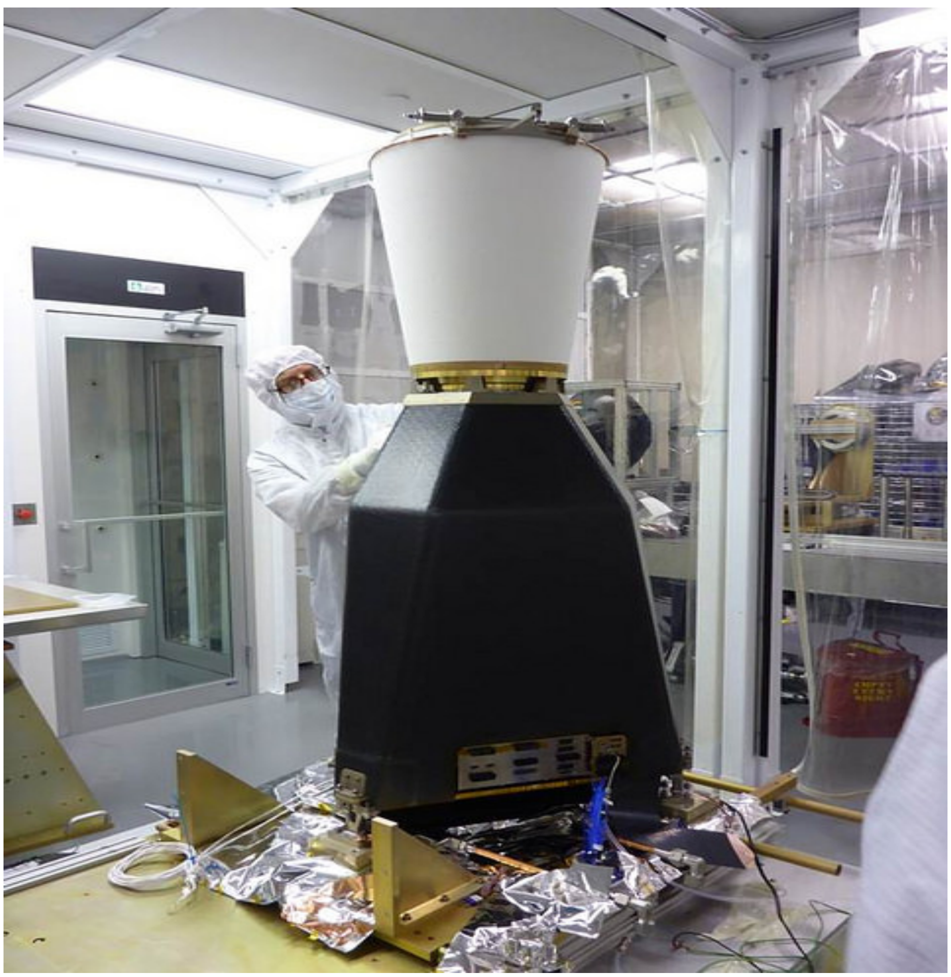


Figure 1. The Geostationary Lightning Mapper (GLM) in a clean-room laboratory setting.

For the benefit of the user community, this document summarizes the key performance and existing issues of the GOES-18 GLM Level 2 (L2) data product that were found at the time of the

Full Validation Peer Stakeholder - Product Validation Review (PS-PVR) on 08 November 2023. Additional information relevant to understanding the GLM L2 product, the performance requirements, and the methodologies for validating requirements are provided in the Product User's Guide (PUG) [1], the Mission Requirements Document (MRD) [2], and the Readiness, Implementation and Management Plan (RIMP) [3]. In order to obtain the most favorable results from the L2 lightning product, users are expected to use the data quality flags described in the PUG (e.g., flash_quality_flag values, and others), and to be aware of existing anomalies and planned improvements identified in this document. Users are also encouraged to contact the GLM calibration/validation scientists (William Koshak, william.koshak@nasa.gov; Doug Mach, dmach@nasa.gov) to report anomalies or suggest improvements.

The remainder of this section introduces some of the key characteristics of the GLM L2 product and a timeline of the GLM product validation process. Section 2 compares the measured on-orbit GLM L2 product performance to mission requirements and the predicted Performance Baseline. Section 3 describes remaining issues within the GLM L2 product, and the process toward mitigating them. Section 4 provides a brief summary, and section 5 contains references.

1.1 GLM Product Description

The GLM L2 product consists of three components:

- *Event:* pixel-level optical detection in one frame.
- *Group:* one or more (side/corner) adjacent pixel detections in one frame.
- *Flash:* one or more groups within 330 ms (i.e., interstroke duration) and within 16.5km.

For each event, group, or flash, the GLM L2 product file includes a location (energy-weighted location for groups and flashes), coverage area (for groups and flashes), time information, and amount of radiant energy. The L2 data files are broadcast every 20 seconds to meet the latency requirement. More information on the data files can be found in the Product User's Guide [1].

1.2 GOES-18 GLM Production Validation Timeline

On 01 March 2022, the third of the GOES-R Series satellites (i.e. GOES-T) was launched, and after successful orbit insertion it formally became GOES-18. The GOES-18 GLM (i.e., GLM-18) instrument was turned on 29 March 2022, and a series of Post-Launch Tests (PLTs) were then conducted to verify that the instrument was functioning properly and that products were being created as expected. Before the end of the PLT activity, some Post-Launch Product Tests (PLPTs) were conducted to assess basic GLM L2 product performance using independent reference lightning datasets. These checks allowed GLM-18 to be Beta Certified on 16 September 2022. Beta Maturity, means that:

- Product is made available to users to gain familiarity with data formats and parameters (via GOES Rebroadcast, GRB),

- Product has been minimally validated and may still contain significant errors,
- Product is not optimized for operational use.

The analysis period, 01 September 2022 – 12 October 2022, was used for the Provisional Maturity validation. This led to the successful achievement of Provisional Maturity on 31 October 2022, which means that:

- Product performance has been demonstrated through analysis of a small number of independent measurements obtained from select locations, periods, and associated ground truth or field campaign efforts.
- Product analysis is sufficient to communicate product performance to users relative to expectations (Performance Baseline).
- Documentation of product performance exists that includes recommended remediation strategies for all anomalies and weaknesses. Any algorithm changes associated with severe anomalies have been documented, implemented, tested, and shared with the user community.
- Product is ready for operational use and for use in comprehensive cal/val activities and product optimization.

On 08 November 2023, the final GOES-18 GLM L2 PS-PVR was held. The review concluded that the GLM L2 product has reached the Full Validation Maturity per GOES-R Program, which means that:

- Product performance for all products is defined and documented over a wide range of representative conditions via ongoing ground-truth and validation efforts.
- Products are operationally optimized, as necessary, considering mission parameters of cost, schedule, and technical competence as compared to user expectations.
- All known product anomalies are documented and shared with the user community.
- Product is operational.

2. KEY PERFORMANCE

This section provides a comparison between the measured on-orbit GLM L2 product performance with MRD requirements and the Performance Baseline predictions. The Performance Baseline is a prediction of the on-orbit product performance compiled by a team at MIT Lincoln Lab based on vendor reports and pre-launch test data. Before this comparison is provided however, it is important to note the following over-arching validation principles since GLM is a new instrument (transient detector) unlike typical imaging instruments. The principles can be summarized as follows:

- **Targets of Opportunity (TOO):** Validation of a lightning sensor differs from that of a typical imager; i.e. since lightning is transient, validation is restricted to TOO.
- **Flash DE is an Estimate:** Determination of flash detection efficiency (DE) is only an estimate because reference data normally don’t detect all lightning.

- **Source Physics:** GLM detects in the optical (near-IR) and many of the reference datasets are in the RF [e.g., Lightning Mapping Arrays (LMAs) see discharge breakdown in the VHF that might not show up in optical, which implies an "apple/orange" comparison].
- **Source Scattering:** Optical is cloud-scattered, but cloud is transparent to radio. So often there are GLM lightning detections near cloud edges where there are no associated radio sources.
- **ISS-LIS is Critical:** Since many independent lightning reference networks operate in the radio, it is critical to obtain optical (i.e., "apple/apple") comparison with GLM. The optical measurements provided by the International Space Station Lightning Imaging Sensor (ISS-LIS) make this possible.

2.1 Performance Baseline Mapping

Table 1 summarizes the Mission Requirements that were directly validated by the Post Launch Product Tests (PLPTs) (see [3] for a detailed discussion of each PLPT).

MRD	Parameter	MRD Value	Perf. Baseline (Model)		Related PLPTs
1259	Production Mapping Accuracy [INR]	**5km** (= $\|\mu\|+3\sigma$ < 140 µrad)	Nav error (7 d averaging) of 103 µrad for GOES-W		-011, (also -001, -002,-003, -004, -005, -006)
1260	Product Measurement Range	(0-41900 evts/s, 0-8170 grps/s, **0-600 flsh/s**)	Instr Vendor showed can handle peak 100Kevts/s (600flsh/s)		G16/17 Independent [see -009,-010 in G16 Full PS-PVR]
1261	Product Measurement Accuracy	**70%** total flash detection efficiency (DE)	Instr. Side	EOL*	-001, -002,-003, -004, -005, -006, -009,-010
			Primary	**90.3%**	
			Redundant	90.5%	
1264	Product Measurement Precision	**5%**	Open, with Flight reporting FAR ~ 2.6%		-001, -002,-003, -004, -005, -006, -009,-010
2112	Product Time Tag	**GOES-R system shall time tag product observations**	n/a		-001, -002,-003, -004, -005, -006

Table 1. The association of Mission Requirements Document (MRD) values & Performance Baseline values. [Note: INR = Image Navigation and Registration; EOL = End of Life (with reduction to flash DE by ~6% due to Coherency Filter removing single group flashes); GS = Ground Segment; WRs = Work Requests.]

2.2 Performance Summary

Table 2 summarizes the performance of the GOES-18 GLM L2 relative to the mission requirements and predicted performance baseline.

MRD	Parameter	MRD Value	Performance Result			
			ValiD	LATA	INR	Mach SIT
1259	Production Mapping Accuracy	5km (= $\|\mu\|+3\sigma < 140$ µrad)	n/a	**4.0 km**	**133 µrad**	n/a
1260	Product Measurement Range	(0-41900 evts/s, 0-8170 grps/s, 0-600 flsh/s)	n/a	n/a	n/a	**no cases where LCFA* unable to handle raw or filtered data rates**
1261	Product Measurement Accuracy	70% total flash detection efficiency (DE)	**81%**	n/a	n/a	n/a
1264	Product Measurement Precision	5% (flash FAR) [also MRD 639 which states same 5% value]	**13%** (inferred to 5%)	n/a	n/a	n/a
2112	Product Time Tag	GOES-R system shall time tag product observations	n/a	**-0.8 ms**	n/a	n/a

Table 2. A summary of the GOES-18 GLM L2 performance results relative to MRD requirements and the Performance Baseline. LCFA = Lightning Cluster Filter Algorithm. The instrument meets the requirements.

Note that both the flash detection efficiency (DE) and flash False Alarm Rate (FAR) vary spatially, diurnally, and seasonally. The DE and FAR values in Table 2 represent a (spatial, diurnal, and seasonal) average across the GLM FOV.

The GLM-18 DE performance improves upon the GLM-17 DE performance of 73% (which in turn was independently validated by Cummins [4]).

Spatial averaging of FAR (i.e. to obtain a single bulk FAR across the FOV) is known to (unfairly) produce an inflated value (i.e., the 13% value shown in Table 2). This is due to spatially averaging across grid cells that have high FAR values but very low flash counts (such as commonly found over the South Pacific). If instead the bulk value is computed as a simple ratio (i.e., # false alarms divided by total # of GLM flashes) the 5% spec is met.

A more detailed perspective of DE performance is provided in Table 3 that shows monthly variability for Jan-Sep 2023. Whereas the 2nd column of Table 3 provides the 24 hr DE estimates, the 3rd column (day) and 4th column (night) represent 6 hr periods of purely day and night periods, respectively, not contaminated by day-to-night transition periods. Figure 2 shows the spatial variability of GLM-18 flash DE for Jan-Sep 2023.

Period (2023)	Flash DE	Flash DE (day)	Flash DE (night)
Jan	0.86	0.85	0.87
Feb	0.84	0.84	0.86
Mar	0.82	0.79	0.84
Apr	0.81	0.79	0.83
May	0.79	0.76	0.83
Jun	0.78	0.72	0.81
Jul	0.76	0.71	0.80
Aug	0.76	0.70	0.80
Sep	0.76	0.72	0.80
Jan-Sep	**0.81**	**0.80**	**0.84**

Table 3. A detailed look at GLM-18 flash DE performance for Jan-Sep 2023. The 2nd column is based on a 24 hr period, whereas the 3rd and 4th columns are based on a 6 hr period during daytime & nighttime, respectively.

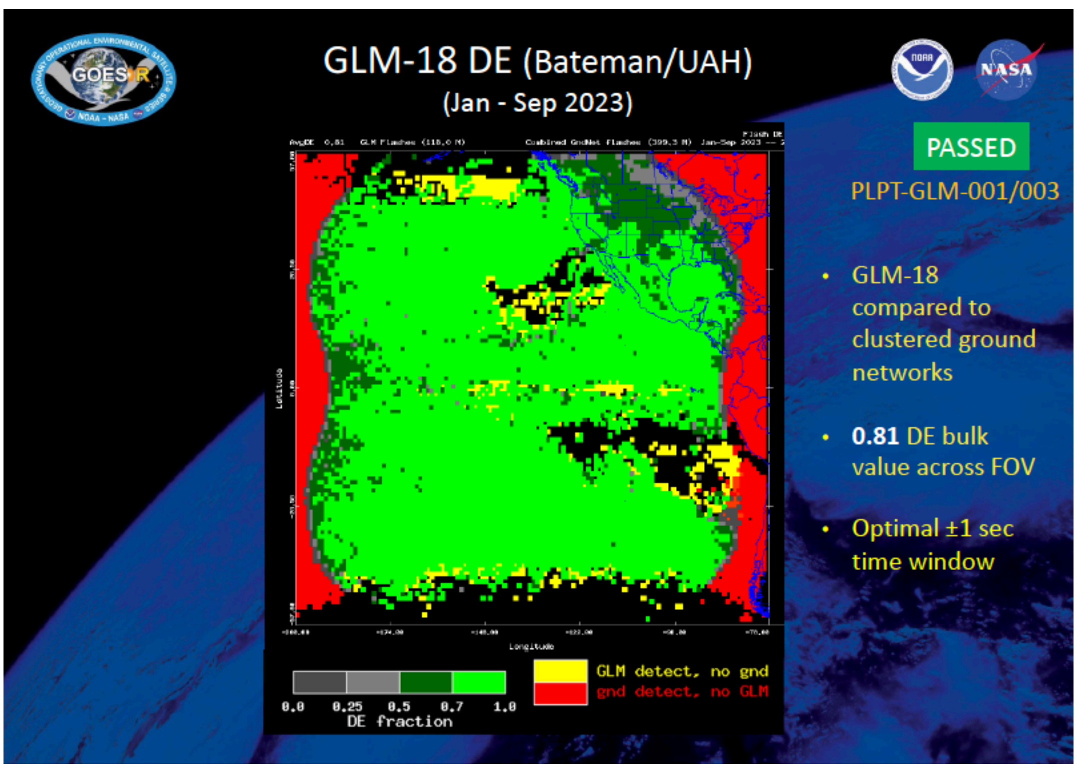


Figure 2. The GLM-18 flash DE for most of 2023. Detection falls off over CONUS since the instrument minimum detectable energy increases with boresight angle, coupled with the fact that land lightning is less energetic than oceanic lightning. Reference network-detected flashes occurring outside the GLM-18 FOV are the regions in red. [Note: gnd = ground, so yellow indicates no detection by ground network].

As described in [5] and references therein, the GLM-18 DE and FAR values were computed using a "virtual network" composed of five networks:

- Earth Network's Global Lightning Network (ENGLN) which combines the Earth Network's Total Lightning Network (**ENTLN**) with the World Wide Lightning Location Network (**WWLLN**). ENTLN provides high DE stroke data that covers the CONUS as well as northern and eastern South America. The WWLLN provides global coverage, but at a significantly lower DE (10%–20%).
- Vaisala's Global Lightning Dataset (**GLD360**) provides near global coverage, high DE lightning stroke data.
- Vaisala's National Lightning Detection Network (**NLDN**) stroke and flash data provide high DE lightning data over CONUS, and extend to about 100 km beyond the shores of CONUS.
- The Canadian Lightning Detection Network (**CLDN**) fills in the northern regions of the GLM FOV in North America. It provides lightning flash data with sensors similar to the NLDN.

Figure 3 provides the spatial pattern of FAR across the GLM-18 FOV; an optimal ±10 min matching window to minimize FAR estimation error is employed. A detailed FAR table similar to Table 3 has also been produced, but for brevity it is not reproduced here; see the online PS-PVR slide package for the details.

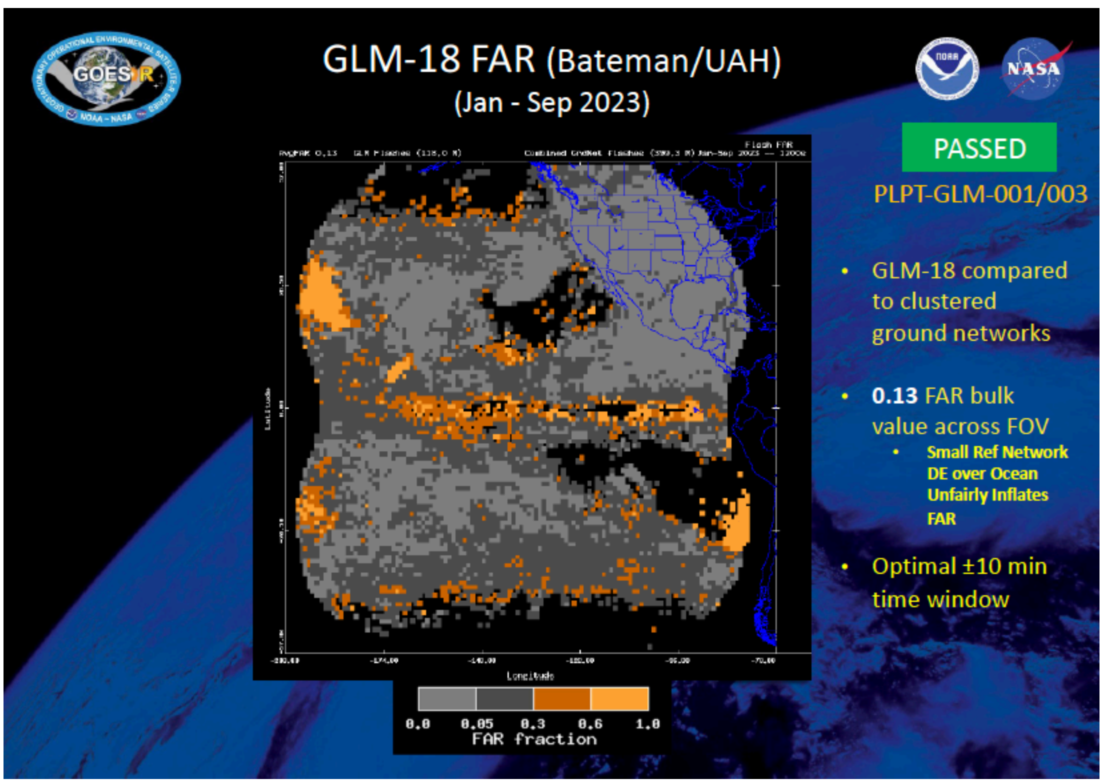


Figure 3. The GLM-18 flash FAR values inferred for Jan-Sep 2023. As one can see, the spec of 5% or less is met over the majority of the FOV. Spatially averaging over the entire FOV gives an inflated (13%) bulk FAR value since averaging over grid cells with a high FAR but very low flash count is an unfair (i.e., uncharacteristically high) contribution to the bulk FAR.

The studies in [5] and [6] discuss the necessity, logic and benefits of employing the ±10 min matching window. If one system has a relatively low DE and detects different components of the lightning flash compared to another system, it is quite possible that the two systems will not see the same flashes; i.e. both systems will likely see other flashes in the same storm. Expanding the time window used to compare the two datasets helps counter this issue (resulting in the detection of some flashes from the storm by both systems). In the validation of GLM-18 the time-comparison window was extended from ±1 sec to ±10 min. The distance criterion was kept fixed at 50 km so as to keep the cross-storm detection chances to a minimum. The time window was not extended beyond ±10 min, since that would increase the chances of the coincident storms moving out of the grid boxes. Extending the time window to this size allows one to use the virtual network as a "storm detector," rather than an individual lightning flash detector when comparing to the GLM-18 data.

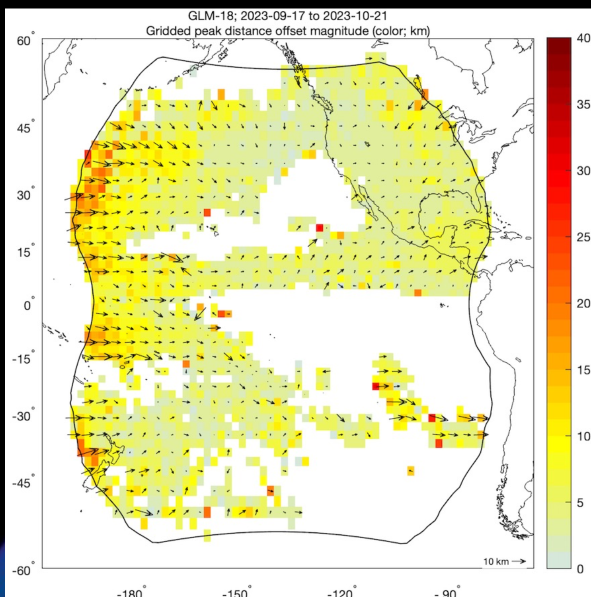
Overall, the following points regarding GLM-18 FAR should be noted:

1. We estimate the **GLM-18 flash FAR to be 5% or less** because that is its value over much of CONUS where the ground reference network DE is optimal within the GLM-18 FOV. This assumes that both nature/instrument are reasonably homogeneous across the GLM-18 FOV, which is reasonable given laboratory tests/modeling of the instrument.
2. Since the reference network flash DE is low over the Pacific Ocean, it is a challenge to adequately assess GLM-18 FAR over this vast region. A low reference network flash DE implies that a legitimate flash can be missed by the reference network while GLM-18 detects it. This leads to our validation tools incorrectly registering a GLM-18 false alarm, when in fact GLM-18 is correctly detecting the flash. Therefore, the low reference network DE would normally lead to inflated (i.e. overestimated) values of GLM-18 FAR in many grid cells over the Pacific. However, since we increase the matching window from ±1 sec to ±10 min, we reduce the FAR overestimation (due to this low reference network DE effect). Objective simulations given in [6] fully justify the opening of the window.
3. As mentioned, the **<u>bulk</u>** FAR gets inflated due to spatial averaging across grid cells that have a high FAR but a very low flash count. So pay more attention to the individual grid cell FAR values in the FAR maps provided, rather than the bulk FAR value.
4. The reader is encouraged to examine the Appendix of the PS-PVR package which provides additional details/insights into our FAR estimates.

Finally, Figure 4 summarizes additional details on the variability of location and timing errors. The vectors indicate how the GLM-18 groups would need to be shifted to match the reference network data.

Timing/Location Consistency (Virts/UAH)

GLM-18 vs. ENGLN and GLD360



Period	Peak Location Offset (km)	Peak Timing Offset (ms)
Nov 2022	3.8 km	-0.8 ms
Dec 2022	3.6 km	-0.8 ms
Jan 2023	3.3 km	-0.8 ms
Feb 2023	3.4 km	-0.8 ms
Mar 2023	3.6 km	-0.8 ms
Apr 2023	3.8 km	-0.8 ms
May 2023	3.9 km	-0.8 ms
Jun 2023	4.3 km	-0.7 ms
Jul 2023	4.0 km	-0.8 ms
Aug 2023	3.9 km	-0.8 ms
Sep 2023	3.8 km	-0.8 ms
Oct 1-21, 2023	4.0 km	-0.8 ms
Nov 2022 – Oct 21, 2023	**3.8 km**	**-0.8 ms**

1

Figure 4. The GLM-18 vector location errors (left), and peak location/timing error results (right). Overall, the instrument meets the location and timing accuracy requirements.

3. EXISTING ISSUES & FIXES FOR USER AWARENESS

Table 4 summarizes relatively recent fixes and a notable planned future improvement regarding the blooming filter. Algorithm Discrepancy Report (ADR) reference numbers associated with completed or planned software fixes are provided. [For earlier fixes, the reader is referred to the historical log that was provided in the Appendix of the GLM-17 Product Performance Guide.] Note that the various revisions (Rev C – Rev F) shown in Table 4 pertain largely to various drafts of Post Launch Test (PLT) Ground Processing Algorithm (GPA) filter updates and involve such things as Real Time Event Processor (RTEP) threshold settings, 2nd Level threshold setting, coherency amplitudes, temperature offset, initial roll/pitch/yaw values, contrast leakage fraction, overshoot settings, focal length reference, optical distortion coefficient, and blooming filter parameters (e.g., Background Most Significant Bit high threshold table, overshoot factor) .

ADR	Title	PR or DO	Date in OE
Updates in months prior to Provisional Validation level (achieved on 31 Oct 2022)			
1211	G18 GLM LUTs for Test Slot (CDRL79 Rev C)	PR.09.08.19	4/1/22
1241	G18 GLM LUTs for West Slot (CDRL79 Rev C)	PR.09.08.27	6/1/22
1264	G18 GLM CDRL79 Rev D	PR.09.08.32	7/29/22
1268	G18 GLM CDRL79 Rev E	PR.09.08.34	9/1/22
Update just after Provisional Validation level			
1291	G18 GLM CDRL79 Rev F	PR.09.08.38	11/8/22
Update to be made (at the time of this writing)			
1345	GLM Blooming Filter tuning - ADR 1345	Flight	LUTs to be delivered

Table 4. A summary of the most improvements made/future that affect GLM-18 performance. Acronyms: PRO (Product Readiness and Operations), PR (PRO Release), DO (Data Operations), OE (Operational Environment), LUT (Look Up Table), CDRL (Contract Data Requirement List).

The subsections below summarize existing issues, and highlight some noteworthy fixes.

3.1 Flash Detection Depletion over CONUS

GOES-18 (and GOES-16/17) GLM L2 products show a notable depression in flash detection efficiency (DE) extending over appreciable regions of CONUS (specifically, see Figure 2 for the case of GLM-18). The GLM-18 instrument filter throughput decreases (as does pixel size) with increasing boresight angle, and this effect is particularly evident moving from nadir toward CONUS. In addition, it is known from independent studies that oceanic lightning is more energetic (so more easily detectable) than lightning over land; hence, CONUS is marked by both large boresight angle and land. By contrast, the far NW, SW, and SE edges of the GLM-18 FOV are over ocean. Efforts are being made at NASA MSFC as part of ongoing National Climate Assessment (NCA) activities to optimally splice GLM-16 and GLM-18 data together to obtain a more spatially homogeneous/improved DE across CONUS.

3.2 Flash DE Depletion in Certain Storm Types

From a local perspective, there is evidence that the flash DE is substantially smaller in anomalous (i.e., inverted polarity) storms, and in severe (e.g., hail-producing) storms, or storms with deep liquid water path. In general, because the flash DE associated with reference data is itself variable and typically below 100%, it is not always possible to exactly/unambiguously determine the GLM flash DE in all cases.

3.3 False Events (Noise)

In this section we briefly summarize several sources of false events. Note that there were improvements to instrument hardware for Flight Model 3 (GLM-18) and Flight Model 4 (future GLM-19) for mitigating stray light and overshoot.

3.3.1 Solar Glint and Solar Intrusion

Solar glint occurs from specular reflection off of lakes, rivers, oceans, and solar farms. Sunrise and sunset leads to solar glint off the Atlantic and Pacific oceans, respectively, resulting in routine sunrise and sunset false events over predictable oceanic regions. Solar intrusion, which involves solar rays intruding directly into the GLM lens system (i.e., for relatively short periods during the eclipse season) is also a source of false events. These various noise sources lead to “blooming” which occurs when the photo-electric charge in a pixel exceeds the saturation level and spills over to adjacent pixels. To combat these noise sources, a new blooming filter algorithm was developed and tested by the Instrument Vendor and then delivered to the Ground Segment; it was implemented into the Operational Environment (OE) on 25 July 2019. The blooming filter has been shown to be effective in removing a substantial fraction of blooming events, but not every last one. Therefore, the blooming filter continues to be tuned (see Table 4).

3.3.2 False Event "Bars" at RTEP Boundaries

Horizontal streaks or "bars" of false events at the boundary between certain GLM Real Time Event Processors (RTEPs) occur; the first was noticed in the Bahamas and coined the "Bahama Bar". These bar artifacts have been mitigated (but not completely removed) from second-level threshold filtering as part of ADR 647 which was implemented into the OE on 27 February 2019.

3.3.3 Residual Radiation "Dots"

False events due to high energy radiation particles, aka "radiation dots" have been largely removed by the implementation of a Single Group Flash (SGF) filter [also referred to as a Single Group Filter, for brevity]. This improvement was implemented on 27 October 2020. This filter is not perfect; i.e., there is a desire to mitigate unintentional removal of legitimate flashes by the SGF filter. One approach being considered is an “Innocence by Association Filter” where the SGF is not removed if it is near (in space and in time) legitimate flashes.

3.4 Additional Notes

See the GLM-17 Product Performance Guide to review general progress that was made regarding reducing position errors, improving the time-stamp, handling of unsigned integer read, gridded data and data quality products, scaling of amplitudes (i.e. granularity, maximum energy, and dark flashes), and other minor fixes.

4. SUMMARY

Overall, GLM on GOES-18 meets mission requirements. Currently, the flash detection efficiency (DE) meets specifications against the ground truth systems. We believe the GLM-18 flash false alarm rate (FAR) is meeting specifications based on its performance over CONUS where ground reference network DE is good, and because we believe that the GLM-18 instrument is a fairly homogenous detector. Over the ocean where ground reference DE is poor, legitimate GLM-18 flash detections are unfairly tallied as false alarms, however we mitigate this effect by opening the matching time window, and believe our FAR estimates over the vast ocean are reasonable. The GLM-18 location and timing accuracy meet specifications. In addition, maximum data processing rate requirements have been met. Fixes continue on lower priority items, and it is the user's responsibility to understand which issues have been and have not been fixed in the data being used.

Contact for further information:

- OSPO User Services at SPSD.UserServices@noaa.gov

Contacts for specific information on the GLM L2 data:

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- William Koshak: william.koshak@noaa.gov
- Douglas Mach: dmach@nasa.gov
- Pete Armstrong: peter.armstrong@ll.mit.edu

5. REFERENCES

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[2] GOES-R Series Mission Requirements Document (MRD), 410-R-MRD-0070, Version: 3.31, January 2021.

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[5] Bateman, M., Mach, D., & Stock, M. (2021). Further investigation into detection efficiency and false alarm rate for the geostationary lightning mappers aboard GOES-16 and GOES-17. Earth and Space Science, 8, 2020EA001237. https://doi.org/10.1029/2020EA001237.

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