Published in final edited form as:

J Appl Remote Sens. 2020 July ; 14(3): . doi:10.1117/1.jrs.14.032402.

Removing solar artifacts from Geostationary Lightning Mapper data to document lightning extremes

Michael Peterson*

ISR-2, Los Alamos National Laboratory, Los Alamos, New Mexico, United States

Abstract

We compare the performance of three different filters that identify solar artifacts in the Geostationary Lightning Mapper (GLM) data. These filters differ in their complexity and intended use. We use the most appropriate filters to document the severity of GLM solar contamination and to compute the frequency of extreme Americas lightning. Solar artifacts occur at an average rate of one every ~8 min. Due to their continuous emissions across a portion of the GLM CCD array, these events disproportionately contribute to the GLM event and group rates. Up to 40% of all events recorded between 10:00 and 12:00 local time during 2018 were solar artifacts. The frequency-domain solar filter also reveals a carrier wave at 50 to 60 Hz in some lightning flashes and solar episodes that appears to be anthropogenic in origin. Removing the relatively frequent solar artifact cases reveals rare cases of extreme lightning flashes. Exceptional flashes on the order of 500+ km in length and 10+ s in duration only occur a few times per year and are produced by storms that are predisposed for exceptional lightning rather than as single random occurrences.

Keywords

lightning; thunderstorms; solar artifacts; GOES-16; Geostationary Lightning Mapper

1 Introduction

Space-based lightning imagers are staring optical instruments that detect transient pulses from lightning in a narrow band around the 777.4-nm neutral oxygen emission line triplet.¹ This class of sensor has flown on multiple satellites over the past 30 years starting with platforms in low Earth orbit, such as the optical transient detector on the MicroLab 1 satellite,² lightning imaging sensor (LIS) on the tropical rainfall measuring mission satellite,³ and the International Space Station⁴ and lightning locating system on the fast on-orbit recording of transient events satellite.⁵

Lightning imagers have been recently included in the sensor packages of geostationary (GEO) weather satellites including NOAA's new R-series of Geostationary Operational Environmental Satellite (GOES). The GOES-16 satellite in the GOES East position at 75.2° W and the GOES-17 satellite in the GOES West position at 137.2° W, both feature a lightning imager known as the Geostationary Lightning Mapper (GLM).^{6,7} GLM records

*Address all correspondence to Michael Peterson, mpeterson@lanl.gov.

lightning pulses from across the Americas and Pacific at ~500 frames per second with a consistent ~8 km pixel resolution across most of its field of view (FOV) (only increasing to 14 km at the edge of the FOV). The ground system then clusters pixel detections that occur near to one another in space and time into distinct lightning flashes (Goodman et al., 2012) that form the basis for operational GLM products.

Lightning imagers including GLM are designed to only trigger on transient optical pulses on typical lightning time scales. Though lightning flashes can last multiple seconds,⁸⁻¹⁰ most of their radiant energy is contributed by optical pulses, such as return strokes and *K*-changes, that are usually captured in a single 2-ms frame. For a detection event to occur, the radiant energy in one of the CCD pixels must rise above a dynamic threshold value for that pixel that is constantly being updated to prevent bright cloud tops from triggering the instrument. Steady optical emissions from processes that evolve slowly over minutes would not trigger a lightning imager such as GLM because the background values would update faster than any changes in illumination.

However, long-lasting, nonlightning-based processes that flicker on typical lightning time scales can still trigger GLM. The primary source of nonlightning artifacts in the GLM data is the sun, and two types of solar artifacts have been identified. Solar glint artifacts occur when solar radiance reflects off of cloud boundaries or the ocean surface before reaching the instrument. Solar intrusion “stray light” artifacts, meanwhile, occur when the Sun shines directly into the instrument optics. Solar artifacts are removed in the operational L0-L1b event filtering, but some solar contamination can make its way to level 2. This was particularly problematic during the first year of GLM’s provisional life, because NOAA and the instrument vendor had not yet validated and optimized the filters for removing these artifacts. As a result, solar artifacts were packaged alongside natural lightning observations in the operational level-2 data product and were prevalent in the data and imagery delivered to end users (particularly during eclipse season). Data files contaminated with extreme solar artifact counts could be 10× larger than normal GLM files with only a small fraction of the data coming from natural lightning.

This solar contamination prevented GLM from meeting NOAA’s maximum 5% false alarm rate (FAR) specification, and work is ongoing between the instrument and ground system vendors to improve the quality of the operational data.¹¹ Recently, the operational GLM software (version D08) has implemented a blooming filter designed to limit solar contamination. Any change to the GLM software will not involve reprocessing the first year of provisional GLM data, however. Moreover, these software changes may have unforeseen consequences on the observations of natural lightning. The creation of a year-long GLM data record with solar artifacts properly flagged for removal will be valuable for assessing changes in instrument performance as the GLM-processing software continues to be refined.

In this study, we develop and compare three distinct filters that flag solar artifacts in the GLM flash cluster data for removal. The three filters differ in complexity (and thus computational expense) and intended use (to produce lightning statistics or to assess extreme cases). The first filter flags possible solar artifacts based on the overall duration of the flash consistent with solar illumination. The second filter looks for the long-lasting periods of

sustained optical emission within the flash typical of glint. The third filter analyzes the frequency-domain energy distribution for each flash to identify solar artifacts. These filters are built for GLM but are anticipated to be useful for other domestic and international staring optical lightning imagers. We apply them to the full 2018 record of “reclustered” GLM flash data where artificial cluster splitting by the GLM ground system is corrected in postprocessing. We use this dataset to populate contingency tables for each algorithm, to quantify the severity of solar artifact contamination in the 2018 GLM record, and to produce GLM statistics on extreme lightning across the Americas.

2 Data and Methods

2.1 GLM Lightning Cluster Feature Data

The GLM ground system clusters the raw event data transmitted from the satellite into features that nominally represent distinct and complete lightning flashes. The GLM lightning cluster filter algorithm (LCFA) is described at length in Ref. 12. It is based on the clustering algorithm used with the previous LIS,¹³ whose performance has been extensively studied.¹³⁻¹⁶ Single pixels lighting up on the GLM CCD array during the same integration frame are termed “events.” Contiguous clusters of events during the same frame are denoted “groups.” Clusters of groups whose events are close in space and time are defined as “flashes.” Periods of sustained optical emission within a single flash are known as “series.” In order to meet NOAA’s latency requirements, however, the GLM LCFA prematurely terminates complex flash clusters once they exceed certain group count (101) or duration (3 s) thresholds. This flash splitting is common during solar episodes that produce sustained emission over multiple seconds. A single episode can contribute hundreds of split flashes to the LCFA data. Most of these flashes would be marked as “degraded” in the operational GLM data product, but the final emissions from each distinct flash would still be marked as “nominal.”

Because solar artifacts are common over the open ocean while lightning is not, artifacts stand out in hemispheric lightning maps that use the LCFA quality flags to suppress degraded data (i.e., Ref. 7). Further, using the quality flags to remove glint is not ideal because, there are complex cases of natural lightning that produce hundreds of GLM groups and last several seconds. These flashes would be removed along with the majority of artifacts.

Reliably differentiating between solar artifacts and natural lightning requires separating the issues of GLM latency and solar contamination. In this study, we evaluate the overall evolution of solar artifact episodes by correcting the GLM LCFA clustering anomalies. In this postprocessed “reclustered” LCFA-R data,¹⁰ each glint or solar intrusion artifact would be captured by a single “flash” cluster feature. This approach allows us to compare solar artifacts with natural lightning on a flash-by-flash basis and to remove all constituent events and groups generated during solar episodes.

2.2 GLM Software Changes During the First Year of Provisional GOES-16 Data

We consider the first full year of public GOES-16 GLM data from January 1, 2018, through December 31, 2018. This period encompassed three versions of the GLM ground system software and four software patches. The software changes outlined in Ref. 17 have the potential to affect our results by attempting to remove solar contamination outright or by changing the conditions that result in reported events. These changes are summarized in the discussion below.

The initial GLM provisional data were generated by software version DO.06.02 (implemented November 28, 2017), which was patched by PR 06.02.03 on December 12, 2017. This patch (before our January 1, 2018, start date) improved the initial glint filter among other fixes. The first change in our 2018 dataset was a patch (PR 06.05.00) implemented on January 1, 2018. This patch improved the second-level threshold filter and overshoot filter in the L1b algorithm. The second patch occurred on February 2, 2018, and applied the lookup tables for GOES-S (unrelated to GOES-16).

Version DO 06.03 was the first major update in the GLM operating software and went live on June 29, 2018. This update removed single-group flashes that are likely “radiation dots,” fixed an incorrect scale factor in the packaged data, and resolved a software crash when processing live data. The next update was the new major version DO 07.00, which was implemented on October 15, 2018. This update refined how events times were reported, fixed some metadata issues, updated the L1b lookup tables, and removed orphaned/childless events and groups in the operational level-2 data.

The final three patches in 2018 were implemented on October 29, November 5, and November 15. The first patch (PR 07.01.00) updated the GOES-16 GLM lookup tables to reduce parallax and mitigate a CCD anomaly that came to be known as the “Bahama Bar.”⁷ The second patch (PR 07.02.00) added an overflow valve for burst events to prevent level-2 processing from falling behind. The final patch (PR 07.03.00) updated the GOES-17 lookup tables.

Of these updates, DO 07.00 on October /15, PR 07.01.00 on October 29, and PR 07.02.00 on November 05 are anticipated to have the largest effect on solar contamination due to how they modified the level-1 processing. Users of GLM L2 data may note that with further refinements being made to the operational product in 2019, a production validation review will take place at the end of the year.

2.3 Solar Artifact Filters for GLM Flash Cluster Data

We identify possible solar artifacts in the reclustered GLM data using three different filters that are all based on the defining characteristic of solar episodes: sustained optical emission. The GLM L2-LCFA-R dataset is ideal for designing and testing solar artifact filters because it contains distinct and complete flash cluster features that are not artificially split by the GLM ground system. Continuous emission at a given location that occurs throughout the 20-s data packet will be documented in a single 20-s flash rather than as hundreds of degraded flashes, each lasting a few tenths of a second. The three filters we assess are intended to

improve the quality of the GLM data record for research applications rather than in operational environments. These filters are defined below.

2.3.1 Flash duration solar artifact filter based on the LCFA threshold—While the maximum group count LCFA threshold is reached by both natural lightning and solar artifacts, most flashes that are flagged as “degraded” for violating the maximum duration LCFA threshold are solar cases. Using the LCFA quality flag as the basis for a solar artifact filter is attractive because it is built into the operational GLM data product distributed by NOAA and can be implemented at a negligible computational cost. The first filter that we consider flags any flash that lasts longer than the LCFA duration threshold (3 s) as a likely solar artifact. This will capture most solar episodes in our LCFA-R dataset but also exceptional cases of natural lightning. Its intended use is for generating GLM lightning statistics.

2.3.2 Series duration solar artifact filter—Series describe periods of sustained optical emission within a lightning flash. As with Peterson et al.¹⁸ and Peterson and Rudlosky,¹⁹ we define series as any collection of groups belonging to the same parent flash and that are separated in time by no more than one empty frame (2 ms). Series that last longer than tens of milliseconds are rare,²⁰ but all types of solar artifacts produce series that last for hundreds of milliseconds up through seconds. By examining thousands of GLM solar artifact and lightning cases, we find that 0.5 s is a reasonable threshold for solar episodes. Few solar artifacts are devoid of series lasting <0.5 s while few lightning flashes produce series that exceed 0.5 s. Our second filter considers any flash that contains a series lasting longer than 0.5 s to be a likely solar artifact. We note that this threshold is completely arbitrary. We will evaluate the skill scores of this filter using this threshold in Sec. 3. Because this filter requires the series data that is created during postprocessing, it has a greater computational expense than the flash duration filter. However, it flags fewer cases of natural lightning and thus could improve statistical GLM lightning analyses.

2.3.3 Frequency-domain solar artifact filter—The third filter identifies solar artifacts based on the frequency-domain distribution of the recorded optical energy. Optical emissions from all GLM detections have a strong energy peak at GLM’s 500-Hz sampling rate due to the impulsive nature of lightning, but only nonlightning artifacts have a second pronounced peak near 1 Hz. The algorithm uses the presence or absence of this low-frequency peak to distinguish solar artifacts from natural lightning.

While the first two filters are straightforward based on thresholds in the recorded flash characteristics, the frequency-domain filter is best described by analyzing examples of valid flash cases and solar contamination cases. Three cases are shown in Fig. 1. Each panel contains the plan view of a GLM flash with pixel events “illuminating” the background advanced baseline imager (ABI)²¹ infrared imagery and the progression of groups in time documented as line segments connecting each group centroid with its nearest preceding group. The top and right portions of each panel depict the longitude (top) and latitude (right) extents of each group in the flash. Finally, a timeseries of normalized group energy (base-10 logarithm of received energy in fJ expressed as a percentage of the maximum recorded energy), and normalized group footprint area (km² expressed as a percentage of peak group

area) is displayed along the bottom of the panel. The grayscale color scheme for the group data is consistent across the plots in each panel with the dark gray representing the first emissions from the flash and light gray representing the final emissions.

The first flash case in Fig. 1(a) is an extreme example of lateral flash propagation. This flash was observed in the stratiform region of a large and mature mesoscale convective system (MCS) on October 31, 2018. It produced 6242 groups and 42,772 events over its 7.4 s duration that describe the incremental development of its spider-like branches.²² The overall length of the in Fig. 1(b) is a GLM bolide detection that was discussed by Rumpf et al.²³ The meteor breaking up in the Earth's atmosphere generated a single GLM flash cluster feature lasting 1.2 s that contained 467 groups and 715 events. The overall length of its streak projected to cloud-top altitudes was 24 km from end-to-end (this will differ from the actual length of the streak at its true altitude).

The final flash cluster feature in Fig. 1 is a solar artifact observed over the southern Pacific Ocean on October 6, 2018. This flash was comprised of 6958 groups and 101,632 events over an 8.5-s duration. The flash footprint represents a common archetype for solar artifacts and extends over a lateral distance of 772 km (projected to the cloud-top). Unlike the previous examples of transient optical phenomena in the Earth-atmosphere system, optical emission from this case changes slowly over its duration. Group extents generally grow as the flash footprint slowly migrates eastward.

Optical energies recorded by GLM during each of these cases are converted to the frequency domain using an inverse fast Fourier transform (FFT). We are able to minimize memory allocation (and thus increase our overall computational efficiency) by adopting a common technique from radio science known as a periodogram or spectrogram. Spectrograms compute the power spectrum across a fixed-width frequency band using a sliding FFT window to produce a two-dimensional contour plot of power as a function of time and frequency. We are interested in the frequency range from 500 Hz (the sampling rate of GLM) to a few hertz. While the upper bound of this band is fixed by the instrument design, the lower bound dictates how many flashes we can effectively apply this methodology to. Flashes that last less than 1 s would not report power at or below 1 Hz.

To determine an appropriate lower bound for our frequency band, we plot 854 cases of large and complex GLM flashes that exceed 320 km in length. Inspecting each case manually looking for signs of nonlightning origin (i.e., random flickering rather than branch-like development, flash footprints that occur in clear air regions, or features that are too circular or linear) reveals that 514 of these flashes were artifacts. The shortest-duration solar artifact lasted 640 ms, whereas the clear majority lasted longer than 1 s. We thus set the lower bound to ~2 Hz or ~0.5 s. The precise value corresponds to an FFT window that encompasses 256 sequential GLM frames or 512 ms.

The sliding FFT window centered on each unique GLM frame in the flash returns a power spectrum from 2 to 500 Hz. We use these spectra to compute the average optical power at each frequency in the band over the flash duration. Mean power spectra for the flash cases in Fig. 1 are shown in Fig. 2. All three flashes have peaks at 500 Hz and power spectra that

generally decrease toward lower frequencies. However, while the extreme lightning flash [Fig. 2(a)] and bolide [Fig. 2(b)] cases reach their minimum optical powers in the lowest 20 Hz on the plot, the solar artifact case [in Fig. 2(c)] has a local maximum at these low frequencies. The solar artifact also has a local maximum between 50 and 60 Hz superimposed on the light curves measured by GLM. This 50- to 60-Hz signature can be found in many extreme GLM flashes. It is not directly related to solar episodes, but it stands out in the frequency-domain filter and we can easily screen for it.

We use this unique behavior to distinguish the transient optical phenomena in the GLM data (lightning and bolides) from flickering solar artifacts. The frequency-domain filter defines three subbands in the 0- to 500-Hz range and computes their average powers: one from 0 to 20 Hz (solid vertical line in Fig. 2), one from 50 to 60 Hz, and one from 100 to 256 Hz (dashed line in Fig. 2). Cases where the 0- to 20-Hz average power (in normalized units) exceeds the 100- to 256-Hz average power by at least 5% are flagged as solar artifacts. We also separately flag cases where the 50- to 60-Hz average power exceeds the 100- to 256-Hz average power by at least 5%. These two flags are independent of each other. Lightning may be flagged as having a 50- to 60-Hz signal, whereas solar artifacts might not.

We apply the frequency-domain filter to all 2018 GLM flashes lasting longer than 1 s and mask the solar artifact and 50 to 60 Hz flags together into a new “artifact flag” parameter in the L2-LCFA-R dataset. We additionally apply this filter to the larger sample of flashes with durations that exceed 512 ms on key solar artifact days throughout the year that will be discussed below. The first digit of the flag specifies whether the flash in question has a 50- to 60-Hz carrier wave signal (0 if no or 1 if yes) while the second digit specifies whether the solar artifact flag is set (also 0 or 1).

3 Results

Lightning and solar artifacts in the 2018 GLM flash cluster data are examined below. In Sec. 3.1, we evaluate the performance of the three solar artifact filters in specific solar filtering applications and identify cases where they might not correctly differentiate between solar contamination and natural lightning. In Sec. 3.2, we use the series-based solar artifact filter to quantify the magnitude of solar contamination and the frequency-domain solar artifact filter to investigate the 50- to 60-Hz signatures in certain GLM flashes. In Sec. 3.3, we use the filtered flash data to mitigate solar contamination and produce statistics that describe GLM lightning extremes.

3.1 GLM Solar Artifact Filter Performance

We evaluate the skill of the three filters by first constructing large sample datasets of GLM flashes, manually partitioning these datasets into lightning and solar artifact cases, and then comparing the output from the filters against our manual assessment of the data based on typical lightning and nonlightning phenomenologies. We are interested in both the objective performance of each filter on arbitrary selections of questionable GLM flashes and in identifying lightning extremes. For the first use case where we want to mitigate solar contamination in an arbitrary sample of GLM data, the overall accuracy of the algorithms will be the key skill parameter to track. In the second use case of documenting lightning

extremes, the FAR will be the key skill parameter. It should be stressed that this is not the same FAR as the GLM lightning detection FAR. Instead, it describes how often the algorithms incorrectly report lightning as solar artifacts.

A total of 4382 cases of GLM flashes are manually cataloged as either being natural lightning or solar artifacts. These flashes are divided between four samples that address our two use cases. The first sample consists of all 854 GLM flashes that exceed 320 km during 2018, placing them on the same scale as the current world record for the longest lightning flash.⁸ This sample is not typical of GLM observations and is comprised of only questionable flashes that may be solar cases. The remaining three samples contain arbitrary flashes to assess the objective skill of the solar artifact filters. Flashes in these samples are selected from September 1, 2018 (a high solar artifact day) and September 30, 2018 (which included thunderstorm activity that produced many cases of mesoscale, lightning). These are particularly difficult days for these filters and represent worst case scenarios in filter performance.

Flashes are divided between the second, third, and fourth samples according to their overall durations. The second sample includes flashes whose durations ranged from 0.5 to 1 s. To keep the sample size reasonable, we only allow up to 30 flashes to be selected arbitrarily from each 15-min window aligned to the UTC hour. This restricts the sample to 729 flashes over the 2 days considered. The third sample includes flashes whose durations ranged from 1 to 2 s, and the same 30-flash limit per time window is applied. This results in 674 flash cases in the sample. The fourth sample consists of all flashes with durations exceeding 2 s. Since few lightning flashes last this long, we do not enforce the 30-flash maximum in the final sample.

We then produce contingency tables for every combination of artifact filter and GLM data sample to compute the accuracy, probability of detection (POD), FAR, and bias scores for each scenario. An example contingency table is shown in Table 1 that quantifies the performance of the frequency-domain filter in identifying solar artifacts in the first sample consisting of extreme flashes. Of the 854 total flashes, 514 were artifacts and 340 were lightning. The algorithm identified 486 artifacts and 368 lightning flashes. There were 28 artifacts misclassified as lightning and 0 lightning flashes misclassified as solar artifacts. The frequency-domain filter had a 96.7% accuracy in this scenario with a 94.5% POD, 0% FAR, and 94.5% bias score.

Skill scores for the first sample are compared between filters in Table 2. The series-based filter and LCFA duration threshold both had lower overall accuracies (53.5% and 57.5%). The key performance metric for this case is a low FAR, however. Low FARs signify that mesoscale flashes are not filtered out as solar artifacts. The frequency-domain filter is not only more accurate in this scenario, it is also the only filter that correctly classified all lightning in the extreme flash sample. It is thus the clear choice for assessing GLM lightning extremes.

The frequency-domain filter does not catch all solar artifacts in this sample, however. Figure 3 shows two examples of the types of solar artifacts that can be falsely identified as lightning

by the filter. The first type of solar artifact that is difficult to identify is the onset of the event shown in Fig. 3(a). The artifact starts as a small and dim flash that grows upscale over several seconds but does not reach a plateau of steady emission before being cut off by the data packet endpoint. We can fix this in future releases of the LCFA-R dataset by reclustering across data packets. Streak features like the case in Fig. 3(b) are also often misclassified as lightning. These flashes are primarily comprised of small groups, each a few pixels in size that describe flickering along a well-defined arc. The power spectra for both types of solar artifact are shown in Fig. 4. They are indistinguishable from lightning, lacking the coherent peak in the 0 to 20 Hz range that the filter attempts to resolve.

The skill scores for the three arbitrary samples of GLM flashes partitioned by flash duration are shown in Table 3. Though the frequency-domain filter excelled at identifying mesoscale lightning, its performance degrades for short-duration flashes. FARs increase from 4.1% in the >2 s sample to 50% in the 1- to 2-s sample, and then to 94.8% in the 0.5- to 1-s sample. This is because the frequency-domain filter benefits from the large number samples generated by the sliding FFT window (one sample for each 2-ms frame beyond 512 ms). When flash durations fall to 512 ms, there is only one FFT window to compute the average power spectrum, causing low-frequency signals to become degraded.

The series-based duration filter excels in this use case, and its accuracy is at least 99% in every arbitrary sample of GLM flashes considered. It has the highest POD in the 1 to 2 s and >2 s samples (75% and 97.3%) and a 0% FAR in the 0.5 to 1 and 1 to 2 s samples. Reduced PODs in the samples <2 s are not a concern for GLM statistics because there are so few solar artifacts on these time scales (<1% of all flashes) compared to >2 s (9% of all flashes). These skill scores demonstrate that the series-based duration filter is the clear choice for removing solar artifacts from arbitrary samples of GLM flashes.

3.2 Frequency of Solar Artifacts and 50- to 60-Hz Signatures in the GLM Flash Data

In this section, we quantify the severity of solar artifact contamination in the 2018 GLM data and also investigate the peak in optical energy in the 50- to 60-Hz range that is occasionally observed during GLM flashes. It should be noted that the sensitivity of GLM to solar episodes changes periodically as the GLM operating software is updated—in part to minimize solar events. See Sec. 2.2 for a discussion of these software changes.

We apply our solar artifact filters to all GLM flashes observed during 2018 and then calculate mean lightning and artifact rates over the entire year in Table 4. Peterson¹⁰ estimated the average flash rate for the GOES-16 GLM field of view to be 11.7 flashes s^{-1} in 2018. We previously used a generous 10-s flash duration filter to mitigate solar artifact contamination. However, the stricter filters considered in this study do not reduce this average flash rate by more than 0.1 flashes s^{-1} . The mean artifact flash rate is four flashes min^{-1} for the frequency-domain filter, one flash/8 min for the series-based duration filter, and one flash min^{-1} for the LCFA duration threshold filter.

Despite these low flash artifact rates, the spatial and temporal scales of solar episodes cause them to contribute disproportionately to the GLM group and event rates. Solar contamination accounted for between 4% (series-based filter) and 10% (flash duration

threshold filter) of the average 2018 group rate. These average rates are not distributed uniformly in time or across the GLM FOV. Instead, solar artifacts are episodic and predominately affect particular regions of the GLM CCD array. Figure 5 shows hemispheric distributions of the flash rate density for all flashes that are not flagged by the series-based duration filter [Fig. 5(a)], flashes that have a 50- to 60-Hz signal reported by the frequency-domain filter [Fig. 5(b)], and flashes identified as solar artifacts by the series-based duration filter [Fig. 5(c)]. Figure 5(d) shows the solar artifact fraction in each latitude/longitude bin. As with the average flash rate statistics in Table 4, the lightning flash rate density plot in Fig. 5(a) is nearly indistinguishable from our previous results in Ref. 10. Differences in real-time event processor (RTEP) performance are not caught by our solar filters, resulting in parallel and sometimes adjoining boxes that stand out in the hemispheric lightning distribution (for example, west of Chile).

The 50- to 60-Hz peak was a prominent signal in the frequency-domain energy spectra from GLM flashes during 2018. Light curves from these flashes resembled relatively steady optical emission with a 50- to 60-Hz sine wave superimposed. It was such a recognizable signature that we contemplated incorporating it into the frequency-domain filter as a second test for solar artifacts until it was discovered to occur in certain lightning cases as well.

Consistent signals in this frequency range are suspicious because they suggest an anthropogenic origin. Electrical equipment generally introduces a 50- to 60-Hz hum because power sources either operate at 50 Hz (parts of South America) or 60 Hz (North America). 60-Hz signals from streetlights were a common anthropogenic signal during optical experiments that laid the groundwork for GLM.¹¹ Platform noise sources and instrument anomalies on the GOES spacecraft could also introduce a carrier wave signal, though not necessarily at this frequency. While we do not screen for it, we note that GLM saturation can produce a 10- to 30-Hz beat pattern in the light curves from individual flashes as new events are not recorded until the instrument recovers after several dozen milliseconds. This 50- to 60-Hz signal is not consistent with the power spectrum for natural lightning. Regardless of whether this 50- to 60-Hz signal comes from the ground or the spacecraft, it appears to be anthropogenic, and its origin may be worthwhile to explore in future research.

The flash rate density plot in Fig. 5(b) supports the idea that the GLM hardware is at least partly responsible for the prominence of these signals. Flashes with the 50- to 60-Hz signature are observed over the remote Pacific Ocean, where there are no large cities. There are clusters of high flash rate density in the tropics that somewhat follow the lightning flash rate density distribution from Fig. 5(a). However, there are stripes of relatively high flash rate densities that extend over well-defined latitude ranges in the subtropics. This behavior resembles the RTEP boxes in Fig. 5(a) [see also Fig. 2(c) in Ref. 7], but the boundaries do not match and the stripes in Fig. 5(b) and span a larger latitude range than the boxes for individual RTEPs in Fig. 5(a). The southern extent of the 50- to 60-Hz stripe in the northern hemisphere is near (but not exactly equal to) the linear Bahama bar artifact that can be noted east of Florida in Fig. 5(a) and the North Atlantic glint maximum in Figs. 5(c)-5(d). The northern extent of the Southern hemisphere 50- to 60-Hz stripe similarly approximates the location of the Southern Atlantic glint maximum in Figs. 5(c)-5(d). We suspect that CCD

readout issues similar to the “lollipops” in the legacy LIS data might explain the large domain that apparently contains the 50- to 60-Hz signals.

Figure 5(c) shows the hemispheric distribution of solar artifact flash rate density. The solar artifacts that are flagged by the series duration filter tend to occur near the edges of the GLM FOV and near the equator. Flash rate densities are highest over the Amazon and around Lake Maracaibo. Since these regions are home to frequent lightning, however, solar artifacts only constitute a few percent of all flashes [Fig. 5(d)]. Solar episodes only account for the majority of GLM flashes in oceanic regions over the Atlantic and Pacific where natural lightning is scarce.

The temporal distributions of solar artifacts and flashes with 50- to 60-Hz signatures are shown in Fig. 6. Figures 6(a), 6(c), and 6(d) include all cases where the 50- to 60-Hz flag is set. Figures 6(b), 6(e), and 6(f) include all solar artifacts. Figures 6(d) and 6(e) compute the GLM flash rates for each local solar hour and day of the year. The outer plots compute the average fraction of GLM detections that are flagged during each week for all hours [Figs. 6(c) and 6(f)] or in each local hour throughout the year [Figs. 6(a) and 6(b)]. Note that the outer plots examine the event rate of flagged flashes rather than the flash rate that is used in the central plots.

Flashes with a 50- to 60-Hz signature were frequently observed at night during the first part of 2018. However, no cases were reported after July 3rd (day number 184). This date does not coincide with any of the software updates discussed in Sec. 2.2, so it is unknown why the signal would abruptly stop on this day. At its peak in 2018, flashes with this 50- to 60-Hz signatures accounted for up to 1% of all events recorded by GLM [Fig. 6(c)], but the signals have been absent over the last few GLM software changes.

We previously noted that solar artifacts had a secondary effect on the overall average GLM flash rate (Table 4). Solar episodes contributed up to $0.12 \text{ flashes s}^{-1}$ during intense periods of solar contamination, which is still a small fraction of the average $11.7 \text{ flashes s}^{-1}$ up to $25 \text{ flashes s}^{-1}$ from lightning. However, because these episodes produce large and long-lasting artifact flashes, their effect on the event rate is significant. On average, solar artifacts contributed 40% of all events detected at 11:00 local time during 2018 [Fig. 6(b)], and the average daily fraction of solar artifact events ranged from <1% to 9% over the year [Fig. 6(f)]. Secondary peaks from solar intrusion are prominent from February 20th (day number 51) to April 14th (day number 104) and from August 28th (day number 240) to October 21st (day number 294). Though the midday solar artifacts produce the most events, these stray light cases are the most visible to end users because they are large artifacts that often occur over the open ocean [i.e., Fig. 1(c)].

Fractions of GLM events from solar episodes decrease from a few percent on any given day to <1% toward the end of 2018. This drop-off coincides with the DO 07.00 GLM software update that occurred on 10/15 (day number 288). An uptick in solar artifact frequency can be noted in the final days of 2018, so it is unclear to what extent these software updates will prevent solar contamination in the 2019 data. We limit our analyses in this study to 2018 to coincide with our LCFA-R data.

3.3 GLM Extreme Lightning Statistics

In this section, we use the frequency-domain solar artifact filter to generate statistics on GLM lightning extremes. In particular, we seek to quantify the frequency at which extreme flashes are detected by GLM and to address whether thunderstorms that produce exceptional flashes do so as a random occurrence or are predisposed toward large lightning flashes. The frequency-domain filter has shown considerable skill for this application (see Table 1), but there are still cases of solar artifacts that are flagged as lightning by the filter (such as those in Fig. 3). It should be understood that the following statistics are subject to the skill scores reported in Tables 2 and 3.

Solar artifact fractions are computed as a function of GLM flash characteristics in Fig. 7. Small and complex flashes that consist of a few events [Fig. 1(a)] or groups [Fig. 1(b)], or that are localized pulses confined to a region <10 km across [Fig. 1(c)] are hardly ever flagged as solar artifacts. Artifact fractions increase with flash complexity, approaching 25% by the GLM LCFA maximum group count per flash threshold [dashed vertical line Fig. 7(a)]. Flashes at this scale are still primarily in the 0.5- to 1-s regime from Table 3 (since we do not apply the frequency-domain filter to flashes <512 ms in duration), where the filter has an exceptionally high FAR, so these fractions are certainly overstated. It is not until we get to complex flashes that the algorithm begins performing well. Extreme GLM flash features are almost exclusively solar artifacts with the occasional natural lightning flash mixed in. Documenting GLM lightning extremes is analogous to finding a needle in a haystack that contains hundreds (longest diameter) to hundreds of thousands (longest duration) of candidate flashes. Without the frequency-domain filter, we would not be able to automatically identify extreme lightning cases, let alone generate flash rate statistics for them.

Figure 8 compares the frequency of GLM flashes observed in 2018 according to the numbers of groups [Fig. 8(a)] and events [Fig. 8(b)] per flash, the maximum separation of groups in the flash [Fig. 8(c)], flash footprint area [Fig. 8(d)], flash duration [Fig. 8(e)], and flash maximum series duration [Fig. 8(f)]. Frequency distributions for all GLM flashes including those flagged as solar artifacts are drawn with solid lines, whereas distributions for flashes not flagged as artifacts are shown with dashed lines. While trivial flashes occur at rates of 10^5 to 10^6 flashes per day, the most complex GLM flashes [Figs. 8(a)-8(d)] are observed less than once per day. Most of these complex flashes are solar artifacts, and the hemispheric nonartifact distributions (black dashed lines) bottom out between 4×10^{-3} day $^{-1}$ and 6×10^{-3} day $^{-1}$ (i.e., one to three cases per year).

The longest lightning flash by maximum group separation [Fig. 8(c)] was 673 km across. The rate of nonflagged GLM flashes in the 600- to 700-km range is 5×10^{-2} day $^{-1}$, or one case every 20 days, on average. This is still an upper estimate for the frequency of extreme lightning since Peterson¹⁰ only identified 4 days in 2018 that had single cases of natural lightning in this range (thus, 1×10^{-2} day $^{-1}$). These flash rates suggest that future assessments of GLM lightning extremes will require analyzing ~ 18 candidate flashes across the GLM FOV each year that pass the frequency-domain filter.

Assessing GLM flash duration extremes [Fig. 8(e)] is still problematic with the frequency-domain filter, however. Candidate flashes that last longer than the current LMA world record (7.78 s) and the longest reclustered GLM flash in 2018 (13.49 s) occur at rates of 10 flashes per day per bin. The total number of flashes that exceeds the 2018 GLM maximum is on the order of 10^5 (Fig. 3 in Ref. 10). The frequency-domain filter only reduces this number by one order of magnitude, leaving 10^4 flashes that need to be verified manually. The same can be said for the maximum series duration extreme [Fig. 8(f)], which we did not assess in 2018.

Since the solar artifacts that pass the frequency-domain filter lack the notable low-frequency signature of most solar cases at these scales, additional filtering will be required to track these GLM lightning extremes. Perhaps the simplest filter we can apply is to restrict the domain of interest to only include regions within the GLM FOV that contributed exceptional lightning cases in 2018. The flashes in the exceptional lightning sample from Table 1 are all examples of propagating stratiform lightning and were found exclusively in mature or dissipating MCSs. The horizontally expansive layers of charge that form in MCS stratiform regions (i.e., Ref. 24) are what enable the large-scale lateral development that we can resolve from space with GLM.^{25,26}

Because these storms form preferentially in the Great Plains in North America and the La Plata basin in South America, contenders for the 2018 GLM lightning extremes are limited to the boxed regions in Fig. 5 that are also nearly devoid of solar artifacts [Fig. 5(c)]. The blue dashed lines in Fig. 8 denote nonflagged lightning distributions for these MCS hotspot regions only. The number of possible candidates for GLM lightning extremes is reduced for every parameter in Figure 8 with the greatest differences from the whole FOV nonflagged curves occurring for flash duration [Fig. 8(e)] and flash maximum series duration [Fig. 8(f)]. Flashes with comparable durations to the 2018 GLM maximum occur around once per month in these regions, on average.

We examine whether extreme flashes occur in isolation as random events in otherwise “normal” storms, or whether the parent thunderstorm must be predisposed toward producing extreme lightning by computing flash rate distributions for each GLM area of interest (or “area”) feature. Area features approximate 15-min snapshots of thunderstorm activity. The flash rate distributions by flash length for each area are then sorted according to the maximum flash length for that area to produce the mean area flash rate contour plot in Fig. 9.

Most flashes in all types of thunderstorm area features are stationary with little (if any) lateral development. These flashes repeatedly illuminate the same cloud with each subsequent group. The jump in the flash length distributions at 8 km results from flashes that illuminate precisely two distinct GLM pixels on its CCD array. The mean flash rates in Fig. 9 decrease along the abscissa with increasing flash length until the maximum flash length for the area is reached. There are no gaps in the distributions above the 1- to 2-pixel jump noted previously or a local maximum along the 1:1 line that would support large flashes being random occurrences in thunderstorms that are producing otherwise smaller flashes.

Area features with 100+ km flashes also tend to produce 75, 50, 25 km, etc. flashes in increasing numbers. They thus seem to be predisposed toward generating larger flashes.

4 Conclusions

This study examines solar artifacts in GLM observations and introduces three different filters to remove them in order to mitigate solar contamination in GLM lightning statistics and to document GLM lightning extremes. These filters offer differing levels of complexity and computational expense and are designed for different applications. The simplest filter identifies likely solar artifacts as any flash whose duration exceeds the GLM LCFA 3-s threshold. Because it uses only standard GLM products, this filter is the easiest to implement. The second filter identifies solar artifacts using postprocessed series data that describe periods of sustained optical emission within an individual flash. This filter classifies flashes that produce sustained optical emission over periods lasting 0.5 s as solar artifacts. The third and final filter calculates frequency-domain energy distributions to look for low-frequency signals characteristic of solar contamination. The series-based duration filter is shown to be the most accurate at removing solar artifacts from arbitrary samples of GLM flashes while the frequency-domain filter is best suited for distinguishing extreme natural lightning flashes from solar episodes.

We use our solar artifact filters to quantify the severity of solar artifact contamination in the reclustered 2018 GLM data that repairs cases where the GLM ground system artificially splits valid flashes. Averaged throughout the year, solar artifacts account for between 0.01% and 0.1% of all reclustered flashes, but their large footprints and long durations cause them to contribute disproportionately to the average GLM group and event rates. Solar artifacts account for 4% of all GLM groups and 3% of all events observed during 2018. Most of this contamination occurred during the late morning (10:00 to 12:00 local time), where solar episodes accounted for up to 40% of all events recorded by GLM. Secondary maxima can be observed at dawn and dusk from solar glint over the open ocean. Since lightning is scarce in these regions, these artifacts stand out in the GLM data products that are delivered to forecasters.

We also find evidence of artificial 50- to 60-Hz signals in certain GLM flashes. This signature occurs in both solar artifact cases and cases of natural lightning and seems to be anthropogenic in origin. It occurs primarily at night in pixels that view both land and ocean regions and seems to be concentrated in certain latitude belts within the GLM FOV. The prominence of these signals probably results from a GLM hardware anomaly, but we cannot rule out city lights that typically radiate at 50 or 60 Hz as a background noise source. These signals, however, have not been observed since July 2018, possibly due to incremental GLM software changes over the year.

Because extreme cases of natural lightning recorded by GLM occur in regions of the GLM FOV that are not affected by frequent solar artifact contamination, we can use the frequency-domain filter over a restricted geospatial domain to produce reasonable statistics for GLM lightning extremes. Exceptional GLM flashes occur at a rate of one case per ~100 days, resulting in fewer than 10 contenders for the GLM lightning extremes per year. However, the

frequencies of solar artifact cases at these spatial and temporal scales are multiple orders of magnitude greater. Identifying the longest-extent GLM lightning flash requires sifting through hundreds of solar artifact cases, whereas identifying the longest-lasting GLM lightning flash require analyzing tens of thousands of cases. We also find that extreme lightning flashes tend to occur in thunderstorms that are predisposed for exceptional lightning, rather than as single random occurrences.

These filters improve the quality of GLM lightning statistics and remove enough solar contamination to make tracking GLM lightning extremes sustainable. The reported methods are applicable to staring optical imagers beyond GLM, and domestic and international operators of similar instrumentation may benefit from the filters we describe. We will continue using these filters to flag solar episodes in the GLM flash cluster data while the GLM vendor works to improve solar artifact removal at the instrument level. These combined efforts will enable the creation of a scientifically valid GLM dataset in addition to the operational level-2 GLM product that minimizes solar contamination.

Acknowledgments

This study was supported by NASA Grant No. NNX17AH63G. The GLM LCFA and ABI datasets may be obtained from NOAA via their CLASS service. GLM LCFA-R data may be obtained from our public data repository at data.wxarch.com. We thank Dr. Douglas Mach for providing helpful insights into the technical aspects of GLM and previous optical instruments.

Biography

Michael Peterson is a scientist at Los Alamos National Laboratory. He received his BS degree in meteorology from Iowa State University in 2009 and then went on to receive his MS and PhD degrees in atmospheric sciences from the University of Utah in 2011 and 2014, respectively. His current research includes applications of space-based lightning imager datasets, combined-phenomenology radio-frequency, and optical investigations of lightning physics, and connections between the meteorological and electrical aspects of thunderstorms.

References

1. NOAA-NASA, "GLM instrument description: GOES-R Series Data Book, CDRL PM-14 Rev A," 2019, <https://www.goes-r.gov/downloads/resources/documents/GOES-RSeriesDataBook.pdf>.
2. Boccippio DJ et al., "The optical transient detector (OTD): instrument characteristics and cross-sensor validation," J. Atmos. Oceanic Technol. 17, 441–58 (2000).
3. Christian HJ et al., Eds., Algorithm Theoretical Basis Document (ATBD) for the Lightning Imaging Sensor (LIS). NASA/Marshall Space Flight Center, Alabama (2000). <http://eosps0.gsfc.nasa.gov/atbd/listables.html> (accessed 1 February 2000).
4. Blakeslee RJ. Lightning imaging sensor (LIS) for the International Space Station (ICC): mission description and science goals; XV hit. Conf. Atmos. Electr.; Norman, Oklahoma. 2014.
5. Suszcynsky DM et al., "Coordinated observations of optical lightning from space using the FORTE photodiode detector and CCD imager," J. Geophys. Res. 106 (D16), 17897–17906 (2001).
6. Goodman SJ et al., "The GOES-R Geostationary Lightning Mapper (GLM)," J. Atmos. Res 125-126, 34–49 (2013).
7. Rudlosky SD et al., "Initial Geostationary Lightning Mapper observations," Geophys. Res. Lett. 46, 1097–1104 (2018).

8. Lang T et al., "WMO world record lightning extremes: longest reported flash distance and longest reported flash duration," *Bull. Am. Meteorol. Soc* 98, 1153–1168 (2017). [PubMed: 28111477]
9. Peterson MJ and Liu C, "Characteristics of lightning flashes with exceptional illuminated areas, durations, and optical powers and surrounding storm properties in the tropics and inner subtropics," *J. Geophys. Res* 118, 11727–11740 (2013).
10. Peterson M, "Research applications for the Geostationary Lightning Mapper operational lightning flash data product," *J. Geophys. Res. Atmos* 124, 10205–10231 (2019). [PubMed: 31807399]
11. Mach, Private Communication, 2019.
12. Goodman SJ et al., GLM Lightning Cluster-Filter Algorithm (LCFA) Algorithm Theoretical Basis Document (ATBD) NOAA NESDIS Center for Satellite Applications and Research, 2012, <https://www.star.nesdis.noaa.gov/goesr/docs/ATBD/LCFA.pdf> (accessed 30 July 2012).
13. Mach DM et al., "Performance assessment of the optical transient detector and lightning imaging sensor," *J. Geophys. Res* 112, D09210 (2007).
14. Boccippio DJ, Koshak WJ, and Blakeslee RJ, "Performance assessment of the optical transient detector and lightning imaging sensor. Part I: predicted diurnal variability," *J. Atmos. Oceanic Technol* 19, 1318–1332 (2002).
15. Buechler DE et al., "Assessing the performance of the lightning imaging sensor (LIS) using deep convective clouds," *J. Atmos. Res* 135–136, 397–103 (2012).
16. Zhang D et al., "Evaluation of the performance characteristics of the lightning imaging sensor," *J. Atmos. Oceanic Technol.* 36, 1015–1031 (2019).
17. Rudlosky S, "GLM ground system status," (2019).
18. Peterson MJ, Rudlosky S, and Deierling W, "The evolution and structure of extreme optical lightning flashes," *J. Geophys. Res. Atmos* 122, 13370–13386 (2017). [PubMed: 29527425]
19. Peterson M and Rudlosky S, "The time evolution of optical lightning flashes," *J. Geophys. Res* 124, 333–349 (2019).
20. Bitzer PM, "Global distribution and properties of continuing current in lightning," *J. Geophys. Res. Atmos* 122, 1033–1041 (2017).
21. Schmit TJ et al., "A closer look at the ABI on the GOES-R series," *Bull. Am. Meteorol. Soc* 98, 681–698 (2016).
22. Peterson M, Rudlosky S, and Deierling W, "Mapping the lateral development of lightning flashes from orbit," *J. Geophys. Res. Atmos* 123, 9674–9687 (2018). [PubMed: 31807397]
23. Rumpf CM et al., "An algorithmic approach for detecting bolides with the Geostationary Lightning Mapper," *Sensors* 19, 1008 (2019).
24. Stolzenburg M et al., "Horizontal distribution of electrical and meteorological conditions across the stratiform region of a mesoscale convective system," *Mon. Weather Rev* 122, 1777–1797 (1994)
25. Peterson MJ and Liu C, "Global statistics of lightning in anvil and stratiform regions over the tropics and subtropics observed by TRMM," *J. Geophys. Res* 116, D23 (2011).
26. Peterson MJ et al., "The properties of optical lightning flashes and the clouds they illuminate," *J. Geophys. Res. Atmos* 122, 423–42 (2017).

Fig. 1.

Example GLM cases of (a) a long-lasting lightning flash with long horizontal channels, (b) a bolide detection, and (c) solar glint. GLM events “brighten” the background ABI infrared $11.2\ \mu\text{m}$ imagery while the evolution of groups is traced with line segments connecting each group to its nearest preceding group. Group cross sections are shown on the top (longitude) and right (latitude) of each panel, and time series of normalized group energy and area are shown along the bottom of each panel. The grayscale denotes group index number and is consistent across the plots in each panel.

Fig. 2. Frequency-domain average energy distributions for the (a) extreme lightning, (b) bolide, and (c) solar glint cases from Fig. 1. The solid vertical line shows the peak optical emission in the 0- to 20-Hz band, and the vertical dashed line shows the average optical emission in the 100- to 256-Hz band.

Fig. 3.

GLM flash evolution plots for (a) a solar onset case and (b) a solar arc case, scenarios that are often misclassified by the frequency-domain solar filter as lightning. As in Fig. 1, GLM events “brighten” the ABI background imagery, while lines on the map show the incremental development of groups. Latitude and longitude cross sections are shown to the right and top of each panel.

Fig. 4.
Frequency-domain energy distributions for the two solar artifact cases in Fig. 3. Markings are identical to Fig. 2.

Fig. 5.

Hemispheric distributions of flash rate density for (a) nonflagged lightning flashes, (b) flashes with an emission peak at 50 to 60 Hz, and (c) solar artifacts, and also (d) the solar artifact fraction of all flashes in each bin. The series-based duration filter is used to classify solar artifacts. Boxes are drawn around the broad MCS hotspot regions where extreme GLM lightning was observed, and horizontal lines exemplify RTEP boundaries in (a) and the lowest-latitude extent of the latitude bands with frequent 50- to 60-Hz signals in (b).

Fig. 6. Distributions of (left) flashes flagged by the 50- to 60-Hz filter and (right) series-based solar artifact filter. (d), (e) Flagged flash rates for each day of 2018 and local hour. (c), (f) The average fraction of all events that are flagged during each week of the year. (a), (b) The average fraction of all events that are flagged during each local hour of the day.

Fig. 7.

Fractions of all flashes that are flagged as solar artifacts by (a) the number of groups and (b) events per flash, (c) the maximum separation of groups in a flash, and (d) the flash duration. LCFA and LIS thresholds, and also ground-based LMA records are shown as vertical dashed lines.

Fig. 8.

GLM flash frequency by the number of (a) groups and (b) events per flash, (c) maximum group separation, (d) flash footprint area, (e) flash duration, and (f) flash maximum series duration. All flashes are considered in the solid line distributions while only nonartifacts are considered in dashed line distributions. The distributions drawn in blue only include the MCS hotspot areas marked in Fig. 5, where extreme GLM flashes were observed during 2018.

Fig. 9. Distributions of average GLM “area” feature flash rate by flash length (x axis) as a function of the maximum thunderstorm flash length (y axis).

Table 1.

Contingency table for frequency-domain solar artifact identification algorithm. The sample dataset is comprised of 2018 GLM flashes with lengths exceeding 320 km

Frequency-Domain Solar Artifact Filter	<u>Manual Solar Artifact Identification</u>		
	ARTIFACT	FLASH	TOTAL
ARTIFACT	486	0	486
FLASH	28	340	368
TOTAL	514	340	854

Table 2.

Verification metrics for three solar artifact filters applied to the extreme sample of GLM flashes from Table 1. Our frequency-domain algorithm correctly identifies the most solar artifacts and does not mis-label extreme lightning as solar events, making it ideal for documenting lightning extremes

Solar Artifact Filter	Skill Scores			
	Accuracy	POD	FAR	BIAS
Frequency-Domain Filter	96.7%	94.5%	0.0%	94.5%
Series Duration Filter	53.5%	31.5%	19.1%	39.0%
LCFA Flash Duration Threshold	57.5%	94.1%	40.8%	159%

Table 3.

Verification metrics for all three solar artifact filters applied to arbitrary samples of GLM flashes on 9/1/2018 and 9/30/2018

Solar Artifact Filter	Skill Scores			
	Accuracy	POD	FAR	BIAS
<i>Sept. 1st and Sept. 30th LCFA-R flashes lasting 0.5 s to 1 s</i>				
Frequency-Domain Filter	91.9%	42.8%	94.8%	828%
Series Duration Filter	99.1%	14.2%	0.0%	14.2%
LCFA Flash Duration Threshold Filter	99.0%	0.0%	N/A	0.0%
<i>Sept. 1st and Sept. 30th LCFA-R flashes lasting 1 s to 2 s</i>				
Frequency-Domain Filter	98.8%	37.5%	50.0%	75.0%
Series Duration Filter	99.7%	75.0%	0.0%	75.0%
LCFA Flash Duration Threshold Filter	98.8%	0.0%	N/A	0.0%
<i>Sept. 1st and Sept. 30th LCFA-R flashes lasting >2 s</i>				
Frequency-Domain Filter	93.0%	24.0%	4.1%	25.1%
Series Duration Filter	99.0%	97.3%	8.3%	106.2%
LCFA Flash Duration Threshold Filter	35.0%	88.0%	89.0%	799%

Table 4.

Average hemispheric 2018 flash, group, and event rates for lightning and solar artifacts classified by the three filters. Despite differences in skill scores for the previous test samples, the resulting overall flash rates vary little between the solar filters

Lightning			Artifacts		
Flash Rate	Group Rate	Event Rate	Flash Rate	Group Rate	Event Rate
<i>Frequency-Domain Filter</i>					
11.6 s ⁻¹	212 s ⁻¹	550 s ⁻¹	0.0735 s ⁻¹	20.0 s ⁻¹	38.5 s ⁻¹
<i>Series Duration Filter</i>					
11.7 s ⁻¹	222 s ⁻¹	573 s ⁻¹	0.00211 s ⁻¹	9.40 s ⁻¹	15.7 s ⁻¹
<i>LCFA Flash Duration Threshold Filter</i>					
11.6 s ⁻¹	207 s ⁻¹	547 s ⁻¹	0.0219 s ⁻¹	23.9 s ⁻¹	41.4 s ⁻¹