A Technique for Automated Detection of Lightning in Images and Video From the International Space Station for Scientific Understanding and Validation

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Abstract A combination of Chiba University's METEOR camera, International Space Station Lightning Imaging Sensor (ISS LIS), Geostationary Lightning Mapper (GLM), National Lightning Detection Network (NLDN) data, and other space and ground based data sets were utilized to develop a METEOR-derived lightning identification technique to automatically identify lightning flashes within International Space Station video and still frame imagery. Approximately 14,000 frames were used from two METEOR camera videos. Zero lightning events were missed by the technique using manual inspection of both videos, and the technique did not identify other sources of light (e.g., city lights). Three-hundred and nine METEOR-identified flashes were matched with 289 GLM flashes and 285 ISS LIS flashes in the METEOR field of view on May 17, 2017. On average, the flash area determined by the analysis technique developed in this study was 266 km² smaller than the flash area observed by GLM. The primary reason for this difference in size was the spatial resolution of GLM and METEOR (>8 km vs. 260 m). When NLDN flashes were observed, there was a 200–500 km² increase in the algorithm-derived flash area within 100 ms of the NLDN time, indicative of return stroke processes as bright light is scattered through cloud top. Accurate reverse geolocation using lightning data alone was difficult due to the different spatial resolution, temporal resolution, and other geolocation assumptions between the camera images and comparison data. However, the use of satellite-derived city lights aided in the geolocation process for scientific comparisons.

Plain Language Summary This work describes a technique developed to identify lightning features in still images and video frames from the International Space Station. This technique allows for utilization of the stunning imagery taken from station each day to study lightning properties from a new perspective for validation and scientific research. This paper walks through two different cases and highlights how the images provide additional scientific understanding on flash area and rapid changes in area related to other lightning datasets.

1. Introduction

The launch of three spaceborne lightning mappers in 2016, 2017, and 2018 enabled new and unique views of lightning processes from cloud top that provide new scientific understanding and applications for severe weather, wildfire detection, volcanic eruptions, and lightning safety. In 2016 and 2018, Geostationary Lightning Mapper (GLM; Goodman et al., 2013; Rudlosky et al., 2019) instruments were launched aboard the Geostationary Observational Environment Series-R (Schmit et al., 2005) satellites. These were the first spaceborne platforms that observe lightning from geostationary orbit, and they cover much of the Western Hemisphere (Goodman et al., 2013; Rudlosky et al., 2019). In 2017, a Low-Earth orbit Lightning Imaging Sensor (LIS) was launched and made operational on the International Space Station (ISS; Blakeslee & Koschak, 2016; Blakeslee et al., 2020). This instrument has heritage back to the Tropical Rainfall Measurement Mission (TRMM; Kummerow et al., 1998) LIS (Bocciuppi et al., 2001; Christian et al., 2000) instrument, where ISS LIS was the spare backup in the event the LIS instrument on TRMM failed during preparation and launch.

One important aspect for the success of these satellite missions was validation of their output relative to reality. Ground-based lightning measurements from very low frequency/low frequency (VLF/LF) systems...
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(e.g., National Lightning Detection Network, Earth Networks Total Lightning Network, Worldwide Lightning Location Network), very high frequency (VHF) systems (e.g., lightning mapping arrays), and electric field systems (e.g., P. M. Bitzer et al., 2013) all measure lightning characteristics differently. Therefore, direct comparisons of the ground-based data and the spaceborne data are possible, but have some limitations (e.g., P. M. Bitzer et al., 2016; Rudlosky et al., 2019).

One opportunity to provide an additional data set for validation was the use of astronaut photography and video from the ISS. The photography and video have their advantages because each photo and video are time/location tagged, and are taken from the same platform as ISS LIS. Furthermore, during the validation period of GOES-16 and ISS LIS, specialized nadir pointing video was being taken during night overpass times to capture meteorites using the Chiba University Meteor camera (METEOR; Arai et al., 2014).

Quantitative scientific analysis of ISS onboard camera system imagery has been limited (e.g., Jehl et al., 2013). However, the combination of video and multiple georeferenced data sets provide the opportunity to develop methodologies by which scientific analysis can be achieved from ISS video and photos. Therefore, the goals of this proof-of-concept study were:

1) Develop a unique method for automated detection of lightning events in the METEOR video camera frames, which is fundamentally generalizable to any near-nadir video imagery, to determine their spatial characteristics
2) Attempt reverse geolocation of METEOR video frames with lightning to understand spatial and temporal offsets of the GOES-16 GLM and ISS LIS instruments
3) Determine if it was possible to intercompare lightning flashes observed by GLM, ISS LIS, ground-based lightning networks, and METEOR video to understand physical quantities of the lightning event (e.g., flash area) from the perspective of different lightning networks

2. Data and Methods

2.1. Lightning Data Sets

A combination of lightning data sets was utilized in this work to take advantage of the strengths of each lightning detection system for accurate geolocation with the video frames. The present study utilized optical detection of lightning from space- and ground-based lightning location sensors (LLS) that observe electromagnetic waves that are emitted by lightning. Each observation type has strengths and weaknesses (e.g., Nag et al., 2015); however, when combined they can provide a more complete picture of individual lightning events and key spatial characteristics of thunderstorms, their intensity, and lifecycle.

2.1.1. GLM

GLM is an instrument onboard the Geostationary Operational Environmental Satellite Series R (GOES-R) that detects lightning occurrence in a 1-nm window around 777.4 nm. GLM detects optical pulses with a 1,372 x 1,300 charged coupled device (CCD) that has a nadir resolution of 8-km by 8-km, and 9-km by 14-km resolution at the edges of the field of view (FOV). GLM contains a three-tier hierarchy of data organization of events, groups, and flashes (Goodman et al., 2013; Rudlosky et al., 2019). A GLM event is defined as the occurrence of a GLM single pixel exceeding the instrument background threshold during a 2-ms period. A GLM group is defined the grouping of one or more simultaneous GLM events that occur in the same 2-ms period and that are adjacent to each other. A GLM flash is defined as a set of GLM groups that are sequentially separated in time and space by no more than 330 ms and 16.5 km, respectively, and the maximum flash duration is 3 s (Goodman et al., 2013; Rudlosky et al., 2019). The additional parameter of flash area (km²) was utilized to directly compare with the areas computed from the video images using processing techniques outlined below.

2.1.2. International Space Station Lightning Imaging Sensor (ISS LIS)

ISS LIS images 600-km swaths, with any specific location in the camera’s FOV for approximately 90 s (Blakeslee et al., 2020). The orbit is inclined approximately 51.6°, which allows for coverage at higher latitudes compared with its predecessor, the TRMM LIS. ISS LIS detects lightning occurrence in the same 1-nm window around 777.4 nm and the data hierarchy is the same as GLM, with events, groups, and flashes as output. The nadir resolution of ISS LIS is approximately 4 km, and near swath edge it is ~6 km.
2.1.3. National Lightning Detection Network (NLDN)

The NLDN has been used to accurately locate the position of cloud-to-ground (CG) lightning flashes within the contiguous United States for nearly 3 decades (e.g., Buck et al., 2014; Cummins & Murphy, 2009; Nag et al., 2015). The system consists of 113 sensors across the CONUS and has a reported detection efficiency (DE) of CG flashes between 90% and 95%, with spatial errors in CG location that are typically less than 500 m (Cummins & Murphy, 2009). This system pinpoints the exact location where flashes come to ground in thunderstorms, or where there are vertical displacements in the flash (e.g., vertically oriented channels) within the cloud. The timing and location precision are used to validate the location of the GLM data and ISS LIS data relative to lightning occurrence within the video camera frames. For this analysis the flash-level (i.e., not stroke) NLDN data were available to be used.

2.1.4. West Texas Lightning Mapping Array (WTLMA)

Data from the WTLMA was utilized for a May 17, 2017 overpass analyzed below. The WTLMA is an 11-station network that operates in the 60–66 MHz range center on Lubbock, TX (V. C. Chmielewski et al., 2018). The thunderstorms on the May 17, 2017 overpass occurred ∼220 km east southeast of the WTLMA, which is within the 80% VHF source DE range from network center (V. C. Chmielewski & Bruning, 2016). The LMA data provide additional information on the location of lightning events and some spatial context to the size of each lightning flash that can be matched with GLM data.

2.2. Radar Data

Radar data were acquired from the National Center for Environmental Information (NCEI) Level-II radar archive (https://www.ncei.noaa.gov/). Horizontal radar reflectivity was utilized to characterize the depth and intensity of thunderstorms during each overpass. Radar data were visualized and synthesized through the Python Atmospheric Radiation Measurement (ARM) Radar Toolkit (Py-ART; Helmus & Collis, 2016) and Gibson Ridge Software analysis packages.

2.3. METEOR Camera

The Chiba University Meteor camera (METEOR; Arai et al., 2014) was a nadir-pointing color high-definition television (HDTV) camera aboard the ISS whose purpose was to observe meteors as they enter the Earth’s atmosphere. The METEOR mission ended in February 2019. Fortuitously, the system also observed lightning while on the night side of Earth. The camera operated at 59.94 frames per second and had a FOV of 1,280 by 720 pixels (which translated to 28.4 degrees by 16.4 degrees from boresight). The camera used a complementary metal oxide semiconductor (CMOS) focal plane and was designed to be ultra-sensitive to detect meteors. The consequence of this was that bright lightning often saturated individual pixels. However, as will be shown later, the automated lightning detection methodology accounted for this oversaturation. Focal length of the lens was 10.5 mm, and resolution of each pixel at the ground was approximately 260 m. An example of a METEOR video of lightning is provided in the supporting information as Movie S01.

2.4. Visible Infrared Imaging Radiometer Suite (VIIRS) Day Night Band (DNB)

Nighttime satellite imagery from Suomi National Polar-orbiting Partnership (Suomi-NPP) VIIRS DNB was utilized given its ability to identify city lights from low Earth orbit (e.g., Cao et al., 2013, 2014; Cole et al., 2013; Molthan & Jedlovec, 2013). VIIRS DNB information was pulled from the NASA Earthdata web-mapping server (https://map1c.vis.earthdata.nasa.gov/). This georeferenced information was used to align video frames from the METEOR camera through matching of the video frame with the background light information from the DNB imagery.

2.5. Geolocation Approach

The ISS camera geolocate open source software (T. J. Lang, 2019) was used to geolocate individual frames from the METEOR video. This software, which is generalizable to any standard camera used from space, makes use of user-provided camera specifications (e.g., focal plane size, focal length, etc.), publicly available
two-line element (TLE) ephemeris data for the ISS, and the Standard General Perturbations Satellite Orbit Model 4 (SGP4) Python module. Basic photogrammetry combined with standard satellite georeferencing approaches (Sapiano et al., 2010; Schenk, 2005) are also included. Required inputs include the coordinated universal time (UTC) date and time stamp of each video frame or photograph, and also include roll, pitch, and yaw of the satellite/camera. The pointing angle information is often not publicly available for the ISS, and may not be necessarily relevant for a given camera (e.g., a handheld camera used by an astronaut). Therefore, manual trial and error is required to back out the camera pointing information, via comparison to an independent data set. While this process can be painstaking, it can ultimately be very accurate, with uncertainties to within 1–2 camera pixels near nadir. An example is shown in Figure 1, where an astronaut photograph of the Ft. Lauderdale coastline has been manually well matched to an independent high-resolution coastline database for Florida.

A similar trial and error process was applied to geolocate individual METEOR frames during the case study overpasses. However, as mentioned in Section 2.4 instead of a coastline database the VIIRS DNB city light database was used as the point of comparison. Then, because the METEOR camera location and pointing are fixed on the ISS, the roll, pitch, and yaw values obtained were assumed to be valid for 5–10 s of video, and thus the same pointing angle information was used for frames within that time window (the ISS orbit position was updated relative to the new time stamp, via the TLE data and SGP4). This provided sufficient accuracy to geolocate individual lightning flashes over their short lifetimes, while limiting how often manual determination of pointing angle was required.

2.6. The METEOR-Derived Lightning Identification Technique

For automated detection of lightning within individual video frames, a bilateral blur technique (e.g., Zhang & Xiao, 2014) was utilized. A bilateral blur is a filtering technique that nonlinearly smooths images, while retaining edges of features of interest. For the purpose of this analysis, the filter was ideal because it helped identify edges of multiple scattering of light in the cloud, and helped generate bounding contours in the video frame that outlined the extent of the light in the frame. Based on trial and error for the METEOR data set, the parameters found to be most effective for the bilateral filter were a kernel size of 9 × 9 pixels, a spatial smoothing of 0.75 standard deviations, and a color smoothing of 0.75 standard deviations.

A red, green, blue (RGB) space was utilized to identify automatically identify lightning flash properties for frame-by-frame analysis (Figure 2). This helped mitigate challenges with overexposure in the METEOR camera due to photons flooding the sensor during lightning occurrence. The overexposed regions had very different light characteristics on their peripheries. Lightning flashes tended to produce more blue hues with far greater scattering of light as the optical emission from the flash traveled through the cloud. Furthermore, it was found that light escaping from the side of the cloud tended to illuminate much of the cloud deck below it, resulting in a region many times the size of the flash itself. The illumination of the lower cloud deck was of a more diffuse nature and did not reach saturation values or alter the hue outside of defined filtering thresholds. The RGB concept also allowed the separation of light from cities from that occurring with lightning flashes. Cities tended to have more red and orange hues associated with them versus the blue tones of the lightning events observed by METEOR.

In order to properly identify lightning flashes, it was necessary to determine a lower threshold value to limit the multiple scattering detected with lower saturations of blue light. This threshold was determined utilizing a representative subset of flashes obtained from multiple METEOR videos. Histograms of these flashes were generated, and an average was taken. Next the image was converted to red-green chromacity (rgC) color space to determine the pixels in each video frame that contained the highest ratio blue values. The result was a binary mask that identified pixels with light from lightning as white, and all other pixels in the image as black. Contiguous white pixels were then identified and a bounding circle and/or a convex hull (e.g., Bruning & MacGorman, 2013; Mecikalski et al., 2015) was then drawn around groups of pixels that had five or more adjacent pixels that were white. The areas of the bounding circle and convex hull were then calculated for each frame in km². The convex hull enabled the inclusion of overexposed pixels in the brightest portion of the flash in the area estimate, as these overexposed pixels get assigned as black by the binary mask (Figure 2). The bounding circle also accounted for this, but tended to overestimate flash area based on visual inspection of the video between the location of light and the circle bounds. Note that the
Figure 1. Astronaut photograph of the Ft. Lauderdale, FL coastline, manually geolocated using the ISS camera geolocate software against a high-resolution coastline database (https://openstreetmapdata.com/). Photograph was taken at 18:01:18 UTC on August 27, 2008 using a Nikon D2Xs camera with a focal length of 70 mm. Roll, pitch, and yaw of the camera and ISS combined observing system were estimated to be $-4.2^\circ$, $-3.3^\circ$, and $-45.9^\circ$, respectively, with an uncertainty of $\pm 0.1^\circ$. Pixel resolution is $\sim 39$ m. Photograph FOV is approximately 120 km by 80 km. Photo available from https://eol.jsc.nasa.gov/SearchPhotos/photo.pl?mission=ISS017&roll=E&frame=14836.
area encompassing the watermark logo in the upper right of each video frame (Figure 2) was excluded from the above flash identification analysis. An example of how the bounding circles encompass METEOR-identified flashes is shown in the supporting information as Movie S02.

2.7. Alignment of Multiple Data Sets to Characterize Offsets

Temporal alignment of the video to the NLDN data was a first step. NLDN was preferred because of the precise timing and geolocation of lightning events. At the time of analysis, there were uncertainties in the offsets in space and time of both the GLM and ISS LIS data (Blakeslee et al., 2020; Rudlosky et al., 2019). Even though the NLDN does not contain spatial information on lightning flashes, it was assumed that the point location of the NLDN would fall inside the blob of light observed in the METEOR video. The key to integration of these data sets for reverse geolocation was found at the subflash level; on the order of milliseconds. For a given flash, individual video frames were assigned the time stamp with the best temporal fit with NLDN based on visible multiple scattering and the frame rate of the METEOR camera (59.94 s⁻¹), assuming that the flash would be brightest in the video during the first NLDN-detected return stroke (indicated by the time associated with each NLDN flash). Isolated flashes were used to establish the reference time stamp, since there was less uncertainty relative to which brightening was related to an NLDN flash in the METEOR FOV. Due to the frame rate of the camera, the timing uncertainty of the video is 16.7 ms. This amount of timing variation accounts for a maximum of ∼150 m displacement over the duration over the exposure due to the movement of the ISS at 7 km s⁻¹, which is negligible compared to the altitude of the camera (∼400 km) and to the nadir resolution of ISS LIS and GLM (4 and 8 km respectively).

For the May 17, 2017 event, GLM flash area, flash, latitude, and flash longitude from GLM flash in the overpass FOV were used to assign METEOR frames to a GLM flash. If an individual METEOR frame's latitude and longitude center point fell within the footprint of a GLM flash, that frame was assigned to the GLM flash. Once all frames were assigned, the largest area computed from the flash identification technique on

Figure 2. Summary of flash detection methodology for color video frames. Step 1 shows the input image. Step 2 shows the image with a color inversion to eliminate city lights but preserve lightning. Step 3 shows a binary mask applied that makes use of manually determined thresholds, erosions, and dilations to identify lightning regions. In Step 4 basic clustering methods such as bounding circles and convex hulls are applied to the mask field. Note that the use of these clustering methods can account for the binary mask hole caused by the lightning-saturated video pixels (center of main flash area in Step 3). For METEOR video, the watermark region (upper right, all images) is not considered in the flash processing.
the METEOR video was compared directly to the GLM area. GLM was preferred to ISS LIS for this computation because flash area is not a level 2 standard feature produced in the ISS LIS data set. Similar analysis for January 2, 2017 is not possible because of a lack of GLM data and because the NLDN only produces a single geolocated point, which does not contain area information by which frames can be compared.

3. Analysis

Two case studies are presented to demonstrate the method by which video frames and lightning data were aligned. One case is prior to the release of GLM and ISS LIS data while the second was during the NOAA GLM Calibration/Validation Campaign in 2017. Approximately 14,000 frames from two METEOR overpasses were utilized in this analysis.

3.1. January 2, 2017 Central Texas

A proof-of-concept case was utilized to determine to what extent the METEOR video could be matched to an independent lightning data set. The goal was to align the video frames with the VIIRS DNB city light information and establish video timing relative to NLDN. A total of 5,694 frames were examined to determine lightning occurrence.

A line of thunderstorms in central Texas was propagating southeastward along the Interstate 35 corridor. The ISS passed over this region between 11:09:00 UTC and 11:10:30 UTC (Figure 3). In Figure 4, a
representative frame from the METEOR video is shown. (The corresponding video for this METEOR over-
pass is available in the supporting information as Movie S01, and the flashes discussed in this section are
shown in Movies S02 and S03). The three main cities of (from west to east) San Antonio, Austin, and College
Station, TX are identified by red stars. Four lightning flashes were identified by the NLDN (purple circles),
and these point location coincided with the optical observation of a lightning flash illuminating its parent
thunderstorm cloud in the northern portion of the video frame. Additional lightning was detected by the
camera just southwest of the illuminated NLDN-detected flashes in the frame.

A representative time series of METEOR-determined flash area relative to NLDN-detected flashes is shown
in Figure 5. The flash used in this analysis occurred around 11:09:44 (i.e., ~2 s before the flashes shown in
Figure 4) and lasted over 1 s in the video. Regardless of methodology used to compute it, significant increas-
es in flash-illuminated area align well with the NLDN-detected flash times, within the uncertainty of the
video frame time stamp. This observation is analogous to previous comparisons between optical and low
frequency measurements of lightning (e.g., Christian & Goodman, 1987; Goodman et al., 1988). As can be
seen, the camera observations provide scientifically useful context for the discrete NLDN events, which are
clearly linked together within a longer-duration in-cloud parent flash observed by METEOR. All the NLDN
flashes were identified as in-cloud with peak currents < 10 kA, and all but one of the events were negative
polarity (Figure 5).

Figure 4. Visible Infrared Imaging Radiometer Suite (VIIRS) Day Night Band (DNB) city lights database with a frame
from the METEOR camera overlaid. Approximate time is 11:09:46 UTC on January 2, 2017. The alpha value of the
overlay is reduced to demonstrate approximate matchup between the city lights in the METEOR video and the VIIRS
database. In the northern edge of the frame two lightning flashes are visible, one of which is spatially collocated with 4
National Lightning Detection Network (NLDN) flashes that occurred within ±400 ms of the frame.
3.2. May 17, 2017 Western Texas

A line of thunderstorms erupted in west central Texas on May 16–17, 2017 as a westward-moving dry line and southeastward-propagating cold front collided (Figure 6). This line of storms propagated southeastward, and around 05:44 UTC intersected with a southwest-northeast oriented ISS orbit. As the passed near the thunderstorm system, observations from both the METEOR camera and LIS were available. (The corresponding video for the METEOR overpass is available in the supporting information as Movie S04). In addition, GLM and NLDN provided continuous coverage of the storms. A total of 8,098 frames were utilized from the METEOR video from this event (not all frames included lightning). A total of 289 GLM flashes fell within the FOV of the METEOR camera, and 285 flashes were observed by ISS LIS.

The first flash highlighted occurred at 05:44:09 UTC southwest of San Angelo, TX. The GLM, ISS LIS, and NLDN all detected this lightning event (Figure 7). In the METEOR frame in Figure 7, note the central blob of light indicating the main turret being illuminated by the lightning, as well as the partial ring of additional multiple scattering occurring from low cloud surrounding the turret. Using uncorrected Level-2 data from GLM during the checkout phase, GLM observed some events within ±300 ms of the frame, but they were not centered on the brightest part of the flash; instead, they were displaced southwestward. By contrast, ISS LIS observed more events than GLM, and they were largely centered near the brightest portion of the flash at this time. The NLDN observed two positive intracloud flashes (i.e., positive peak current), and these were georeferenced right over the brightest part of the flash in the frame. Thus, METEOR, ISS LIS, and NLDN appeared to be consistent in terms of the main flash location, while uncorrected GLM data (which during May 2017 were known to suffer from geolocation errors) did not agree as well on flash position.

The time series for this flash is shown in Figure 8. Notably, the color-based flash detection algorithm applied to METEOR was able to detect the initial brightening of the cloud from the flash approximately 200 ms prior to any activity detected by ISS LIS or GLM, and nearly 300 ms before NLDN registered any activity. This capability was confirmed by visual inspection of the video as well. ISS LIS and GLM appeared to be most sensitive to the first two rapid brightening periods (first and second maxima in METEOR flash area) that occurred around 200 and 300 ms into the flash, with especially ISS LIS observing significantly fewer events after that period, despite a third METEOR flash area maximum occurring around 450 ms into the flash. The reason METEOR detected this particular flash earlier could have been related to its higher spatial resolution.
relative to GLM and ISS LIS. However, as we will discuss below, it is not always the case that METEOR activity obviously leads the other optical sensors.

The May 17, 2017 case also demonstrates some of the challenges in precise geolocation between the METEOR camera observations and other lightning data sets. During the overpass, around 05:44:49 UTC, the portion of the storm observed by METEOR was ∼220 km from the WTLMA. Figure 9 shows a frame from the storm around this time, with NLDN, WTLMA, ISS LIS, and GLM within ±1 s of the frame also overlaid. In this still image it is difficult to fully capture the dynamic nature of active lightning observed by the METEOR video around this time. The corresponding animation of the 2 s of imagery is shown in the supporting information as Movie S05. There is good overall bulk spatial correspondence between the METEOR scene of flashes and the independent data sets. Note in particular the cluster of light blobs centered near −100.8° longitude and ∼31.5° latitude, which are spatially collocated with multiple LMA sources, NLDN flashes, as well as ISS LIS and GLM events. A similar well-defined grouping match is seen in the light blob observed near −99.5° longitude and 32.6° latitude.

In Figure 9, also note that surrounding METEOR frames showed corresponding transient light blobs that matched the general locations of the “orphaned” cluster of ISS LIS sources near −101.3° longitude and 31.2° latitude, as well as the cluster of NLDN flashes, GLM events, and LMA sources observed near −99.5° longitude and 32.8° latitude. Movie S05 demonstrates this, and indicates that sometimes ISS LIS and GLM activity apparently preceded later METEOR activity in the same location. While METEOR, ISS LIS, and GLM are optically based, there may be differences in their sensitivity to flash processes given their different wavelengths (visible vs. near-infrared) and frame rates (∼60 s⁻¹ vs. 500 s⁻¹). Moreover, given the active flashing (evidently > 1 s⁻¹), it becomes difficult to interpret which data set is leading which. Movie S05 also shows interesting “splitting” behavior in a flash seen by METEOR that started early in the animation near the center of the FOV. While other data sets showed the ends of this splitting flash, they don’t resolve the narrowing (i.e., cooling) of the channel-like structure that connected the two ends.
These spatiotemporal differences between the different data sets may also be due to the following factors: measurement of different lightning properties (e.g., radiation from electromagnetic breakdown vs. optical light emission), and different spatiotemporal errors associated with these measurements (particularly relevant for GLM since this overpass occurred during its postlaunch test period when significant timing and geolocation issues were being addressed). Therefore, if \textit{a priori} pointing information is unavailable, it is more advantageous to geolocate frames and images from spaceborne cameras using more permanent characteristics like city lights or coastlines. However, the analysis that developed Figure 9 and Movie S05 could be used to support examination of the relative detection efficiencies of lightning data sets against geolocated video from space (see next section).

3.3. Flash Population Statistics Using METEOR

In this section we will demonstrate how the geolocated video imagery of lightning can be used to derive accurate flash statistics. Flash area and length have been shown to be important to separate convective and stratiform regions individual in storms (e.g., Bruning & MacGorman, 2013; Calhoun et al., 2013; T. J. Lang et al., 2015; Schultz et al., 2015) and providing seasonal and climatological characteristics for lightning occurrence (e.g., Fuchs et al., 2016; Harkema et al., 2019; López et al., 2017; Rudlosky et al., 2019; Yoshida 2019).
et al., 2019). In total, 7,105 unique METEOR frames with lightning were assigned to 289 flashes observed by GLM during 05:43:48–05:46:03 UTC (when METEOR was observing lightning). Several frames had more than one lightning event; therefore, a total of 10,138 flash-frames were utilized to determine the largest flash area derived from the METEOR camera derived identification technique for each GLM-matched flash. The median flash size from the largest individual video frame for each METEOR flash matched to GLM was 2,613 km². The median size for each GLM flash within the METEOR FOV was 2,879 km². This resulted in a difference of 266 km² (∼10%), which indicated that the METEOR-derived lightning identification technique was producing realistic area results as compared to GLM.

Similar temporal constraints to what GLM uses for flash clustering were applied to the METEOR camera frames, and a relative DE for GLM was computed. METEOR frames with lightning identified by the METEOR-lightning algorithm were considered one flash if a series of frames occurred within 330 ms of each other, and METEOR-derived lightning centroid location fell within the radius of a previous observed lightning frame (not including the initial frame where lightning was first observed in METEOR). This resulted in 309 lightning flashes identified by the METEOR-derived lightning technique. Thus, during this overpass, GLM had a relative DE of 93% (289/309) against the METEOR-derived technique, which is higher than the observed 81% DE observed at night with GLM validation studies using ground-based networks for the entire FOV (e.g., Bateman & Mach, 2020). There were 285 ISS LIS flashes matched to lightning identified from METEOR camera frames, which is a relative DE of 92%. Blakeslee et al. (2020) observed that ISS LIS relative DE ranged from 51% to 75% when compared to other lightning observing systems, and the higher DE obtained here again is likely in part due to nighttime, the optical nature of METEOR, and the large average flash size during this period of time.

Figure 10 illustrates the distribution of the METEOR-derived flash length observed in the 7,105 individual frames (Figure 10a), and the maximum flash length for each of the 309 individual flashes (Figure 10b). In general, the flash length computed by the METEOR-derived method were larger than the medians observed in LMA and GLM studies. The median flash length for both the frame and the flash distributions are 44 km. This was significantly larger than most LMA studies, as median flash lengths have been observed to be 3–15 km in length (Fuchs et al., 2016; López et al., 2017; Yoshida et al., 2019). This is not surprising because LMA flash area computations are not affected by light scattering; thus, LMA flash sizes will be smaller than optically detected flashes. Comparing to GLM observations of flash area and length places most of the flash...
lengths observed from the METEOR-derived technique between the 90th and 99th percentile in observed flash area and radii (Harkema et al., 2019; Rudlosky et al., 2019). However, as noted earlier, the median difference in flash area between METEOR and GLM was 266 km$^2$, and the matched GLM flashes had a median flash length of 51 km. Thus, the flashes in this thunderstorm may have been large compared to the overall GLM population. There is some credence to this hypothesis given the system was linear in structure (Figure 6), and large flashes are known to occur in these linear systems (e.g., Peterson et al., 2020; Schultz et al., 2015).

Additionally in Figures 2 and 7 there is evidence from this May 17, 2017 case of illumination of a lower level cloud deck. This artifact tends to inflate flash size because the spaceborne sensor cannot distinguish the light generated from the updraft region and out of cloud top from that scattered from a lower cloud deck (e.g., Peterson et al., 2017). Given the short temporal window of the overpass, and that these thunderstorms were generating several flashes during the overpass time, it is plausible that reflection of light off a lower cloud deck occurred multiple times during the overpass, thus resulting in the larger median flash lengths in both the METEOR-derived lightning identification algorithm and in the GLM Level-2 lightning data set for this period.

Figure 9. VIIRS DNB city lights database with a frame from the METEOR camera overlaid. Approximate time is 05:44:49 UTC on May 17, 2017. The alpha value of the overlay is reduced to demonstrate approximate matchup between the city lights in the METEOR video and the VIIRS database. Multiple lightning flashes are observed in the METEOR frame. Also shown are the positions of ISS LIS and GLM events, WTLMA sources, and NLDN flashes that occurred within ±1 s of the frame.
4. Discussion and Conclusions

Based on the cases examined, it was determined that this study’s approach for video analysis was capable of automated lightning detection at night, as well as reasonable geolocation and timing accuracy, enabling scientifically useful comparison between spaceborne color HDTV video cameras and other lightning data sets. This was true even despite the limitations of the METEOR camera, such as the relatively coarse temporal resolution (~16.7 ms), the need to manually determine pointing angles, and the tendency for the high-sensitivity camera’s pixels to saturate during bright lightning events.

Though color HD video is only useful for lightning detection at night, it has the advantage of very high spatial resolution (~260 m) when used in Low-Earth orbit, which can be improved even more using recently released 4K+ resolution video cameras. Moreover, automatically geolocated and timestamped video imagery would be applicable to many additional Earth science-related topics (e.g., tropical cyclones, volcanic eruptions, convective cloud development, etc.), and HD video cameras can easily and cost-effectively fit within the confines of a cubesat.

Approximately 14,000 frames were utilized from two separate events to evaluate the METEOR-derived lightning identification technique. This color-based methodology used to automatically identify lightning flashes and distinguish them from city lights shows significant promise given that all lightning flashes within the two videos were identified and city lights were not flagged as flashes. In particular, it provides a wholly independent yet still optically based method for detecting lightning, which can be compared and contrasted with the time-differencing approach used by ISS LIS and GLM. The color-based methodology, when coupled with the higher spatial resolutions provided by HDTV, suggests that flashes can be identified sooner than NLDN, LIS, or GLM can identify them, and can better resolve certain flash structures. Thus, HD color video can provide a potentially more comprehensive time series of flash development and duration than is available from those other instruments.

A total of 289 GLM flashes and 285 ISS LIS flashes were compared with METEOR video frames in which lightning was identified from the May 17, 2017 video. Results indicate that the METEOR-derived lightning identification technique identified more lightning (309 flashes), and when matched with GLM-observed flashes, produced reasonably close flash areas as compared to the GLM flash area. The median difference between GLM areas and the METEOR-derived lightning identification technique was 266 km². Furthermore, when compared with the NLDN, rapid increases in flash area observed by this technique corresponded to return stroke processes observed by the NLDN.

This study’s overall approach is fundamentally scalable to spaceborne high-speed video cameras, which could enable a more detailed examination of lightning physics from orbit than is currently possible with the state of the art. The key ingredients to unlock the potential of this study’s approach is the addition of accurate and automated pointing angle and timestamp data, which were not available with the METEOR...
video clips that were used. With those ingredients in hand, any near-nadir-staring video camera in space can become a tool for detecting and studying lightning in a quantitative manner.

Data Availability Statement

NLND data were procured from Vaisala Inc. (https://www.vaisala.com/en), and is available for these cases through the GOES-R Calibration/Validation Portal (https://goes-r.nsstc.nasa.gov/home/). ISS LIS are available from the Global Hydrology Resource Center (https://ghrc.ngdc.noaa.gov/lightning/data/data_lis_iss.html). GLM data are available from the National Oceanic and Atmospheric Administration (https://registry.opendata.aws/noaa-goes/). West Texas LMA data are courtesy of Dr. Eric Bruning at Texas Tech University (https://pogo.tosm.ttu.edu/about/).

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