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Comparison of High-Speed Optical Observations of a Lightning Flash From Space and the Ground

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Abstract We analyze a nighttime negative cloud-to-ground lightning flash in Colombia observed from the ground with a high-speed camera at 5,000 images per second and from space by the Atmosphere-Space Interactions Monitor (ASIM) on the International Space Station (ISS), the Lightning Imaging Sensor also on the ISS (ISS-LIS), and the Geostationary Lightning Mapper (GLM) on GOES-16. The space instruments measure the oxygen band at 777.4 nm, allowing for direct comparisons of measurements, and the ground-based camera observes in a wide visible band. After conversion to energy emitted at the cloud top, we find a good linear correspondence of the optical energies measured by the three space instruments, except that GLM values were 3 times higher. We attribute this mainly to the difference in viewing angles between spacecraft and the cloud. Over the entirety of the ASIM observed flash, optical pulses were detected by GLM and LIS, only when the energy reported by ASIM was greater than 332 J and 949 J, respectively. Their detection rate corresponds to 14% and 2.5%, respectively, of the flash duration observed by ASIM. The temporal variation of the high-speed camera luminosity matched well the features observed by ASIM around the time of the stroke but reached ~3.9 times higher peak intensity during the return stroke, attributed to its broader spectral sensitivity band and a viewing angle advantage.

Plain Language Summary This paper describes the detection of the same lightning flash in Colombia by three different optical imaging systems monitoring lightning activity from space, as well as a high-speed camera at the ground. Each space instrument (ASIM imager and photometer, ISS-LIS, and GLM) has different characteristics, from the spacecraft orbit altitude to the detector spatial and temporal resolution. To make meaningful comparisons, we demonstrate how to calculate the optical energy emitted at the cloud top from the original luminosity values as received by each instrument. Then, reported cloud top energy and lightning detection efficiency for parts of the lightning flash duration are compared. The results show that during this flash, GLM detected only 14% of its total luminous activity as recorded by the sensitive ASIM photometer, and those features were reported 3 times more intense, most likely because of the different viewing angle to the storm. GLM detected a wider luminous cloud top area during the cloud-to-ground stroke than ASIM. The spatial resolution of the ASIM imager allows to identify cloud features also seen in GOES-16 meteorological satellite images.

1. Introduction

The first dedicated instruments in space for global mapping of lightning flashes were the Optical Transient Detector on MicroLab-1, launched in 1995, and the Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measurement Mission satellite, launched in 1997 (Boccippio et al., 2002; Christian et al., 1989). The imagers of these missions monitor a narrow 777.4 nm oxygen triplet band containing the bright emissions by lightning that allow for lightning detection both day and night (Christian & Goodman, 1987; Goodman et al., 1988). The Geostationary Lightning Mapper (GLM; Edgington et al., 2019; Goodman et al., 2013; Rudlosky et al., 2019) on the GOES-16 and -17 weather satellites over the Americas, launched in 2016 and 2018, builds on the heritage of the Optical Transient Detector and LIS sensors. The GLM is the first instrument that allows continuous monitoring of lightning from geostationary orbit, observing lightning event
pulses over the Americas, the Pacific and Atlantic Ocean (Goodman et al., 2013; Figure 2) at 777.4 nm with a temporal resolution of 2 ms and a nearly constant spatial resolution of 8 km. A similar Lightning Imager (LI) will be on the Meteosat Third Generation satellite, planned for launch into a geostationary orbit in 2022 to cover the region of Africa, Europe as well northern South America and parts of the Atlantic and Indian Ocean (European Space Agency [ESA] Earth Observation Portal, 2020; European Organisation for the Exploitation of Meteorological Satellites [EUMETSAT], 2014). Since the GLM and the LI will be used operationally for the next two decades, it is of interest to understand their sensitivities to various lightning and cloud properties (e.g., Erdmann et al., 2020).

Currently, there are two high-speed lightning detection experiments on the International Space Station (ISS). One is the Atmosphere-Space Interactions Monitor (ASIM), which carries three photometers and two cameras for detection of lightning and transient luminous events such as blue jets, sprites, and elves (Neubert et al., 2019). The photometers measure at 180–240 nm (UV), 337.0 nm at 4 nm bandwidth (blue) and 777.4 nm at 5 nm bandwidth (red), with a sample rate of 100 kHz. The cameras measure in the blue and red (3 nm wide) bands at 12 frames per second and ~400 m resolution. The instruments are integrated in the Modular Multispectral Imaging Array with all the sensors pointing toward the nadir (Chanrion et al., 2019). The other instrument, the ISS-LIS (Blakeslee et al., 2020), is a flight spare copy of the LIS instrument on the Tropical Rainfall Measurement Mission satellite, detecting lightning with 2 ms and ~4.5 km resolution.

We succeeded in imaging lightning activity at 5,000 frames per second from a site in Colombia at the same time as the ISS passed overhead and have secured a unique data set of lightning activity at high temporal resolution simultaneously from space (GOES/GLM, ASIM, and ISS-LIS) and the ground. The following is a quantitative comparison of these data, which is possible by the conversion of native radiance and energy units to cloud top energy (−density).

## 2. Methods and Data

A negative cloud-to-ground (−CG) flash was detected by the Keraunos very low frequency lightning network in Colombia, which is a LINET detection system (Betz et al., 2009). The main stroke was registered at 02:02:38.031 UTC on 13 November 2018, at 8.3594°N, 76.8005°W, near the Colombia–Panama border. It had a peak current of −24 kA and was preceded by a +9 kA intracloud (IC) pulse near the same location 361 ms earlier at 02:02:37.670 UTC.

The high-speed camera system is a Vision Research Phantom V7.3 fitted with a Gen III image intensifier (broadband visible and near-infrared response) with fast P24 phosphor and mounted with a Nikon 50 mm F1.8 lens, fielded in Cartagena (van der Velde et al., 2019) at the coast of the Caribbean Sea (10.3947°N; 75.5627°W), 263 km from the flash. It recorded the bright stroke at 5,000 images per second with data capture triggered by a low-speed camera and flash detection software. Time was synchronized to the...
Table 1

| Instrument | Wavelength (\(\lambda\)) (nm) | Aperture diameter (\(D\)) | Exposure and interval (\(\Delta t\)) | Orbit altitude (\(z\)) | Local footprint (\(a\)) | Pixel solid angle (\(\omega\)) | Original units |
|------------|-------------------------------|---------------------------|-------------------------------------|------------------------|--------------------------|-------------------------------|---------------|
| ASIM PH1   | 337.0                         | 4                         | 1.0 mm                              | 10 \(\mu\)s             | 402 km                    | 0.25 Mm\(^2\)                 | \(E_e\) \(\mu\)W m\(^{-2}\) |
| ASIM PH3   | 777.4                         | 5                         | 2.3 mm                              | 10 \(\mu\)s             | 402 km                    | 0.25 Mm\(^2\)                 | \(E_e\) \(\mu\)W m\(^{-2}\) |
| ASIM CHU   | 777.4                         | 3                         | 3.0 mm                              | 83.33 ms               | 402 km                    | 0.325 km\(^2\)                | \(8.15 \times 10^{-7}\) sr \(L_{eo}\) \(\mu\)W m\(^{-2}\) sr\(^{-1}\) |
| ISS-LIS    | 777.4                         | 0.91                       | 100 mm                              | 1.9 ms                 | 402 km                    | 34.7 km\(^2\)                 | \(1 \times 10^{-4}\) sr \(\xi_e\) \(\mu\)J m\(^{-2}\) sr\(^{-1}\) \(\mu\)m\(^{-1}\) |
| GLM        | 777.4                         | 1                         | 110 mm                              | 1.9 ms                 | 35,786 km                 | 64.0 km\(^2\)                 | \(5 \times 10^{-8}\) sr \(q_e\) \(\phi\) |

Global Positioning System (GPS) with a precision of 1 \(\mu\)s. The Phantom memory allowed for 569 ms of imaging at 800 \(\times\) 600 pixels with 10 bits representation. However, only the data corresponding to the period surrounding the return stroke and subsequent pulses has been permanently stored.

The flash appeared in the lower left side of the trigger camera frame as shown in Figure 1a. The circle on the figure marks the field of view of the Phantom camera, which does not catch the flash, but rather its reflection via surrounding cirrus cloud. Figure 1b shows the position and view of the International Space Station at the time of the observation (red dot, 11.143°N, 77.177°W) and its orbit (green line), the ISS moving northeastward. Also shown is the full field of view of the ASIM instruments and the cropped region of the camera images downlinked. The accuracy of the absolute timing of the ASIM photometer data (~20 ms) was improved by lining up the optical pulses of the return stroke with the precise GPS time of the high-speed camera detection of the \(-24\) kA stroke onset and by accounting for the propagation delays to the ISS and camera at the ground. The raw data are included in the supporting information.

The three space instruments have different optics, sensor resolution, and distance from the Earth. In order to compare their output quantitatively, we convert their native units to cloud top energy (in Joules) and cloud top energy density (in Joules per square kilometer) under the assumption of isotropic hemispherical emission (Bohren & Clothiaux, 2006; Koshak, 2017; Zhang & Cummins, 2020, p. 208). This energy is calculated during the exposure time and for every image pixel. Tables 1 and 2 show, respectively, the instrument characteristics and their conversion formulas to obtain cloud top energy, as well as the lowest, highest and integrated values. Here we used the local pixel footprint area (\(a\)) which in the corner of the field of view of the instruments on the ISS is significantly larger than in nadir direction. For a detailed explanation about the conversion, refer to Zhang and Cummins (2020, Appendix A). For conversion of the photometer flux density values (W m\(^{-2}\)), we multiplied by sample time, yielding \(q/(\pi D^2/4)\), then used their formula A.7 (left side) where it can be noted that pixel footprint area \(a\) divided by pixel solid angle \(\omega\) yields distance squared (\(z^2\)), eliminating the need to know the emitting area.

The raw ASIM Camera Head Unit (CHU) 777.4 nm image has been processed in the following way. Background noise energy levels are read from the darkest row of pixels at the side of the image. The mean value is subtracted from all pixels. After that, only pixels with values above the 2\(\sigma\) level of the noise are

Table 2

| Instrument | Threshold/max/sum (in original units) | Conversion to cloud top energy in surface footprint | Cloud top energy (J) (2 ms) Thr/max/sum of pixels | Cloud top energy density (J km\(^{-2}\)) Thr/max/mean |
|------------|---------------------------------------|---------------------------------------------------|--------------------------------------------------|-----------------------------------------------|
| ASIM PH1   | 0.21/21.75/21.75                      | \(\Phi_e\Delta t = \pi \Delta \omega \xi_e^2 E_e\) | 5.027 \(E_e\) 36 --- 8.89 k                   | --- --- 6.3                                  |
| ASIM PH3   | 0.33/76.31/76.31                      | \(\Phi_e\Delta t = \pi \Delta \omega \xi_e^2 E_e\) | 5.027 \(E_e\) 70 --- 53.9 k                   | --- --- 38                                  |
| ASIM CHU   | 0.67/2091/3,490 k                    | \(\Phi_e\Delta t = \pi \Delta \omega \xi_e^2 E_e\) | 0.2618 \(aL_{e}\) 52 178 286 k               | 159 547 210                                 |
| ISS-LIS    | 3.349/55,330/815.3 k                 | \(\Phi_e\Delta t = \pi \Delta \alpha \xi_e \xi_L E_e\) | 2.858 \(a\xi_e/1000\) 332 5,478 80.3 k       | 9.5 158 57                                  |
| GLM        | 1.53/54.9/525                        | \(\Phi_e\Delta t = 4a\xi_e/(\alpha D^2)\) 6.612 \(a\xi_e\) 647 23.2 k 222 k | 10 363 157                                  |                                         |

Note. For the ASIM Camera Head Unit, the mean background noise energy was not subtracted from these listed values, and the energy is for all light accumulated during its long exposure.
displayed. The background mean is 47.8 J (147 J km$^{-2}$) and the standard deviation ($\sigma$) 1.9 J (5.9 J km$^{-2}$). Thus, the minimum detectable cloud top energy after background subtraction is 3.8 J (2$\sigma$) and minimum detectable cloud top energy density 11.8 J km$^{-2}$, which is slightly higher than ISS-LIS and GLM. The image projection has been fine tuned to the CG stroke location and corresponding features in the GOES-16 satellite image.

3. Results

3.1. Location and Extent of the Lightning Flash Observed From Space

The GOES-16 infrared satellite image (channel 9, 6.9 $\mu$m, midlevel tropospheric water vapor) of the cloud cover at the time of the flash is shown in Figure 2a. The −CG is located at the eastern edge of a small, local cold cloud top (dark) at −63°C obtained from channel 13 (10.3 $\mu$m, clean infrared). The altitude of the cloud top is estimated to 13.7 km from an atmospheric sounding profile taken at Corozal (Panama), 78807 MPCZ, at midnight UTC. The optical flash corresponding to the return stroke as observed by the ASIM camera at 777.4 nm is shown in Figure 2b. GLM is shown in Figure 2c and ISS-LIS in Figure 2d. As the energy per pixel varies greatly with the area covered by the different instrument’s pixels, we normalized energy by pixel...
footprint area and display the images (projected to ground) expressed in cloud top energy density (J km$^{-2}$; Table 2).

Comparing the ASIM image to the cloud image, the two brightest parts of the flash detected at cloud top are directly north and south of the detected –CG stroke location, directly at the eastern flank of the local highest cloud top, which itself does not pass as much light. The region of weak luminosity in the ASIM image east of the CG also aligns with a higher cloud, which blocks some of the lightning channel emission from lower attitudes, so the brightest section appears to match with a trough of lower cloud tops near the return stroke location, where the cloud is thinnest. The arc of brightness at about 10 km west, north, and east of the return stroke corresponds with the flank of the broader cloud tower (gradient from light to dark in Figure 2a), which includes the coldest top west of the CG stroke. A west-east oriented dark band in the ASIM image is just outside this arc, with a textured sheet of moderate brightness at further distances. This feature can be recognized in the satellite cloud image as a strip of lower cloud (less dense gray color).

The two brightest pixels of GLM approximately match the two ASIM maxima. The regions of moderate brightness regions (green blue) and the larger region of weak luminosity (dark blue/purple) compare very well among all three imagers. However, GLM appears to detect stronger emissions from the region of the ASIM image that is obscured by the cloud (west of the −24 kA stroke) and produces a much higher maximum near the CG stroke (444 J km$^{-2}$ vs. ISS-LIS 246 J km$^{-2}$ and ASIM 400 J km$^{-2}$), despite its shorter exposure time compared to ASIM. This may be an effect of the viewing angle difference between ISS and GOES-16. The latter looks almost directly down at the storm, while the ISS was 50° high in the sky at the stroke location, which could mean that surrounding higher cloud tops prevented the brightest area to be seen. The ASIM to ISS-LIS difference in maximum intensity is reasonable because the maximum is very localized whereas the averaged intensity within the ISS-LIS pixel footprints is much closer. Additionally, energy emitted by the brightest region may have been divided over more than one ISS-LIS pixel (Zhang & Cummins, 2020). This may apply to some extent to GLM as well, where energy of the brightest pixel may have contributions from adjacent bright cloud. However, the large GLM pixel shows an average energy density value greater than the averaged intensity of ASIM in its footprint, and surrounding ASIM cloud is weaker illuminated, which could not have raised the GLM pixel average value.

Quantitatively, this affects also the total cloud top energy (obtained by summing all the pixel energies). ISS-LIS totals 116 kJ during its two frames detecting the −CG stroke, across its storm area measuring 1,283 km$^2$. The ASIM imager detected 87 kJ (over the background energy) over 1,350 km$^2$ and GLM 262 kJ over 5,568 km$^2$. While ISS-LIS shows a similar size cloud illumination as ASIM, it appears truncated at the northeast side, even though the pixels are not on the edge of the imager. A part of the ISS may possibly have obscured the view (Blakeslee et al., 2020). The ASIM image is slightly clipped as well, only a rectangular subsection of the full frame was stored for transmission to ground. The GLM total luminous cloud top area is 4 times larger than the area detected by ASIM, which may be explained by its slightly better energy detection threshold (10.2 J km$^{-2}$ vs. 11.8 J km$^{-2}$ of ASIM and 9.5 J km$^{-2}$ for ISS-LIS for this boresight angle—using each instrument’s self-reported energy values).

The GLM energy value would seem so high because of the three much brighter pixels, but without those, 189 kJ is still detected, far higher than ASIM and ISS-LIS, so the contribution really comes mostly from the large area of low and medium intensity. Still, ASIM had the chance to gather some additional energy from lightning processes before and after the stroke during its 83.33 ms lasting exposure. On the other hand, it performs similarly to ISS-LIS, even more so when applying a small correction factor for the off-boresight angle (Boccippio et al., 2002). Note that the maximum cloud top energy values for a single 2 ms frame (group level) are indicated in Table 2 (80.3 kJ for ISS-LIS and 222 kJ for GLM).

### 3.2. Temporal Variation of the Complete Flash Observed From Space

The flash optical evolution is shown in Figure 3. Panel Figure 3a is the cloud top energy integrated over the active pixels of the GLM and ISS-LIS frames, and the ASIM photometer energy binned in 2 ms intervals that correspond directly to those of GLM. Figures 3b and 3c are the processed data of the 777.4 and 337.0 nm photometers (20-point moving average). The flash observed by the three sensors is in overall agreement regarding the main features such as identification of three main pulses and their peak energies. Because of its higher sensitivity, ASIM observes activity extending in time both before and after the main peaks.
identified by the other space instruments. ISS-LIS and GLM started to detect the start of the flash 4 and 5 ms after its start indicated by the ASIM 337.0 nm signal onset. The amplitudes of the blue signal (c) lie in general within a factor of 2 smaller or larger compared to the red signal (b) during the period leading up to the CG, whereas the red signal clearly dominates during the return stroke and in isolated peaks during the intracloud part of the flash. The main peak around the time of the return stroke is discussed in section 3.4. The period afterward (>38.063 s) is characterized by a lack of continuous activity observed by ASIM. Instead, eleven brief pulses are detected at 777.4 nm until the end of the photometer record. These are likely recoil processes (K changes) along old leader channels, typical for the late stage of lightning flashes (e.g., van der Velde & Montanyà, 2013).

Figure 3. Optical evolution of the flash of 13 November 2018 at 02:02:37 UTC, (a) the optical cloud top energy in 2 ms intervals measured across active pixels of GLM (cyan), ISS-LIS (blue squares), and the ASIM 777.4 nm (red) and 337.0 nm (dark blue line) photometers as functions of time. (b) The signal of the ASIM photometers at 777.4 nm and (c) 337.0 nm, both smoothed by a 20-point moving average.
3.3. Quantitative Comparison of GLM, ISS-LIS, and ASIM

The GLM detected a signal in 27 of the 198 2 ms sample bins (13.6%) that cover the continuous part of the flash as observed by ASIM (37.668–38.063 s) and the ISS-LIS in 5 intervals (2.5%). For the ASIM photometers, we define a signal energy threshold as $2\sigma$ over the mean level during the 157 ms of data registered before the flash start, integrated over 2 ms (70 J for 777 nm and 36 J for 337 nm), and find that the ASIM detected a signal in 98.4% of the bins at 337.0 nm and 83.3% at 777.4 nm.

Figure 4 shows the relationship between the energies detected in 2 ms bins by GLM (red dots) and ISS-LIS (blue squares), both against corresponding ASIM 777.4 nm energy on the vertical axis. The diagonal line is the ideal situation where the instruments match exactly. As was suspected from Figure 3a, GLM (x axis) reports systematically higher energies compared to ASIM (y axis). This seems consistent with the comparison of imaging, hinting at a possible viewing angle cause.

There appears to be a minimum ASIM cloud energy of 332 J below which there are no GLM detections. GLM reports energies down to 646 J, but this energy value corresponds to ASIM energies between 332 and 791 J. These are in line with those reported by Zhang and Cummins (2020). For ISS-LIS events, the lowest reported energy is 439 J with a corresponding ASIM energy of 947 J, although with just one sample this threshold is less established. The self-reported minimum value of 439 J is 2.7 times the minimum noted by Zhang and Cummins (2020), which may confirm an off-boresight observation angle disadvantage. We can now use these threshold values of ASIM energy to determine detection efficiency for the 2 ms bins of the flash bright enough to be detectable by GLM or ISS-LIS: 46.6% for GLM (27 of the 58 time bins exceeding 332 J) and 62.5% for ISS-LIS (five of the eight time bins exceeding 947 J).

The total cloud top energy of the flash detected by the three instruments is 369 kJ (GLM), 121 kJ (ISS-LIS), and again 121 kJ (ASIM 777.4 nm). It can be divided into the low brightness episode before the stroke, which contributes 102 kJ in GLM, 5.4 kJ in ISS-LIS, and 37.7 kJ in ASIM, and the stroke itself, producing 266 kJ in GLM, 116 kJ in ISS-LIS, and 79.0 kJ in ASIM. The stroke values are consistent with those found in the imaging comparison. For ASIM, imager energy should turn out a bit higher, as observed, because the exposure included luminosity before and after the −CG stroke as well. The 337.0 nm channel in ASIM observed a total of 55.8 kJ, with more energy produced during the activity before the stroke (39.7 kJ) than during the stroke (15.1 kJ). This means there is about equal amounts of energy in the 337 nm channel as the 777 nm channel during the intracloud part of the flash. The final stage of the flash, marked by several impulsive optical peaks, contributed 4.3 kJ in 777.4 nm versus 1 kJ in 337 nm and 1 GLM detection of 645 J (present but hard to see in Figure 3a). Note that mean photometer background noise energy integrated over time (48.7 J per 2 ms for 777.4 nm and 19.3 J for 337 nm) have already been subtracted from these values.

3.4. Temporal Variation of the Main Cloud-to-Ground Stroke Observed by ASIM and From the Ground

We next discuss the luminosity detected by the high-speed camera with the measurements by the ASIM photometers during the main stroke. Figure 5a shows the luminosities on a logarithmic scale. The photometer signals have been smoothed by a 20-point moving average to downsample the signals to a value close to the frame rate of the high-speed camera for proper comparison. The averaging by this amount sufficiently reduces the number of zero values in the 337 nm signal for calculation of the ratio. The brightness response curve of the high-speed camera was reproduced with a gamma setting of 1.0 (linear response to photons), normalized, and scaled to match the level of the low-intensity features of the 777.4 nm photometer signal. The 337 nm band is well beyond the spectral sensitivity range of the camera system.
One can note a broad peak lasting ~6 ms (38.031–38.037 s) that is followed by a smaller peak at 38.039 s. The onset of the broad peak is the −24 kA return stroke detected by the lightning detection network. The high-speed camera measurement reproduces many of the details of the 777.4 nm signal, including the three modulations of the amplitude during the main peak. The peak amplitude resulting from the best fit of the camera is 3.9 times higher than the peak amplitude of the 777.4 nm photometer. In Figure 5b, the last pulses at the end of the flash are shown with the same scaling of the camera. It can be noted that the 777.4 nm pulses appear larger than the ground-based camera. This may result from differences in viewing angle with respect to the location of the actual process and cloud attenuation. At all times, it should be kept in mind that the camera luminosity curve is scaled and not the absolute luminosity. The light integrated across the visible spectrum should in reality be higher than that of a single spectral line, and their relative contributions are different among lightning processes and change over time.

Figure 5c shows the increasing contribution (ratio) of the red signal compared to blue during the period leading up to the CG stroke (indicated by a red bar) where the leader channel approaches the ground. As discussed earlier, this likely reflects an intensification of the leader emissions. The signal amplitude in 777.4 nm rises gradually (a) consistent with a report of high-speed imaging observations of progressively...
brightening leaders as they approach the ground (Montanyà et al., 2014). The base ratio remains below 3 during this stage, while the spikes occur whenever the 337 nm channel has a minimum in its highly fluctuating signal. The 0.5–1 ms before the –CG signal, red almost doubled in intensity, while blue simultaneously decreased by that amount, resulting in a final large spike in ratio (~12). The high-speed camera luminosity also increased slightly at this time.

The –CG signal rise time in the ASIM photometers lasted about 160 μs, using the raw data. This is consistent with the dispersion of arrival times by multiple particle scattering of light through the cloud (Koshak et al., 1994; Light et al., 2001; Thomason & Krider, 1982). During the broad return stroke peak, the ratio red to blue remains greater than 3, peaking at about 6.5–7.5 (briefly 8.5). The ratio declines after 38.0322 s (the first, highest luminosity peak). The high-speed camera luminosity peaks 3.9 times higher than the red curve, decreasing subsequently until equal values are reached again at 38.0365 s. A separate (small) peak occurs at 38.039 (ratio of 5) that was recorded by both the camera and the ASIM photometer.

4. Discussion

The analysis of optical emissions produced by a lightning flash observed from space shows a consistent image footprint among the three different space instruments, with GLM showing the largest area in agreement with its slightly better pixel sensitivity. ISS-LIS did miss the lower brightness area extending to the east of the stroke, likely because of obscuration by ISS solar panels (Blakeslee et al., 2020). How much of the illuminated area away from the –CG stroke actually had leader activity underneath is best determined using 3-D lightning mapping array data (Thomas et al., 2000), which was not available in the location of the storm studied here. The ASIM imager was able to identify two spatially separated maxima and their location at the flank of an updraft tower, which itself was only partially illuminated, likely because of increased absorption of light by higher concentrations of hydrometeors (Peterson, 2019). The image also revealed texture in the surrounding cloud. Although its resolution did not permit detail in the cloud top, GLM did not show this top as dark as the ASIM imager. The intensities converted to cloud top energy density are consistent between ASIM and ISS-LIS, both viewing from the ISS, whereas GLM registered ~3 times higher total cloud energy values than ASIM and ISS-LIS at any brightness level. It must be noted that GLM radiances matched the GOES 16 Advanced Baseline Imager surrounding wavelengths (640 and 890 nm), within 10–20% (Edgington et al., 2017). A possible reason for the difference is the viewing angle to the storm, which was rather oblique for the ISS. This suggests partial obstruction or nonisotropic emission by the cloud. A factor of ~1.6 in energy reduction may be explained by the increased distance between storm and spacecraft (>510 km) compared to nadir (402 km) in agreement with the $z^2$ in the cloud energy conversion formula for the photometers in Table 2.

The ASIM photometer is the most sensitive of the three and documents 7 times more optical activity during the flash than GLM and ~39 times more than ISS-LIS, essentially confirming the continuous activity of lightning processes during the flash, similar to observations by 3-D lightning mapping systems over several hundreds of milliseconds (e.g., van der Velde & Montanyà, 2013). In total flash optical energy (871 fJ in native units of GLM over the entire flash duration), this flash ranks well above the 90th percentile recorded by GLM (Rudlosky et al., 2018) although this may be expected because it is a CG flash which are a minority compared to the weaker IC flashes. On the other hand, GLM does have a lower efficiency detecting IC compared to CG flashes (Zhang & Cummins, 2020).

The contributions of 777.4 nm and 337.0 nm emissions varied mostly between ratios of 0.5–2, with a 5 ms long peak especially in 777.4 nm (ratio of 3 to 8 red/blue) following the return stroke. This is in line with expectations since 777.4 nm line emissions from atomic oxygen would come primarily from the hot leaders and return stroke channel, while the 337 nm line is from molecular nitrogen emitted both by the leader channel and from their corona streamers (e.g., Raizer, 1991) associated with its propagation. Overall, the energies reported by the photometers during intracloud part of the flash were virtually the same between 337 and 777 nm, while the return stroke with continuing current and the late stage pulses had 4–5 times more energy in the 777.4 nm band, indicative of their thermal dominant processes.

The luminosity evolution of 777.4 nm ASIM and the high-speed camera during the main flash are highly similar down to variations at the submillisecond scale. For both instruments, the signals are from indirect photons scattered in the cloud, thereby compensating for the differences in the viewing geometry. The
higher peak values reached by the ground-based camera during the initial most intense part of the return stroke are in part caused by additional spectral emissions in the broad visible spectral range of the ground camera not observable by ASIM. In addition, it is possible that light transmission was reduced by denser cloud when observed from space compared to the side of the updraft tower seen from ground. The effects of cloud and precipitation particles on optical detection from space and ground appear quite significant and are not fully understood. The issue is complicated by the varying depth of lightning inside the cloud and differences in spectral emission intensity produced by different lightning processes over time, as hinted at in this study as the varying ratio of red to blue emissions during the intracloud part of the flash and the stroke. In the near future, the interpretation of optical emissions related to the flash features and their cloud scattering will be improved by comparing ASIM photometer evolution against precise evolution of lightning leaders detected by 3-D lightning mapping systems. This will benefit also the understanding of detection efficiency of operational space-based lightning imagers as GLM and the future LI and forthcoming geographical statistics.

Data Availability Statement

Data associated with this work has been made available in the Zenodo scientific repository (van der Velde et al., 2020). Data access to ASIM is available by registering at https://asad.space.dtu.dk/ website. GLM data are available from NOAA (GOES-R Algorithm Working Group and GOES-R Series Program, 2018; https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc: C01527#) and ISS-LIS from NASA Global Hydrology Resource Center (Blakeslee, 2019; https://ghrc.nasa.gov/pub/lis/data/science/nqc/hdf/).

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