A simultaneous observation of lightning by ASIM, Colombia-Lightning Mapping Array, GLM and ISS-LIS

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Abstract

The Atmosphere-Space Interactions Monitor (ASIM) on the International Space Station (ISS) provides optical radiances and images of lightning flashes in several spectral bands. This work presents a lightning flash simultaneously observed from space by ASIM, the Geostationary Lightning Mapper (GLM) and the Lightning Imaging Sensor on the International Space Station (ISS-LIS); and from ground by the Colombia Lightning Mapping Array (Colombia-LMA). Volumetric weather radar provides reflectivity data to help to interpret the effects of the cloud particles on the observed optical features. We found that surges in radiance in the band at 777.4 nm, appear to be related mostly with lightning processes involving currents as well with branching of lightning leaders with new leader development. In cloud areas with reflectivity <18 dBZ above the lightning leader channels at altitudes >7 km, these have been imaged by ASIM and GLM. But in the region with reflectivity <23 dBZ, despite its lower cloud tops and similar altitudes of lightning channels, these have been almost undetectable. The estimated relative optical depth results consistent with the observed optical features at the different locations of the flash. Despite of the effects of the cloud particles and the altitude of the lightning channels on the attenuation of the luminosity, the luminosity of the lightning channels due to different processes is fundamental for the imaging of lightning from space.

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Key points:

1. Features of luminosity from a lightning flash detected by ASIM, GLM and LIS are related with leader development and cloud properties.
2. Surges in 777.4 nm luminosity are associated with return stroke currents, continuing currents, recoil leaders and leader branching.
3. Altitude of lightning leaders, cloud particles above lightning channels as well channel luminosity influence the attenuation of light.

Abstract

The Atmosphere-Space Interactions Monitor (ASIM) on the International Space Station (ISS) provides optical radiances and images of lightning flashes in several spectral bands. This work presents a lightning flash simultaneously observed from space by ASIM, the Geostationary Lightning Mapper (GLM) and the Lightning Imaging Sensor on the International Space Station (ISS-LIS); and from ground by the Colombia Lightning Mapping Array (Colombia-LMA). Volumetric weather radar provides reflectivity data to help to interpret the effects of the cloud particles on the observed optical features. We found that surges in radiance in the band at 777.4 nm, appear to be related mostly with lightning processes involving currents as well with branching of lightning leaders with new leader development. In cloud areas with reflectivity <18 dBZ above the lightning leader channels at altitudes >7 km, these have been imaged by ASIM and GLM. But in the region with reflectivity <23 dBZ, despite its lower cloud tops and similar altitudes of lightning channels, these have been almost undetectable. The estimated relative optical depth results consistent with the observed optical features at the different locations of the flash. Despite of the effects of the cloud particles and the altitude of the lightning channels on the attenuation of the luminosity, the luminosity of the lightning channels due to different processes is fundamental for the imaging of lightning from space.

1. Introduction

The Atmosphere-Space Interactions Monitor (ASIM) on the International Space Station (ISS) consists of a suite of optical instrument (MMIA) and x- and gamma-ray detectors (MXGS) for measuring lightning, Transient Luminous Events (TLEs) and Terrestrial Gamma-ray Flashes (TGFs) (e.g. *Chanrion et al.,* 2019; *Neubert et al*., 2019). MMIA is equipped with three photometers at 180-230 nm, 337.0 nm (4 nm bandwidth) and 777.4 nm (5 nm bandwidth) spectral bands plus two one-megapixel cameras at 337.0 nm (5 nm bandwidth) and 777.4 nm (3 nm bandwidth). The objective of the 337.0 nm (blue) and 777.4 nm (red) instruments is to quantify optical energy leaving out from the top of the clouds and to provide images of lightning events. The selected far UV (180-230 nm) allows to discriminate the occurrence of a TLE in the higher atmosphere since the optical emissions in this band coming from tropopause level (e.g. from lightning) would be highly attenuated.

In the near future, much of the Earth's lightning activity will be continuously monitored from space by lightning imagers placed in geostationary orbit, thereby opening a new era of weather monitoring and prediction, and of research into the role of thunderstorm processes in the dynamics of the atmosphere and in climate change. The Geostationary Lightning Mapper (GLM) on the first of the Geostationary Operational Environmental Satellite GOES-R Series (GOES-16 at 75.2W) is the first lightning detector in geostationary orbit (*Goodman et al.*, 2013; *Rudlosky et al.*, 2019ab). GLM is based on its predecessors, the Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) (*Christian et al.,* 1989). In China, the lightning imager on the Feng-Yun4 is detecting lightning in Asia (*Yang et al.,* 2017) and in the near future, Europe and Africa will be continuously monitored by the Lightning Imager (LI) on of the Meteosat Third Generation satellite (MTG) (*Stuhlmann et al.,* 2005). All of these systems, new to the geostationary orbit, use optical imagers at the narrow spectral line at the 777.4 nm infrared emission of atomic oxygen that is associated with hot lightning channels. Because ASIM instruments provide higher temporal and spatial resolution of optical activity in the clouds with additional spectral bands, ASIM then offers an opportunity to explore in more detail the performance of the lightning imagers in geostationary orbit (e.g. *van der Velde et al.,* 2020). The comparison of data from ASIM in the low-Earth-orbit of the ISS (~400 km, 51.6^{o} inclination) to the geostationary instruments is facilitated by a LIS instrument, also on the ISS (*Blakeslee et al*., 2020).

The optical emission from lightning that escapes from a cloud is highly affected by scattering and absorption of photons by cloud particles which reduce the signal intensity, and broadens emissions in space and time (e.g. *Thomason and Krider,* 1982; *Peterson,* 2019; *Thomason and Krider,* 1982; *Koshak et al.,* 1994; *Light et al.,* 2001; *Peterson,* 2014; *Luque et al., 2019; Brunner and Bitzer,* 2020). This effect has been the subject of several studies that compare detection from space with data from lightning detection systems at ground. In particular, the measurements of Lightning Mapping Array (LMA) systems (*Rison et al.,* 1999) has been useful because they provide 3D reconstructions of lightning leader development inside the clouds. The early comparisons between LIS and LMA (*Thomas et al*., 2000) showed that most of the detected optical events were associated with lightning channels at the upper part of the storms. In the cases of cloud-to-ground (CG) flashes confined to mid and lower altitudes were less detected. In addition, the strongest light emissions were identified to be related with impulsive high current events from recoil leader activity. Most of the works comparing space-based optical detections and LMA flash data focused on the evaluation of the detection efficiency (e.g. *Montanyà et al*. 2019; *Erdmann et al., 2020; Zhang and Cummins,* 2020). In these works, only lightning is considered but not the microphysical characteristics of the clouds in which lightning flashes are immersed and affect to the propagation of light. Recently, *Rutledge et al*. (2020) has incorporated radar data together with the LMA to evaluate GLM. In this work it has been identified that GLM detection efficiency depends on the lightning flash geometric size, in agreement with *Zhang and Cummins* (2020), and the cloud water path. The size of the flash was found to be correlated with the optical brightness whereas the cloud water path was related to the optical extinction. The cloud water path, in turn, depends on the height of the flash that was derived from LMA clustered data and the cloud water content. Using radar, the mean precipitation-sized hydrometeor ice water paths were determined but, with S-band radars, cloud particles that cannot be detected. The authors pointed that despite the small surface areas of cloud particles compared to precipitation-sized ones, their greater concentrations can provide more attenuation of light optical energy. In this work we compliment the previously introduced works by relating lightning processes and cloud properties in a LMA flash case observed with the high resolution ASIM photometers and cameras.

This study presents the first lightning flash occurred in a location with simultaneous coverage by the optical photometers and cameras of ASIM, the Colombia-LMA, the GOES-16 Advanced Baseline Imager (ABI), weather radar data, the GLM and the ISS-LIS. The flash occurred on November 22, 2018 at 08:57:21.4413 UT. We analyze the measurements of the ASIM, GLM and ISS-LIS instruments relative to the lightning propagation detected by the LMA and the influence of cloud properties estimated from weather radar data.

2. Data

As ground support for the ASIM mission, a group at the Polytechnic University of Catalonia (UPC) installed one LMA in the Ebro river delta in North-Eastern Spain and another in Colombia (*van der Velde and Montanyà*, 2013; *López et al.,* 2019). At the time of the event, the Colombia-LMA was composed of 6 stations close to the city of Barrancabermeja (~7ºN, 73.85ºW). The LMA system detects sources of radio emissions in the very high frequency range (VHF, 30-300 MHz) that originate from the breakdown processes related to the propagation of lightning leaders. The sources are located in three dimensions using the time-of-arrival technique. Detailed information about the LMA can be found in *Rison et al.* (1999) and *Thomas et al.* (2004).

The Modular Multispectral Imaging Array (MMIA) optical sensors of ASIM are three photometers at 180-230 nm (UV), 337.0 nm (4 nm bandwidth) (hereafter the blue signal) and 777.4 nm (5 nm bandwidth) (hereafter the red signal) at 10 microsecond resolution, and two cameras with 1000x1000 pixels and 12 frames per second at 337.0 nm (5 nm bandwidth) and 777.4 nm (3 nm bandwidth) with 400 m resolution towards nadir. The field of view of the instruments is square 80º diagonal, except for the UV photometer, which is circular with a diameter at 80º. A more detailed description of the instruments is found in *Chanrion et al.* (2019).

The Geostationary Lightning Mapper (GLM) and the Lightning Imaging Sensor (ISS-LIS) provide locations of the sources (events) of luminosity for the investigated lightning flash with 2 ms resolution (*GOES-R Algorithm Working Group and GOES-R Series Program*, 2018). The minimum pixel footprint of GLM and ISS-LIS imagers are 8 km and 4 km, respectively. Radiance at the measured 777.4 nm narrow band for each event is provided.

Cloud-to-ground (CG) lightning locations and peak currents are provided by the Keraunos SAS LINET type lightning network in Colombia (*Betz et al.*, 2009; *Aranguren et al.,* 2017) and by the World-Wide Lightning Location Network (WWLLN, e.g. *Rodger et al*., 2006). Additionally, ELF magnetic fields (<0.01 to 300 Hz) measured by the UPC Schumann resonance station in Cape Verde (16.73ºN, 22.93ºW) are used to identify the presence of continuing currents for those transient events superimposed over the continuous Schumann resonance background (e.g. *Boccippio et al.,* 1995; *Burke and Jones,* 1996; *Huang et al.,* 1999).

Finally, radar reflectivity (Z) products are provided by the dual polarization C-band Doppler weather radar located in Barrancabermeja of the Colombian Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM). It makes volumetric measurements every 8 minutes with 6 elevations and a gate resolution of 100 meters *Cáceres* (2017). Although the radar scan strategy was configured to sample the precipitation, the highest 2 elevations were able to measure heights from 8 to 17 km for distances from 30 to 67 km where the investigated flash occurred. The derived products used in this study are the maximum Z - Z_{max}, which corresponds to the maximum Z observed in the column at the gate position, and the contoured-frequency-altitude diagram (CFAD) of Z along the corresponding locations of lightning leaders during ASIM video frames. The CFADs (*Yuter and Houze*, 1995) provide information on changes in the vertical distribution of radar reflectivity that help to identify the cloud depth and hydrometeors types above the altitude of the lightning leaders. For instance, narrow distributions with height imply homogenous precipitating sized particles, while bi-modal or broad distributions mean different types or size of hydrometeors.

3. Results

On November 22nd 2018, a lightning flash occurred at 08:57:21.4413 UT near Barrancabermeja (Colombia) at ~7.4º latitude and -73.85º longitude (Figure 1). The flash was in a cell of a large nighttime thunderstorm system within the coverage of the Colombia LMA in Barrancabermeja and ranging from 36 to 67 km from the radar. The initial part of the flash was outside the field of view of the MMIA sensors (white markers in the south-east view in Figure 1a and b) in a region with cloud top temperatures between -73 ºC and -75 ºC, corresponding to heights of ~14.5 km according to ERA-INTERIM reanalysis (*Dee et al.,* 2011). The part of the flash observed by ASIM (Figure 1c and black filled markers in Figure 1a and b) mostly developed in a less deep region with warmer cloud top temperatures of -66 ºC to -68 ºC (~13.5 km). For later analysis, the five regions (boxes) depicted in Figure 1-b and 1-c will be used to relate features of optical observations with lightning processes and cloud properties.

3.1 The lightning flash

The flash originated at 7.223º/-73.91º in the coldest cloud top. LMA sources in Figure 2 show that the flash initiation (marker a in Figure 2) was at a height of 5 km with a negative leader propagating upwards at ~10^5 m s^{-1} up to 11 km. After ~50 ms (b), new negative leaders appeared at the same location as the previous one and expanded simultaneously to southward and northward directions for 450 ms (b-c). During this period, sources associated with positive leader breakdown were identified at a lower level, ~5 km altitude. The negative and positive leaders during this first 500 ms (a-c) period of the flash revealed the existence of positive polarity electric charge between 6 to 11 km altitude and negative electric charge below 5 km.

At 441.85 new IC breakdown occurred at the north-end of the flash (c') at the time when a negative CG (-CG) stroke of -24 kA was detected by LINET and WWLLN. From the location of the –CG stroke, slow negative leaders (<10^5 m s^{-1}) expanded radially 5 km for 150 ms (c'-d and LMA sources in Box 1, Figure 1). After this time (d), a fast negative leader (~10^5 m s^{-1}) was initiated from this area and propagated towards the east into a stratiform region for about 175 ms (d-f) and progressively descending from 9 km to 7 km altitude branching 40 ms (e) before ending (sources in Box 2, Figure 1). After the end of this leader (f), a positive +CG stroke with 11 kA occurred close to the location (f') of the earlier –CG stroke. As can be deduced from the presence and characteristics of the ELF transient waveform, and using a similar optical discrimination criterion as *Bitzer et al.* (2016), we assume that this +CG produced continuing current. During this continuing current phase, a fast horizontal negative leader (0.5 10^6 m s^{-1}) at < 7 km extended the propagation of the flash further east (g-h). This leader presented two branches extending simultaneously towards the south-east (f-g and Box3, Figure 1) and to the north (f-h and Box 4, Figure 1). From the leader at the north, a branch propagated at 0.5 10^6 m s^{-1} towards the north-east (h-j and Box 5, Figure 1). The flash ended with the end of this leader propagation followed by a short-isolated breakdown (k) at the northeast of the two CG locations.

In summary, this two-stroke bipolar CG flash started in a convective core of the storm with leaders propagating for 500 ms. A –CG stroke occurred at the north end of the previous leader activity followed by negative leader propagation into the stratiform region of the cloud for 300 ms. A +CG stroke followed at the location of the previous –CG stroke. This +CG stroke produced continuing current likely supplied by the propagation of a fast negative leader.

3.3 MMIA photometer, GLM and ISS-LIS radiances

Altitudes of the located LMA sources versus time during MMIA detections are plotted in Figure 3a. Radiances measured by MMIA in the three spectral bands (337.0 nm, 777.4 nm and 180-230 nm) are depicted in Figures 3-b, c and d. Radiances of ISS-LIS (red line) and GLM (black line) have been computed by integrating radiances from all the events detected every 2 ms frame (Figure 3-c). Since both ISS-LIS and GLM observe the 777.4

nm spectral band, there is very high consistency with the same MMIA photometer spectral band (red line in Figure 3-b). Note that ISS-LIS (red line) radiance stops before GLM (black line) because the flash was no longer in the field of view of the sensor.

Inspecting the photometer radiances (Figure 3-b), after 442.05 s, the blue and red channels showed a progressive increase of radiance superimposed with small surges. At 442.15 s the red signal abruptly increased producing several peaks just before the +CG. This increase was also present in the GLM and ISS-LIS radiances. Just after the time of the +CG stroke, the peak was more pronounced in the red than in the blue band. The red pulse presented faster rise and decay times (2.2/12.9 ms) compared to the blue (5.4/71.1 ms). Starting right after the +CG stroke, the ELF magnetic field signal measured in Cape Verde (Figure 3-e) indicates the presence of continuing current. This continuing current is noticeable in the ELF signal for about 30 ms that corresponds to a decay to the ~25 % of the peak value in the MMIA red and GLM radiances. The presence of continuing current is also supported by the identified LMA sources of fast ($0.5\ 10^6$ m s^{-1}) negative leaders progressing during this period. Note that the transients in the magnetic field occurring after 442.25 s (Figure 3-e) might belong to a different flash, according to the detection of a distant flash at that time by GLM. The small signal in the MMIA 180-230 nm photometer (Figure 3-d), seems to present a small increase at the time of the +CG, but behaves more similarly to the blue band although its amplitude is more than three orders of magnitude smaller.

3.4 MMIA imaging data and weather radar

In the last four video frames recorded by MMIA, the flash was entirely in the field of view, so the previous frames have been omitted in this study. The periods of each video frame are indicated with vertical lines in Figure 3b and displayed in Figure 4. The four camera images of ASIM are shown in Figure 4 with the blue channel (337 nm) images in the left column and the red channel (777.4 nm) images in the right column. The location of the investigated boxes on the MMIA images can be easily identified in Figure 1c.

In the video frame 1 (Figure 4-a) the luminosity of the flash comes from the location of the –CG stroke that occurred 125 ms before the frame start and where the LMA detected some negative leader breakdown activity (Box 1 in Figure 1). During frame 1, the LMA detected a new leader propagating out of the main luminosity core towards the east (Box 2). This new leader is seen in both cameras, but remained undetected by GLM and ISS-

LIS. The radar cross-sections along the LMA sources during this frame indicate that the sources occurred above the altitude of the 20 dBZ reflectivity echo tops. During frame 2, the leader entered into a more stratiform region (Box 2) with reflectivity <15 dBZ echo tops above the leader height (8 km) and coldest cloud top temperature of -67 ºC (13.5 km). The leader is clearly seen in both MMIA cameras (Figure 4-b) and GLM reports events within the high radiance region in the red MMIA image. At the beginning of frame 3 (Figure 4-c), a +CG stroke located in Box 1 triggered a fast negative leader (0.5 10^6 m s^{-1}) that propagated and branched during the frame exposure. The branch towards the southeast (Box 3) produced more LMA sources than the branch that propagated to the north (Box 4) but only the latter is well identified in the red image. Figure 4-d depicts the most remarkable difference between the blue and red channel images occurring during frame 4. The leader propagating to the north-east (Box 5) can be more easily distinguished in the red image than in the blue. It is also remarkable that the leader tip is brighter than its channel behind. The north-east branch (Box 5) is responsible for the radiance peak after 442.25 s in the MMIA red channel photometer (Figure 3-b) and GLM (Figure 3-c).

To relate cloud properties with the optical observations, contoured-frequency-by-altitude diagrams (CFAD) of radar reflectivity are computed along the leader propagation paths and shown in Figure 5. Box 1 corresponds to the area where the CG strokes were located; and Box 2 includes the area within ±1 radial gate (representing 750 m width) along the central leader channel mapped by the LMA during frames 1, 2 before it branches. Box 3 and 4 the same as Box 2 for southeast and north branches during frames 3 and 4, respectively; and the same in Box 5 of the leader branch towards the northeast. In each CFAD, the altitude of the leader is indicated by the dash-dotted line whereas the 50th and 90th percentiles of the cumulative reflectivity Z are indicated by the solid and dashed lines, respectively.

The LMA sources within Box 1 are located at an altitude of ~9 km (Figure 2). At this altitude, the CFAD (Figure 5-a) shows a thinner region with weak Z values with 90 % of the reflectivity below 18 dBZ. In this area, the maximum radiances of the flash in both spectral channels are found in frame 3 (Figure 4-c), in particular, at the time of the +CG stroke being the measured red signal the highest. In the same region defined by Box 1, the blue signal surpasses the red after the continuing current in frame 5 (figure 4-d). In Box 2, the CFAD shows a shallow cloud above the leader height at ~8 km with 90 % of the reflectivity below ~17 dBZ. This low reflectivity and the shallow cloud above the leader channel did not prevent the lightning leader at this location to be imaged in frames 1 and 2. Much higher reflectivity <23 dBZ is found above the south-west lightning leader channel in Box 3 that propagates at 7.5 km altitude. Although Box 3 has low cloud tops according to the radar and satellite images, and the lightning leader channel is close to the top, the high reflectivity above the channel might be an indicative of high concentration of cloud particles. The dense cloud in Box 3 could be the responsible of the almost undetectable luminosity from the lightning channels there. In Box 4 the north leader channel propagates during frame 3 at an altitude of 7 km with reflectivity of the cloud above it <18 dBZ. In this area luminosity of the leader is much higher in the red than in the blue image (Figure 3-c). Finally, the cloud in Box 5 has convective characteristics as indicated by its cloud tops in Figure 1 and the reflectivity profile in Figure 5. The north-east leader in Box 5 during frame 4d is clear in the red image and well tracked by GLM, but highly attenuated and diffuse in the blue. The leader travels at 7 km and above this level we found reflexivity of <20 dBZ.

4. Discussion

4.1 Radiances and radar reflectivity

The average blue (337.0 nm) and red (777.4 nm) radiances observed by the ASIM cameras of the five selected boxes are shown in Figure 6.

At the location of the CG strokes (Box 1), lightning leader sources are identified at an altitude of ~9 km with a shallow cloud of low reflectivity (< 18 dBZ) above it. This may had produced little attenuation compared to other deeper areas. The ratio of the received red to blue starts with values from ~1.85 during the frames 1 and 2 before the +CG stroke. At the time of the +CG stroke (frame 3), radiances peak and the ratio increases to 2.2. The ratio remains higher than 1 for the 30 ms corresponding to the continuing current phase until both radiances equalize. Later, in frame 4, the ratio of the average radiance decreases to 0.9 or 0.6 for the maximum radiances, meaning that the received blue radiance is more intense than the red. From Figures 3 and 4, the consistency of the red radiance with the continuing current suggest that the observed red channel (777.4 nm) oxygen atomic line is more related with the evolution of lightning currents than the blue band. The relation of red radiance pulses with impulsive lightning current events identified by the LMA was previously observed by *Thomas et al.* (2000). In the laboratory, *Windmar et al.* (1991) found a proportional relation of the peak amplitude of the red radiance with the kiloampere current of a long spark. In Box 1 the slow decay of the blue signal different to the red may indicate the prevalence of streamer/corona discharge activity, in particular, at the region of the location of the CG strokes. This assumption is based on experimental laboratory woks such as *Machala et al.* (2011) and *Janda et al.* (2016) showing the emission of the N_2 2[nd] positive system being associated with the streamer phase of a spark discharge.

The radiance in Box 2 includes the leader channel emerging from the location of the CG strokes at frame 1. This negative leader propagated at 10^5 m s^{-1} and ended at the time of the +CG (frame 3). From this central leader channel two branches occurred after the +CG corresponding to the LMA sources in Box 3 and 4. At the time of frame 3, the central leader channel presented higher red radiance than its south-east, north and north-east branches in Boxes 3, 4 and 5, respectively. As seen in Figure 5 and Figure 6, at the regions of the south-east (Box 3), north (Box 4) and north-east (Box 5), the cloud above the leader was thicker in terms of reflectivity than in Box 2. This thicker cloud mostly affected the blue band. This is reflected in the ratios of the average radiance in Figure 5-b, c, d and e at the time of frame 3 corresponding to 2.9 (18 dBZ), 3.8 (23 dBZ), 4 (18 dBZ) and 5.4 (20 dBZ), respectively. The reflectivity in parenthesis correspond to the maximum above the leader. During this frame, the charge that feeds the continuing currents to ground is assumed to be provided by the south and north leader branches based on the fast propagation (0.5 10^6 m s^{-1}) of the leaders and their higher radiances compared to the extension of the north-east leader.

One of the salient features of the observation is the imaged north-east leader branch (Box 5) by the red camera at frame 4 (Figure 4-d). This leader end produced an increase in the 777.4 nm radiance after 442.25 s (Figure 3b) which is not observed in the blue channel image. The level of the blue radiance in Box 5 during frame 4 corresponds almost to the background level and it is lower than the corresponding radiance at the same frame but in the leader channel behind in Box 2. For comparison, the red radiance during frame 4 is ~1.2 times greater in Box 5, at the leader end, compared to its trailing channel in Box 4 and Box 2 although Box 5 had the deepest cloud above the leader. This negative correlation between the radiance and radar reflectivity suggests that the detected surge in the radiation might be related with the occurrence of some intra-cloud process involving high currents (e.g. recoil leader event) at the leader end in Box 5.

In addition, taking into account that the used weather radar is more sensitive to the back-scatter of ice and water particles and these precipitating ice particles are related to icy cloud particles (*Baker et al.,*1999), it is plausible to state that higher the ice content above 8 km the higher will be the concentration of cloud ice particles. Moreover, the broader it is the CFAD distributions above the freezing level more cloud ice particles are produced reflecting higher updrafts that consequently produce more super-saturation. Therefore, the optical emissions would more attenuated depending on the concentration of ice particles and it is size above the leader (*Brunner and Bitzer*, 2020*, Rutledgle et al.,* 2020) as well as on the water vapour (*Thomason and Krider* 1982) fed those particles. At Box 3, the higher and large sized ice cloud particles concentration attenuated both the red and blue channels, while at Boxes 4 and 5, the presence of more water vapour and smaller ice cloud particles might have contributed to attenuate more the blue channel than the red.

In summary, the red radiance is close related to the occurrence of the currents on the leader channels according to the identified CG strokes, continuing currents and the recoil leader event consistently with previous works (e.g. *Thomas et al*., 2000). The longer time decay of the blue emissions relative to the red and their lower correlation with the evolution of the currents can be indicative that these blue emissions are related to the streamer zones of the leader channels. The detected blue radiation allowed to properly image the leader channels in the regions less intervening cloud above the lightning flash.

3.3 Surges of radiance associated with leader branching

The small surges in red and blue emissions at 442.127 s in Figure 3b during frame 2 (marker e) are related to a new branch of the developing leader. This branch continues for 40 ms until the time of the +CG stroke. This leader branch can be associated with the downward positive leader approaching the ground, including the last 12 ms where both the blue and red radiances increased, oscillating in the red. Such feature is consistent with the development of the positive leader to ground accompanied by recoil leader activity (K-changes) (*Montanyà et al.* 2012; *Tomas et al*., 2000). About 50 ms after the +CG stroke (frame 3), at 442.226 s, a new radiance surge in the red channel is associated with new negative leader branches (from g and h in Figure 2) propagating for 20 ms with speeds 0.5 10^6 ms^{-1} (Box 3, 4). Finally, the red surge at 442.256 s in frame 4, Box 5, also occurred in association with a leader branching and further propagation (i-j in Figure 2).

In the blue photometer, these surges are unnoticed at the indicated times although there are some smoothed and delayed pulses that might be related. This is the case of the peak in the blue at 442.226 s occurring 7 ms after the peak in the red (Figure 3-b). If both peaks are related, then the significant delay might be due to the blue radiance originating from the region of the CG stroke (Box 1) whereas the red originates from the location of the leader branching (Box 3, 4). Possible delays due to higher scattering in the blue than in the red are possible (e.g. *Luque et al.,* 2020).

3.3 Optical depth

Light et al. (2001) and *Beirle et al*. (2014), among others, stated that clouds mostly affect the propagation of light causing spatial smearing via multiple scattering. Light absorption by ice and water at the 337.0 nm and 777.4 nm is small (e.g. *Warren,* 1984; *Thomason and Krider,* 1982; *Light et al.,* 2001) but the absorption and scattering differences can be significant between the two wavelengths (*Luque et al.,* 2020). Some previous works (e.g. *Thomason and Krider,* 1982; *Koshak et al.,* 1994; T*homas et al.* 2000; *Light et al*. 2001, Brunner and Bitzer, 2020) found that the optical depth between the light source and the cloud edges highly affects the detectability of lightning. These works also indicate the need to know the location and the progression of the source within the cloud. *Rutledge et al. (2020)* found that optical emissions are not completely correlated with the ice water path above individual lightning flashes derived from radar data because the precipitating particles are not necessarily the main responsible of the light attenuation. Small cloud particles with can present higher concentrations and producing collectively higher light attenuation than precipitation-size particles.

We now attempt to evaluate the effects of the cloud on the light propagation at the investigated regions of the flash. Due to the radar limitations, we adopt the cloud particle distribution from vertical radar reflectivity and temperature profiles using the parametrization by *Heymsfield* et al. (2002 and 2013). The calculated particle distributions at each level are limited from a minimum diameter of 20 μm up to a parametrized maximum diameter. Optical depth of the cloud sections above the lightning leader channels at each box are calculated by following *Thomason and Krider* (1982). Optical depths are limited up to an altitude of 10 km because, as pointed by *Rutledge et al.* (2020), we found unrealistic high particle densities for the low temperatures at higher levels. Details on the calculations of particle distribution and optical depth are provided in the appendix section of this paper. Results of the estimated optical depths are presented in Table 1. The values are relative to the optical depth in Box 1. We present relative optical depths because the high sensitivity of the cloud particle distribution on the temperature (*Heymsfield* et al. 2002 and 2013). Despite this dependence, the relative optical depths between boxes remain almost independent to temperature offsets. The calculated relative optical depths are consistent with some of the characteristics of the observed radiance from each box. The lower optical depth of Box 2 relative to Box 1 is in accordance with the more stratiform nature of the cloud in this region where the red and blue radiances were less effected by cloud. The reduction of 50 % of the optical depth in Box 2 results from the decay of 3 dBZ and a shallower cloud above the leader compared to Box 1. Contrary, Box 3 presents the highest relative optical depth ~2 coinciding with the region with the almost undetected blue and red radiances. Compared to Box 1, despite of the median reflectivity above the leader is 1 dBZ higher, the maximum reflectivity (90th percentile) is 6 dBZ greater and with lower lightning leader channel height. In between, the 0.9 relative optical depth of Box 5 allowed the detection of the red radiance but strongly attenuated the blue. The median reflectivity in Box 5 at the leader altitude is 2 dBZ lower than in Box 1 whereas the reflectivity corresponding to the 90th percentile is 3 dBZ higher.

In summary, to overcome the limitation of radar on the detection of cloud particles the used parametrized ice particle size distributions have provided consistent relative optical depth with the optical observations. Consistently with *Brunner and Bitzer* (2020), the results highlight the importance on the combination of the light emission by different lightning processes and the optical depth features due to cloud ice particles surrounding the lightning channels at high cloud altitudes (>7 km). The location at Box 1 where the return stroke currents produced high channel luminosity together with low optical depth due to lightning channels at high altitudes would evidence the CG features pointed by *Zhang and Cummins* (2020) to produce high detection efficiency of CG flashes by GLM. In the area of the lowest relative optical depth (Box 2) corresponding to a stratiform region, progression of negative lightning leaders has been resolved by MMIA and GLM. The detection of this leader by GLM might has been possible by the occurrence of a branching of the leader that produced a surge in the radiance (marker e in Figure 3-b) if compared to the undetected leader by GLM in frame 1 (Figure 4-a). The increase of a factor of 2 on the relative optical depth in Box 3 attenuated the optical emissions of a fast negative leader producing abundant LMA sources. The undetected leader did not present any feature such as branching or recoil leader that might had involved a surge in channel luminosity. Box 5 with lower optical depth than Box 1 and a surge in radiance, allowed GLM to image the propagation of the leader (Figure 4-d) all along the channel from the tip to the location of the former CG. Our results compliment the recent study by *Rutledge et al.* (2020). Instead of using the ice water path derived from radar we have estimated the cloud particle size distribution from parametrization data and we have found consistency with the observations. In addition, we have investigated the features in different parts of the flash considering their cloud and lightning features.

5. Conclusions

We have presented concurrent measurements of a lightning flash from space by ASIM, GLM, ISS-LIS and from the ground by the Colombia-LMA, WWLNN, a local weather radar, and an ELF electromagnetic wave receiver. This observation has provided the means for interpretation of the optical observations with respect lightning leader processes. This flash included negative and positive strokes as well the occurrence of continuing currents. In addition, weather radar data allowed estimation of the attenuation of optical radiance by the clouds above the lightning leaders at different locations along the path of the lightning channel propagation.

The following summarizes our findings:

- Surges in the photometer radiance, especially in red (777.4 nm), besides return stroke and recoil leader process have been found to be associated with lightning leader branching involving new leader development. These surges associated to leader branching are not always noticed in the blue (337.0 nm) signals, so this processes appear not to involve significant emissions in this wavelength.
- The radiance at red correlate with the continuing current identified from the magnetic ELF signals and the fast leader development.
- The oscillations in the red signal photometer just before the +CG stroke are likely recoil leader events during the downward propagation of the leader to ground prior to the return stroke.
- Based on the above, the detected red signals are likely from the highly conducting leader channel and associated with high luminosity of the channel involving impulsive and continuing current processes.

- The camera images showed long persistence of blue radiation at the location of the +CG stroke after the decay of the continuing current and even surpassing the detected red radiance.
- The blue emission has been shown to not be closely related to lightning current processes but able to image the flash development especially in the stratiform areas with low cloud tops. The nature of the N_2 optical emission in this wavelength suggest the origin from non-thermal discharges (streamers) on the leader channels and probably in the thundercloud.
- Cloud depth or thickness appears to affect more the blue than the red.
- Relative optical depths at different parts of the cloud where lightning leaders propagated have been estimated from radar and temperature data using parametrized models of particle size distribution.
- Besides the position of the lightning leaders and the properties of the cloud above and around them, detection of optical emissions of lightning depends on the different lightning processes, which can be inferred from their temporal and spectral properties.

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Data availability

Data associated with this work will be made available in the Zenodo scientific repository. Data access to ASIM is available by registering at https://asdc.space.dtu.dk/. GLM data are available from NOAA (GOES-R Series Program, 2019, https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C01527#) and ISS-LIS from NASA Global Hydrology Resource Center (*Blakeslee et al. 2019*, https://ghrc.nsstc.nasa.gov/pub/lis/iss/data/science/nqc/hdf/). The ABI imagery can be accessed from the NOAA's Comprehensive Large Array Storage Service (CLASS) or the Google (gcp-public-data-goes-16) or Amazon cloud.

References

Aranguren, D., López, J., Inampués, J., Torres, H., and Betz, H. D. (2017). Cloud-to-ground lightning activity in Colombia and the influence of topography *Journal of Atmospheric and Solar-Terrestrial Physics*, doi: 10.1016/j.jastp.2016.08.010.

Baker, M. B., Blyth, A. M., Christian, H. J., Latham, J., Miller, K. L., and Gadian, A. M. (1999). *Atmospheric Research*, 51, 221-236.

Beirle, S., Koshak, W., Blakeslee, R., and Wagner, T., (2014). Global patterns of lightning properties derived by OTD and LIS. *Nat. Hazards Earth Syst. Sci.,* 14, 2715–2726.

Betz H. D., Schmidt, K., and Oettinger W. (2009). LINET – An International VLF/LF Lightning Detection Network in Europe. Lightning: Principles, Instruments and Applications. *Springer*, doi: 10.1007/978-1-4020-9079-0_5.

Blakeslee, R. J. (2019). Non-Quality Controlled Lightning Imaging Sensor (LIS) on International Space Station (ISS) Science Data. NASA EOSDIS Global Hydrology Resource Center Distributed Active Archive Center, Huntsville, Alabama, U.S.A. doi:10.5067/LIS/ISSLIS/DATA107. [Accessed: 11 March 2020]

Blakeslee, R. J., Lang, T. J., Koshak, W. J., Buechler, D., Gatlin, P., Mach, D. M., Stano, G. T., Virts, K. S., Walker, T. D., Cecil, D. J., Ellett, W., Goodman, S. J., Harrison, S., Hawkins, D. L., Heumesser, M., Lin, H., Maskey, M., Schultz, C. J., Stewart, M., Bateman, M., Chanrion, O., and Christian, H. (2020). Three years of the Lightning Imaging Sensor onboard the International Space Station: Expanded Global Coverage and Enhanced Applications. *Earth and Space Science*, https:/doi.org/10.1002/essoar.10502896.1.

Boccippio, D. J., Williams, E. R., Heckman, S. J., Lyons, W. A., Baker, I. T., and Boldi, R. (1995). Sprites, ELF transients, and positive ground strokes. *Science*, 269, 1088.

Burke, C. P., and Jones, D. L. (1996). On the polarity and continuing currents in unusually large lightning flashes deduced from ELF events. *J. Atmos. Terr. Phys.,* 58, 531.

Brunner K. N., and Bitzer, P. M. (2020). A first look at cloud inhomogeneity and its effect on lightning optical emission. *Geophysical Research Letters*, 47, e2020GL087094. https://doi.org/ 10.1029/2020GL087094.

Cáceres-Leon, R. (2017). Meteorología Aplicada a la Seguridad de las Operaciones Aéreas, Colección Ciencia y Poder Aéreo, ISBN: 978-958-59961-1-3.
[Available online: https://libros.publicacionesfac.com/index.php/libros/catalog/book/22].

Chanrion, O., Neubert, T., Lundgaard Rasmussen, I., et al. (2019). The Modular Multispectral Imaging Array (MMIA) of the ASIM Payload on the International Space Station. *Space Sci. Rev.,* 215, 28. https://doi.org/10.1007/s11214-019-0593-y.

Christian, H. J., and Goodman, S. J. (1987). Optical observations of lightning from a high altitude airplane. *J. Atmos. Ocean. Tech*., 4, 701-711.

Christian, H. J., R. J. Blakeslee, and S. J. Goodman (1989), The detection of lightning from geostationary orbit, *J. Geophys. Res.,* 94, 13329–13337.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., ... and Bechtold, P. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), 553-597.

Erdmann, F., Defer, E., Caumont, O., Blakeslee, R. J., Pédeboy, S., and Coquillat, S. (2020). Concurrent Satellite and ground-based Lightning Observations from the Optical Lightning Imaging Sensor (ISS-LIS), the LF network Meteorage and the SAETTA LMA in the northwestern Mediterranean region. *Atmos. Meas. Tech.*, 13, 853–875.

GOES-R Algorithm Working Group and GOES-R Series Program, (2018): NOAA GOES-R Series Geostationary Lightning Mapper (GLM) Level 2 Lightning Detection: Events, Groups, and Flashes. NOAA National Centers for Environmental Information. doi:10.7289/V5KH0KK6.

Goodman, S. J., H. J. Christian, and Rust, W.D. (1988). Optical pulse characteristics of intracloud and cloud-to ground lightning observed from above clouds, J. Appl. Met., 27, 1369-1381.

Goodman, S. J., Blakeslee, R. J., Koshak, W. J., Mach, D., Bailey, J., Buechler, D., Carey, L., Schultz, C., Bateman, M., McCaul, E., and Stano, G. (2013). The GOES-R Geostationary Lightning Mapper (GLM). *Atmospheric Research*, 125-126, 34– 49.

Heymsfield, A. J., Bansemer, A. , Field, P. R., Durden, S. L., Stith, J., Dye, J. E., Hall, W., and Grainger T. (2002). Observations and parameterizations of particle size distributions in deep tropical cirrus and stratiform precipitating clouds: Results from in situ observations in TRMM field campaigns. *J. Atmos. Sci.,* 59, 3457–3491.

Heymsfield, A. J., Schimitt, C., and Bansemer, A. (2013). Ice Cloud Particle Size Distributions and Pressure-Dependent Terminal Velocities from In Situ Observations at Temperatures from 0º to -86ºC. *J. Atmos. Sci.,* 70, 4123–4154.

Huang, E., Williams, E., Boldi, R., Heckman, S., Lyons, W., Taylor, M., Nelson, T., and Wong, C. (1999). Criteria for sprites and elves based on Schumann resonance observations. *J. Geophys. Res*., 104(D14), 16943-16964.

Koshak, W. J., Solakiewicz, R. J., Phanord, D. D., and Blakeslee, R. J. (1994). Diffusion model for lightning radiative transfer. *J. Geophys. Res*., 99, 14361-14371.

Light, T. E., Suczcynsky, D. M., Kirkland, M. W., and Jacobson, A. R. (2001). Simulations of lightning optical waveforms as seen through clouds by satellites. *J. Geophys. Res*.,106 (D15), 17103–17114. https://doi.org/10.1029/2001JD900051

López J. A., Montanyà, J., van der Velde, O. A., Pineda, N., Salvador, A., Romero, D., Aranguren, D. and Taborda, J. (2019). Charge structure of two tropical thunderstorms in Colombia. *J. Geophys. Res*.: *Atmospheres*, doi.org/10.1029/2018JD029188.

Liu, H., and V. Chandrasekar, 2000: Classification of Hydrometeors Based on Polarimetric Radar Measurements: Development of Fuzzy Logic and Neuro-Fuzzy Systems, and In Situ Verification. *J. Atmos. Oceanic Technol.*, **17**, 140–164, https://doi.org/10.1175/1520-0426(2000)017<0140:COHBOP>2.0.CO;2.

Luque, A., Gordillo-Vázquez, F. J., Li, D., Malagón-Romero, A., Pérez-Invernón, F. J., Schmalzried, A., Soler, S., Chanrion, O., Heumesser, M., Neubert, T., Reglero, V., and Østgaard N., (2020). Modeling lightning observations from space-based platforms (CloudScat.jl 1.0). *Geoscientific Model Development*, doi.org/10.5194/gmd-2020-161.

Montanyà, J., van der Velde, O. A., March, V., Romero, D., Solà, G., and Pineda, N. (2012). High-speed video of lightning and X-ray pulses during the 2009–2010 observation campaigns in northeastern Spain. *Atmos. Res.*, 117, doi: 10.1016/j.atmosres.2011.09.013.

Montanyà, J., van der Velde, O. A., Pineda, N., and López, J.A. (2019). ISS-LIS data analysis based on LMA networks in Europe. EUMETSAT Science Studies, [Available online: https://www.eumetsat.int/website/home/Data/ScienceActivities/ScienceStudies/ISSLISDataAnalysisBasedonLMANetworksinEurope/index.html#OB].

Neubert, T., Østgaard, N., Reglero, V., Blanc, E., Chanrion, O., Oxborrow, C. A., Orr, A. , Tacconi, M., Hartnack, O., and Bhanderi, D. D. V. (2019),.The ASIM mission on the International Space Station. *Space Sci. Rev.*, 215:26 https://doi.org/10.1007/s11214-019-0592-z.

Peterson, M. (2019). Using lightning flashes to image thunderclouds. *J. Geophys. Res.: Atmospheres*,124. https://doi.org/10.1029/2019JD031055

Peterson, M. J. (2014). Variations of optical and radio lightning characteristics and the relationship between storm convective intensity and above-cloud electric fields. Dissertation, The University of Utah, 253 pp [Available online at: https://search.proquest.com/openview/2d481bb6a222ae8958de1016fd602870/1?pq-origsite = gscholar&cbl = 18750&diss = y].

Rison, W., Thomas, R., Krehbiel, P., Hamlin, T., and Harlin, J. (1999). A GPS-based three dimensional lightning mapping system: Initial observations in central New Mexico. *Geophysical Research Letters,* doi: 10.1029/1999GL010856.

Rodger, C.J., Werner, S., Brundell, J. B., Lay, E. H., Thomson, N. R., et al. (2006). Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): initial case study. *Annales Geophysicae*, European Geosciences Union, 24 (12), 3197-3214.

Rutledge, S.A., Hilburn, K. A., Clayton, A., Fuchs B., and Miller, S. D. (2020). Evaluating Geostationary Lightning Mapper flash, *Journal of Geophysical Research: Atmospheres*, 125, Special Section: A New Era of Lightning Observations from Space. doi: 10.1029/2020JD032827.

Rudlosky, S., Goodman, S. J., and Virts, K. S. (2019a). Lightning detection: Geostationary Lightning Mapper, The GOES-R series: A new generation of geostationary environmental satellites pp. ISBN– 13: 978–0128143278, ISBN–10: 0128143274): Academic Press; Amsterdam, The Netherlands. http://www.worldcat.org/oclc/1127541502.

Rudlosky, S. D., Goodman, S. J., Virts, K. S., & Bruning, E. C. (2019b). Initial Geostationary Lightning Mapper observations. *Geophysical Research Letters*, 46, 1097– 1104. https://doi.org/10.1029/2018GL081052

Stuhlmann, R., Rodriguez, A., Tjemkes, S., Grandell, J., Arriaga, A., Bézy, J.-L., Aminou, D., and Bensi, P. (2005). Plans for EUMETSAT's third generation Meteosat Geostationary Satellite Programme, *Advances in Space Research*, 36(5), 975– 981.

Thomas, R. J., Krehbiel, P. R., Rison, W., Hamlin, T., Boccippio, D. J., Goodman, S. J., and Christian, H. J. (2000), Comparison of ground based 3-dimensional lightning mapping observations with satellite-based LIS observations in Oklahoma, *Geophysical Research Letters*, 27 (12), 1703–1706. https://doi.org/10.1029/1999GL010845.

Thomas, R. J., Krehbiel, P. R., Rison, W., Hunyady, S., Winn, W., Hamlin, T., and Harlin, J. (2004). Accuracy of the lightning mapping array. *Journal of Geophysical Research: Atmospheres*, doi: 10.1029/2004JD004549.

Thomason, L. W., and E. P. Krider (1982). The effects of clouds on the light produced by lightning. *J. Atmos. Sci*., 39, 2051-2065.

van der Velde, O. A., and Montanyà, J. (2013). Asymmetries in bidirectional leader development of lightning flashes. *J. Geophys. Res. Atmos.,* 118, 13,504–13,519, doi:10.1002/2013JD020257.

van der Velde, O., Montanyà, J., Neubert, T., Chanrion, O., Lopez, J. A., Fabro, F., Østgaard, N., Goodman, S., and Reglero, V. (2020), Comparison of high-speed optical observations of a lightning flash from space and the ground, *Earth and Space Science*, https://doi.org/10.1029/2020EA001249.

Warren, S. G. (1984). Optical constants of ice from the ultraviolet to the microwave. *Appl. Opt.,* 23, 1206-1225.

Yang, J., Zhang, Z., Wei, C., Lu, F., and Guo, Q. (2017). Introducing the new generation of Chinese Geostationary Weather Satellites, Fengyun-4. *Bulletin of the American Meteorological Society*, 98(8), 1637– 1658. https://doi.org/10.1175/BAMS-D-16-0065.1

Yuter, S. E., and Houze Jr., R. A. (1995). Three-dimensional kinematic and microphysical evolution of Florida cumulonimbus. Part II: frequency distributions of vertical velocity, reflectivity, and differential reflectivity. *Mon. Wea. Rev.,* 123, 1941-1963.

Zhang, D., and Cummins, K. L. (2020). Time evolution of satellite-based optical properties in lightning flashes, and its impact on GLM flash detection. *Journal of Geophysical Research: Atmospheres*, 125. Special Section: A New Era of Lightning Observations from Space. doi: 10.1029/2019JD032024.

Figure Captions and Tables

Figure 1. a) GOES-16 infrared satellite image overlaid with LMA sources. **b)** Maximum reflectivity Z_{max} and LMA sources. White filled circles correspond to LMA sources before ASIM video frame 1 and after frame 4. Black filled squares are LMA sources in the field of view of MMIA. The white squares and the numbers indicate the five analyzed areas of interest (boxes). **c)** Composition of 777.4 nm (red) MMIA camera stacked frames with the indication of the five considered areas, LMA sources and the markers (letters) used to identify the leaders. LINET Cloud-to-ground strokes: negative (×), positive (+).

Figure 2. LMA data of the flash on 22 November 2018 at 08:57:21.4413 UT. The top panel is altitude of LMA sources versus time (seconds); the left panel is a plan view map; the panels at the right show altitude (km) by latitude and longitude. LMA sources are colored by time. Markers *a* to *k* are used as reference in the text. LINET cloud-to-ground strokes (symbols: × negative, + positive). The exposure times of the four MMIA video frames are indicated as well the part of the field of view (FOV) of MMIA.

Figure 3. a) LMA; **b)** ASIM 337/4 nm (blue) and 777.3/5 nm (red) including the reference markers (letters); **c)** 2 ms-integrated radiances of GLM (red) and ISS-LIS (black); **d)** MMIA 180-230 nm (UV) photometer; **e)** Magnetic field measured at the UPC's Cape Verde ELF station. Vertical lines indicate the times of the MMIA video frames 1-4.

Figure 4. Consecutive MMIA camera frames in blue (337.0/4 nm) (left column) and red (777.4/5 nm) (right column) channels. LMA sources (white dots) are overlaid in each image. Locations of GLM events are plotted in the MMIA red images. GLM radiances (grey) at each location are integrated for the time of the frame.

Figure 5. Reflectivity contoured-frequency-by-altitude diagram (CFAD). **a)** Box 1: location of the CG strokes; **b)** Box 2: central leader channel emerging from the location of the CG towards east; **c)** Box 3: southeast leader branch; **d)** Box 4 north leader branch; **e)** Box 5: northeast leader branch. Dash-dotted line indicates the altitude of the leader sources in each box. Solid line marks the 50^{th} percentile of the reflectivity Z and the dashed line the 90^{th} percentile

Figure 6. Average radiance of the blue (337.0 nm) and red (777.4 nm) frames for the boxes 1 to 5. Dot-dash line indicates the altitude of the leader in each box. Solid line corresponds to the 20 dBZ radar echo top.

Table 1. Relative optical depth of the cloud section above the lightning leader channels up to 10 km. Optical depths are relative to Box 1.

	Relative optical depth
Box 1	1
Box 2	0.5
Box 3	2
Box 4	0.9
Box 5	0.9

Appendix

Heymsfield et al. (2002 and 2013) have presented assimilation of experimental data to provide ice particle size distributions. One of the common functional forms of the particle size distribution $N(D)$ is the gamma function:

$$N(D) = N_{o\Gamma}\, D^{\mu}\, e^{-\lambda_{\Gamma}\circ T} \quad (cm^{-4})$$

Where D is the particle diameter, $N_{o\Gamma}$ is the intercept, λ_{Γ} is the slope, and μ is the shape. The last three parameters are derived from radar and temperature variables as presented by *Heymsfield et al.* (2002). The simplified equation for the intercept:

$$N_{o\Gamma} = \frac{Z\ \lambda_{\Gamma}{}^{(5.5+\mu)}}{1.2\ 10^{8}\ \Gamma(5.5+\mu)}$$

Where Z is the radar reflectivity factor $(mm^{6}\ m^{-3})$ converted from observed weather radar measuring in dBZ. Taking into account the use of a C-Band weather radar and measurements above the 0 °C, Z can be expressed as (*Heymsfield et al.*, 2002):

$$Z = 10^{\left(\frac{dBZ+7.2}{10}\right)}$$

where, 7.2 dBZ is to correct the ice/water dielectric constant effect. To simplify, we adopt the median dBZ reflectivity at each level shown in Figure 5. The slope λ_Γ and the shape μ are estimated from the median fitted functions in *Heymsfield et al.*, (2002), respectively:

$$\lambda_\Gamma = 24\, e^{-0.049T} \qquad (cm^{-1})$$

$$\mu = 0.13\ \lambda_\Gamma{}^{0.64} - 2$$

Where T is the temperature in ºC. The maximum diameter for each distribution is calculated according to the region of the cloud. For Box 1 and 5 the maximum diameter is selected for convective type (*Heymsfield et al.*, 2013):

$$D_{max} = 2.1\, e^{0.070T} \quad (cm)$$

Whereas for the stratiform areas in Box 2, Box 3 and Box 5:

$$D_{max} = 1.1\, e^{0.069T} \quad (cm)$$

In the lower part of the distribution *D* has been limited to 20 μm. Once the fitted gamma functions $N(D)$ are obtained, photon mean free paths are calculated according to *Thomason and Krider* (1982):

$$\Lambda \approx \frac{1}{\int_{D_{min}}^{D_{max}} \pi D^2\, N(D) dD}$$

Finally, the optical depth τ is calculated according to the corresponding geometric deepness *L* of the given reflectivity region above the lightning channel:

$$\tau = \frac{L}{\Lambda}$$

With the available data and the presented calculations, we cannot provide a precise estimation of the optical depth. From our experience some of the aspects to consider in the future are:

1) Better radar vertical resolution is convenient. Here we cannot resolve levels higher than 10 km for all the regions of the flash, because the radar has been configured to monitor rain mainly.
2) By increasing the number of elevations or scanning continuous vertical cross sections (like sector range height indicator – RHI) with a polarimetric radar, like this one, polarimetric variables like differential radar reflectivity (ZDR), specific differential phase (K_{DP}) and correlation coefficient among horizontal and vertical polarization can be augmented to estimate the type of ice particles and its size (*Liu and Chandrasekar*, 2000);
3) C-band radars detect mostly precipitation size particles. The referenced works allow to extend to lower size particles, even to the few μm size. However, we have found that at temperatures lower than -40 ºC (~11 km) the density of low sized particles increases several orders of magnitude providing very dense clouds that result in an increase of the optical depth by an order of magnitude. A similar unrealistic effect is found by *Rutledge et al.* (2020) in relation of the temperature dependence of the intercept parameter.

Despite the assumptions and limitations, the relative optical depths presented in Table 1 present a reasonable agreement with the observed luminosity features in each box.