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Halos generated by negative cloud-to-ground lightning

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[1] The Imager for Sprites and Upper Atmospheric Lightning (ISUAL) on the FORMOSAT-2 spacecraft observes Transient Luminous Events (TLE) like sprites, elves, and halos from space. We analyzed halos that were observed in Central America close enough to ELF/VLF receivers that allowed for the determination of the polarity of the parent lightning. All halos were created by negative cloud to ground lightning (−CG) strokes that occurred almost exclusively over the open water. Only three out of the 31 events happened over land. We conclude that the Central American region seems to be special with respect to the large proportion of −CG created halos. Such a behavior is very different from the occurrence of sprites that are mostly created by positive cloud to ground lightning. **Citation:** Frey, H. U., et al. (2007), Halos generated by negative cloud-to-ground lightning, *Geophys. Res. Lett.*, *34*, L18801, doi:10.1029/2007GL030908.

1. Introduction

[2] The Imager for Sprites and Upper Atmospheric Lightning (ISUAL) was launched in May 2004 with the FORMOSAT-2 spacecraft and is the first space instrument that is dedicated to observe transient luminous events (TLEs) [*Chern et al.*, 2003]. As of March 2007 it has observed over 50,000 lightning events. About 10% of these lightning events are accompanied by TLEs, but still their number is much larger than the number of TLEs obtained during any other previous space-based observation (see e.g. [*Boeck et al.*, 1998; *Yair et al.*, 2004; *Blanc et al.*, 2004]. ISUAL data have so far been used to determine the electric fields in sprites [*Kuo et al.*, 2005; *Adachi et al.*, 2006] and the amount of ionization in elves [*Mende et al.*, 2005].

[3] ISUAL's limb viewing observation geometry from space provides the image of the TLE together with the in-cloud scattered luminosity of the parent lightning. Data are collected from about 20 msec before the triggering lightning flash up to 200 msec after it. It is therefore possible to determine not just the temporal evolution of the TLE but also the spectral and spatial properties of the parent lightning, if both signals can be separated temporally and/or spatially. It has been established that a large number of elves is created by negative cloud to ground (−CG) lightning that follows beta-type stepped leaders [*Frey et al.*, 2005]. Consistent with previous reports of almost exclusively +CG triggered sprites [*Boccippio et al.*, 1995; *Lyons et al.*, 2003], it was also shown that many of the observed sprites occur during the continuing current and can be delayed up to many tens of milliseconds after the return stroke [*Frey et al.*, 2005].

[4] Here we investigate the occurrence and creation of another class of TLE, namely halos. Halos are brief, diffuse flashes of light with diameters of less than 100 km at 70–85 km altitude [*Barrington-Leigh et al.*, 2001; *Wescott et al.*, 2001]. This definition distinguishes halos from elves which have diameters of more than 200 km and occur at altitudes of 85–95 km [*Barrington-Leigh and Inan*, 1999]. Halos originate in the high-altitude quasi-electrostatic field [*Pasko et al.*, 1997] while elves are created by the electromagnetic pulse (EMP) of the return stroke [*Taranenko et al.*, 1993; *Inan et al.*, 1996].

[5] The majority of sprites and halos are created by +CG [*Williams et al.*, 2007], while there are reports of elves produced by both +CG and −CG [*Barrington-Leigh and Inan*, 1999]. There is one report of halos that were created by −CG [*Bering et al.*, 2004], but it contains a puzzling discrepancy that with a diameter of 400 km the reported halos were more likely elves, while their time delay of 6 msec after the lightning contradicts an origin in the EMP. It was recently suggested that a large number of −CG flashes may create only dim halos that are not detected in conventional video imagery [*Williams et al.*, 2007]. Here we investigate halos that were observed from space simultaneously with their recorded lightning polarity and we will show that they were all created by −CG flashes occurring predominantly over the open ocean.

2. Instrumentation and Data Analysis

[6] ISUAL is mounted on the FORMOSAT-2 spacecraft and observes an area of about 1100 km in latitude and 900 km in longitude before midnight local time from 890 km altitude [*Chern et al.*, 2003]. It consists of an image intensified CCD camera, a six-channel Spectrophotometer (SP), and a two-channel Array Photometer (AP). Only images with the N_2-1P filter (633–751 nm) are used in this study. All instruments cover approximately the same field of view [*Chern et al.*, 2003].

[7] Duke University operates a set of magnetic field sensors in the ELF/VLF (50 Hz–30 kHz) range that can be used to determine the polarity of lightning and its vertical charge moment. Once the trigger time and approximate geographic location of a lightning stroke is determined in ISUAL images and time delays due to propagation are

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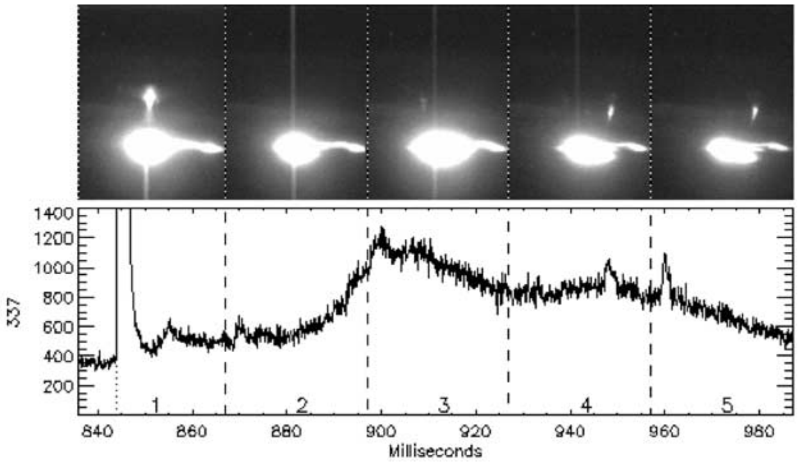

Figure 1. Example of a sprite observation on September 23, 2005 where a total of four sprites occur immediately after the parent lightning and with 62, 104, and 116 msec delay, respectively. The long elevated signal in the photometer and the long lasting brightness of the lightning in the images are caused by the continuing current after the +CG stroke.

properly accounted for, the corresponding VLF data can be found in most cases without ambiguity. The data provide the best quality for events within a few thousand kilometers from the detector and we therefore concentrate this study on the Central American region.

3. Observations

[8] FORMOSAT-2 is in a sun-synchronous orbit that repeats its ground track after every 14 orbits again (orbital period 103 minutes). ISUAL operates between about −45 to +45 degrees latitude. This mission design allows for the investigation of the global distribution of TLEs [*Chern et al.*, 2003]. Several well known regions of increased thunderstorm activity (Indonesia, Congo Basin, and central America) are observed daily. The Central American region is close enough to the ELF/VLF receivers at Duke University (35.975°N and 79.100°W) to allow for a determination of the polarity of the parent lightning for almost any TLE observed in that area. We searched the ISUAL data from July 2004 to September 2005 for pure halo observations that were clearly not an elve in terms of the size in our images (less that 100 km diameter compared to more than 200 km diameter for elves), that were not accompanied by a sprite or bright sprite streamers, and that occurred in the central American region. We found 31 such events.

[9] The vast majority of sprites are created by +CG [*Boccippio et al.*, 1995; *Lyons et al.*, 2003; *Williams et al.*, 2007]. Examples in ISUAL data appeared after substantial time delay from the return stroke of the parent lightning during the continuing current (see, e.g., *Frey et al.* [2005, Figures 1 and 4] or *Kuo et al.* [2005, Figure 3]). Figure 1 shows another example where one sprite occurs shortly after the return stroke and three more with time delays of 62, 104, and 116 ms, respectively. This example clearly demonstrates that one lightning event may create more than just one sprite.

[10] Halo observations show a different behavior. All halos occur immediately after the onset of the return stroke without substantial time delay. So far we did not find multiple halos during one lightning event. The photometers do not record any continuing brightness after the return stroke. The images following the triggered image are completely black (Figure 2). Figure 2 shows the 150–280 nm (N_2 LBH) and 609–753 nm (N_2 1P) photometers together with the AP channel aimed at the halo altitude and the azimuthal component of the radiated magnetic field. There is almost no time difference (<0.5 msec, time resolution is 0.1 msec) between the increase of all signals.

[11] This different behavior of the halos compared to sprites already suggests different characteristics of the parent lightning. 25 of the 31 halos could be identified unambiguously as caused by a −CG. The ELF/VLF data for the other six events was either missing or too noisy for a certain determination of the lightning polarity. We found several other halo events (mostly in central Africa and not shown here) with clear sprite streamers below the diffuse halo emission. The photometer signals of these events often indicated sprites after a +CG which may occasionally have a bright enough simultaneous halo emission.

4. Discussion

[12] We investigated at which altitude these halos occurred. Following the previous report that halos are centered over the parent lightning [*Wescott et al.*, 2001], we determined their most likely altitude by first determining the pixel numbers of the parent lightning and of the halo centroids independently. The geographic locations of the lightning and halo were then calculated assuming ranges of 5–25 km altitude for the lightning (in 1 km steps), and 60–95 km for the halo (in 5 km steps). Then the distances between the lightning and halo geographic locations were calculated individually for every combination of altitudes and averaged over the 31 events of this study. This method resulted in clear average distance minima of less than 15 km for 8/75, 14/80, and 23/85 km altitude combinations, respectively. The lightning return stroke illuminates the clouds from below and what ISUAL observes from space are mostly the illuminated cloud tops. Altitudes of 8 km or 23 km appear too low and too high for normal thunder clouds and we therefore adopted the 14/80 km altitude

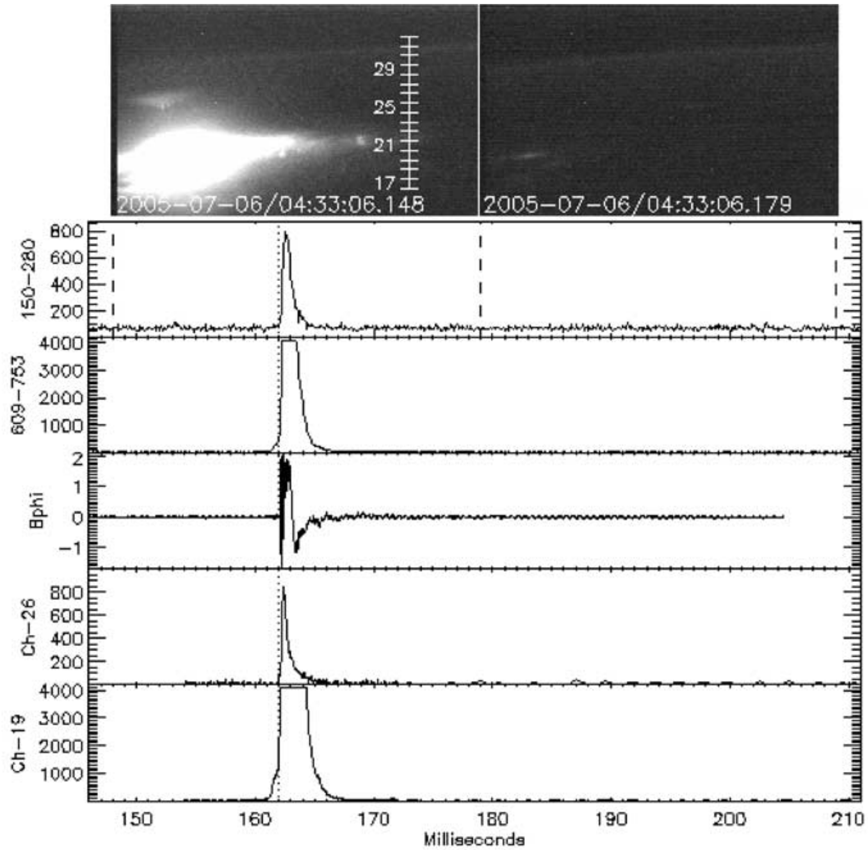

Figure 2. Photometer observations during a halo observed on July 6, 2005. The two images at the top are aligned to their 30 msec exposure times. The vertical scale illustrates the pointing and angular (altitude) extent of the AP channels and the halo is centered at channel 26 above the very bright cloud illumination. The top two panels show the photometer data of the LBH and N_2-1P channels. The following panel gives the azimuthal (Bphi) component of the VLF radiated magnetic field. The bottom two panels give the AP-channels number 26 and 19. AP channel 26 measures only the signal from the high-altitude halo while channel 19 measures only the signal from the lightning return stroke demonstrating that there is no time delay between the two phenomena.

combination as the most likely one. This 80 km halo altitude is also consistent with earlier triangulation, which found an average of 80 km [*Miyasato et al.*, 2002] and 78 km [*Wescott et al.*, 2001], respectively.

[13] The establishment of the halo altitude allowed for a determination of their diameter. The average FWHM-diameter of the halos was 62 km with a standard deviation of 14 km. This value is close to the previously reported 66 km diameter [*Wescott et al.*, 2001]. Our slightly smaller value is either the result of variations between different data sets or the result of the longer integration times of the ISUAL-CCD images (30 msec compared to 1 msec in the work of *Wescott et al.* [2001]) and the short duration of the halos ($\approx$0.5 msec).

[14] We then determined the geographic locations of the halos (Figure 3). 28 of the 31 halos occurred over the oceans and only 3 occurred over land. One of those land-events was clearly created by a -CG (330 km inland over Peru in Figure 3). The stroke polarity of the other two events (70 km inland over northern Chile and 30 km inland over Panama) could not be determined because the ELF/VLF data were missing in one case and very noisy in the other. Of all ocean events 4 occurred within 100 km of a coastline, but we are confident that the errors of our location determination were small enough to assign them their correct position over water. It is possible that the three land-events may have happened over lakes or rivers, however with an estimated localization accuracy of 20 km we can not draw substantiated conclusions about this possibility.

[15] A comparison between lightning over oceans and land masses will always depend on the separation between land and water areas. For instance *Christian et al.* [2003] considered every 2.5 $\times$ 2.5 degrees region that contained any land (continent or island) as land area. On the other hand, *Lay et al.* [2007] added a coast region to pure land and ocean areas whenever there was a coast within 600 km distance.

[16] In order to get an estimate of the land/ocean distribution in our study area we limited our investigation to 1–28° latitude and 249–309° longitude where 28 of the 31 halos occurred and we ignored the three halos south of the equator. Within the selected region there is about 75% water and 25% land. This water/land ratio is very different from our result of halo distribution even if we include the two land-halos below the equator (90% over water and 10% over land). Our ratio is also very different from the global lightning activity distributions that show a land/ocean ratio

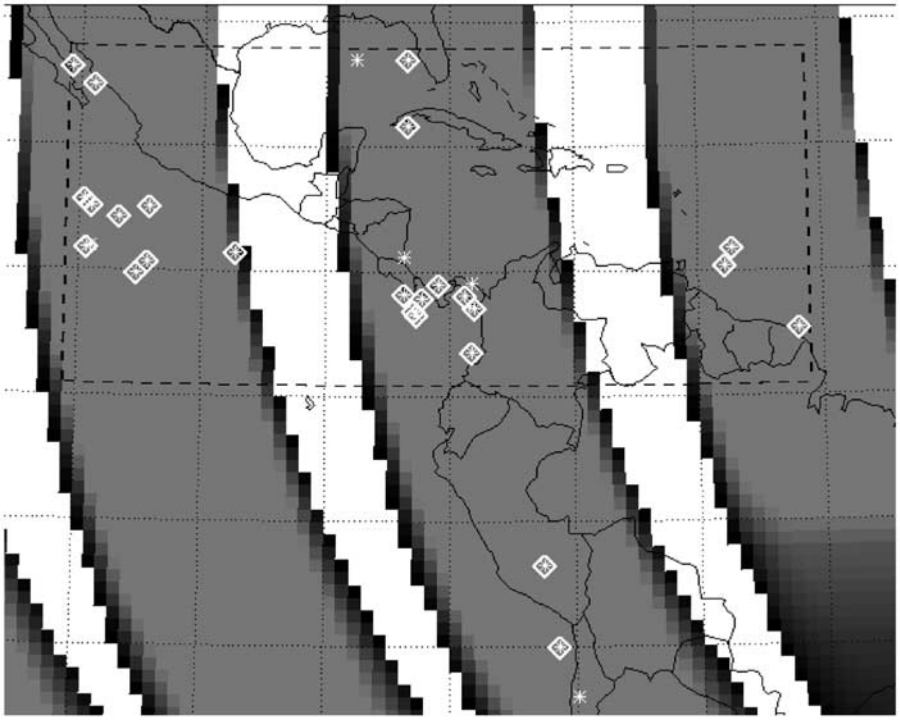

Figure 3. Map of central America with the location of observed halos. The shaded region indicates the area that is regularly observed by ISUAL. Halo locations are marked as asterisks and a diamond is over-plotted if that halo was definitely caused by a -CG stroke. The dashed lines mark the region that was used for the land/ocean estimate (see text).

of 10:1 [*Christian et al.*, 2003]. Even if we adopt the same selection criterion of 2.5 $\times$ 2.5 degrees we obtain 16 events over land and 15 events over oceans. We therefore conclude that halos at least in the Central American region do not follow the global lightning distribution and that they occur more often over open water than over land.

[17] In addition to local differences global lightning activity is also not evenly distributed over local time [*Williams and Heckman*, 1993]. An analysis with data from the World Wide Lightning Location Network (WWLLN) showed a global peak in lightning activity at 1800 local time with regional time differences up to 5 hours [*Lay et al.*, 2007]. Lightning activity in the Caribbean region and especially over water peaks later (around 2300 LT) and is therefore within the local time region that is covered by ISUAL (22:30–23:30 local time). This explains the large portion of lightning events that ISUAL observed in the Caribbean region. Of all the lightning events that ISUAL recorded globally during the study period of 2004–2005 it recorded 21% of all events in this region while the satellite spent only 8% of the total operation time in that area. However, this temporal coincidence does not explain the large portion of halo events over water.

5. Conclusions

[18] We report the characteristics and the occurrence of halos in Central America where the proximity to ELF/VLF receivers at Duke University allow for an identification of the parent lightning polarity. All halo events that were observed by ISUAL between July 2004 and September 2005 in this region were caused by negative cloud to ground lightning strokes (except 6 where identification was impossible because of missing or noisy data). This result is very different from the almost exclusive +CG cause for sprites and may indicate differences in the quasi-electrostatic thunder cloud fields that either create halos or sprites. It could also be the result of the polarity asymmetry between positive and negative lightning [*Williams et al.* 2007].

[19] We also found a strong disparity between the land/water ratio in the observation region and the occurrence distribution of halos. Only 10% of our observed halos occurred over land or 16 out of 31 events (52%) if we consider any region within 2.5 degrees of a coast as land. Both ratios are very different from the general worldwide lightning distribution of 90% lightning over land [*Christian et al.*, 2003]. Central America appears to be a "hot-spot" for -CG halo creation over water and more work needs to be done to investigate if similar results can be found for instance over Indonesia and if a distinct difference can be found between ocean- and land-halos. A combination of halo observations with other lightning observations (ELF/VLF, electric field etc.) should investigate if the different propagation characteristics of positive and negative discharges and the coupling to land or sea water may account for these differences [*Williams*, 2006].

[20] We should also note that only 4 of the 31 halos were observed in February/March and 27 were observed in June–October with a strong peak in August. This temporal distribution coincides with the maximum of lightning activity in northern summer and the largest peak currents of lightning [*Lyons et al.*, 1998]. The geographic region of the Caribbean also coincides with the region of the unexpectedly high population of very large peak currents of -CG events over the Gulf of Mexico and the Atlantic [*Lyons et*

al., 1998] that might explain the role of halos over the oceans in the discussion of the polarity paradox [*Williams et al.*, 2007].

[21] Halos are generally dimmer than sprites. In the limb view of ISUAL elves often appear brighter than halos. However, this may just be the result of the long integration along the line of sight (400 km) through the elve compared to the much shorter integration (60 km) through the smaller halos. This observation may support the speculation of a large number of undetected dim halos in common video recordings [*Williams et al.*, 2007]. One consequence of these brightness differences may be the almost ten times more elves and about two times more sprites that are found in ISUAL data. However, these occurrence rates will be described in a separate study.

[22] Future studies should investigate if pure halos are mostly created by −CG while halos with sprites may always be created by +CG. It should further be investigated if halos can be observed in northern winter and if they follow the same spatial distribution with a maximum occurrence over water. Furthermore, a follow-up investigation will determine the charge moment changes during these halo events and investigate their spectral properties, but such a comparison was beyond the scope of this paper.

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