# OBSERVATIONS OF SPRITES FROM SPACE AT THE NADIR: THE LSO (LIGHTNING AND SPRITE OBSERVATIONS) EXPERIMENT ON BOARD OF THE INTERNATIONAL SPACE STATION

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**Abstract** The experiment LSO (Lightning and Sprite Observations) on board of the International Space Station is the first experiment dedicated to sprite observations at the nadir. Such observations are difficult because the luminous emissions of sprites and lightning can be superimposed when they are observed from space at the nadir. Such observations are however needed for measuring simultaneously all possible emissions (radio, X-$\gamma$, high energy electrons) associated with sprites for a better understanding of the implied mechanisms. They are possible in specific spectral lines where sprites are differentiated from lightning. Absorption bands of the atmosphere are well adapted for this differentiation because the light emissions from sprites occurring in the middle and upper atmosphere are less absorbed in these bands than lightning emissions occurring more deeply in the atmosphere. The most intense spectral emission band of the sprites, corresponding to the $N_2$1P band at 761 nm, partly superimposed with the oxygen absorption A band of the atmosphere, is used by the LSO experiment. The experiment is composed of two micro-cameras, one in the visible and near infra red, the other equipped with an adapted filter. Only sprites, halos and superbolts, which correspond to a class of rare very intense lightning, are transmitted through the filter. Sprites, halos and superbolts are identified by the ratio of the intensities received through the filter and in the whole spectrum. This ratio is lower for superbolts than for sprites and halos. The response of the sprites is also more complex and variable than the response of superbolts which is very flat and comparable from an event to another. Finally, LSO observed 17 sprites, 3 halos and 9 superbolts. Several examples of differentiation of sprite and superbolts are given. The results of a first global statistical study are also presented.



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## 7.1 Introduction

Most of the observations of sprites are performed from planes (Sentman et al., 1995) and from the ground in different parts of the world (Lyons et al., 2003; Hardman et al., 2000; Neubert et al., 2001; Su et al., 2002) at the horizon where sprites are spatially differentiated from the lightning flashes. Different types of emissions (jets, halos, elves) called TLE (Transient Luminous Events, Lyons et al., 2000) have been identified. Recent observations provide details of the space and time evolution of these phenomena (Gerken et al., 2000; Moudry et al., 2003). The first space observation of sprites was performed during thunderstorm observations (Boeck et al., 1998). Few experiments are now designed for sprite observations from space at the horizon: (i) MEIDEX onboard of the Space Shuttle performed 7 hours of sprite observations over thunderstorms (Yair et al., 2004), (ii) the ISUAL experiment is the first sprite experiment onboard a satellite (Chapter 6).

However sprites are complex phenomena and the emissions in the visible constitute only a part of the emissions related with sprites. Theoretical studies show that sprites can be produced by electrostatic electric fields above the altitude where the thunderstorm electric field exceeds the air breakdown electric field threshold (Pasko et al., 1997). This process predicts ELF electrostatic emissions which can be observed at the ground (Cummer et al., 1998; Füllekrug et al., 2001). Electromagnetic pulses are involved in the elve formation (Barrington-Leigh et al., 2001). Sprites have also been explained by relativistic runaway electrons triggered by cosmic radiation (Roussel-Dupré and A., 1996; Roussel-Dupré et al., 1998). The resulting high energy electron beam interacts with the atmosphere producing intense electromagnetic radio emissions in a large frequency range in the HF-VHF part of the spectrum and X-gamma emissions by bremsstrahlung process. Both conventional and runaway processes could occur in parallel (Roussel-Dupré et al., 2002). The runaway electron theory is supported by the observations of X and $\gamma$ ray emissions from the Earth's atmosphere (Fishman et al., 1994; Feldman et al., 1995; Lopez et al., 2004). Ground based observations of energetic radiation up to many tens of MeV, produced during rocket triggered lightning shows that this process is more frequent than expected (Dwyer et al., 2004).

For a better understanding of these mechanisms, simultaneous measurements of all these emissions from space are needed. However, these observations are difficult to realize, because the light emissions of sprites are then superimposed on the intense light emissions of the lightning diffused by clouds.

The LSO (Lightning and Sprite Observations) experiment on board of the International Space Station (ISS) has been designed to perform sprite observations at the nadir using an original method of spectral differentiation between sprites and lightning by an adapted filter. The first sprite observations obtained in the frame of the Andromède and Odissea missions were shown by Blanc et al. (2004). The results of new observations performed in the frame of Cervantes and Delta missions are presented in this chapter. A first statistic of the global LSO observations obtained up to now is also presented.

## 7.2 Spectral Differentiation of Sprite and Lightning Emissions

The frequency band, used for the selective spectral measurements of sprites, corresponds to the most intense emission line of sprites $N_2 1P$ at 762.7 nm, or $N_2 \left(B^3\Pi_g - A^3\Sigma_u^+\right)$ $(3-1)$. The interest of this spectral band is that it includes a significant part of the absorption band of the $O_2$ $\left(b^1\Sigma_g^+ - X^3\Sigma_g^+\right)$ $(0-0)$ absorption band near 761.9 nm. For this reason, the sprite emission line $N_2 1P$ does not appear on the sprite spectra measured at the ground (Hampton et al., 1996; Morrill et al., 1998) where the dioxygen density is important. On the contrary, this emission will be observed from space because of a weaker dioxygen density above the sprite. The light emissions, within this band, from lightning, produced deeper in the atmosphere, will be absorbed, as well as all man made emissions from the ground surface. The spectral band selected for LSO corresponds to the most intense emission band of the sprites determined by using the theoretical spectrum of sprites provided by Milikh et al. (1998), see Figure 1. Figure 2 shows the solar light transmission from 754 to 770 nm (Solar Survey Archive-2000, 2005) superimposed with the filter response and the sprite spectrum $N_2 1P$ peak. The filter width of the LSO filter is 10 nm, it has been optimized for receiving the maximum of energy from the sprites and filtering the lightning emission through the atmospheric absorption. A narrower width selected where the absorption band is the most intense would optimize the spectral differentiation of sprites and lightning but a more sensitive camera is necessary to measure very low sprite intensities.

The possible emission of lightning in the same spectral band has been estimated by using the lightning spectrum measured by Orville and Henderson (1984) and the camera and filter responses. The intensity received through the filter is expected to be about $1\%$ of the total spectrum.

## 7.3 Experiment

The first LSO measurements were performed in the frame of the flight of the French astronaut Claudie Haigneré (Andromède mission) on the International Space Station in October 2001. The experiment was developed by the Commissariat à l'Energie Atomique with the participation of the Centre National d'Etudes Spatiales. The measurements were realized with the collaboration of RKK Energia (Russia). Additional observations were performed in 2002

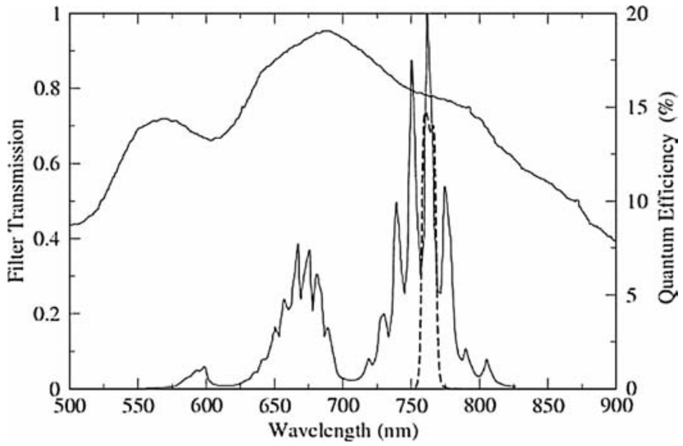



*Figure 1.* LSO filter response (in dashed bold line) is adapted to the observation of the most intense sprite emission band (Milikh et al., 1998). The camera response is also shown in dotted line.

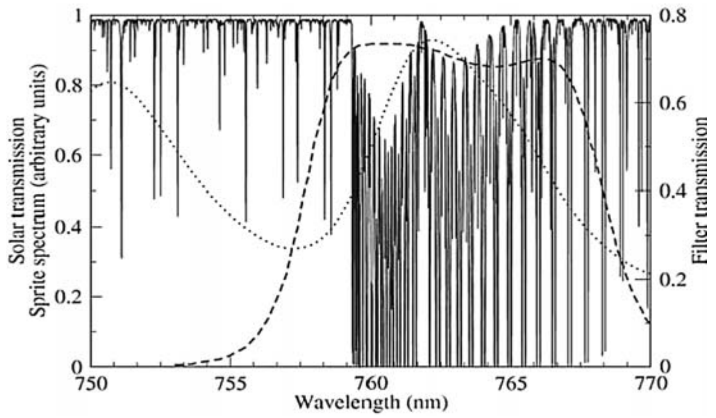



*Figure 2.* Solar light transmission (solid line) in the vicinity of the LSO filter (dashed line). The sprite spectrum in this band is indicated in the dotted line.

during the Odissea mission of the flight of the Belgium astronaut with the participation of the European Space Agency. The first results obtained during these missions are described by (Blanc et al., 2004). New results were also obtained from September $1^{st}$ to $5^{th}$, 2003 and from $1^{st}$ to $5^{th}$ October 2003 in the frame of the ESA Cervantes mission (flight of the Spanish astronaut) and from April $24^{th}$ to $26^{th}$, 2004 in the frame of the ESA Delta mission (flight of the Netherlands astronaut). However one camera failed during the Delta experiment and only the Cervantes data were used for sprite observations. In total, 19 h of effective observations are available up to now.

The ISS orbit is at about 400 km altitude, the inclination is 51.6°. This orbit is well adapted to the observation of sprites and lightning flashes which mainly occur at low and middle latitudes. The observations are performed when the station is stabilized during several days per month. The two-line norad orbital elements are used by LSO programs to predict the ISS orbit characteristics.

The experiment (Figure 3) is composed of two microcameras, one equipped with the filter adapted to the observations of sprites and the other in the total camera spectral range which extends from 400 up to 1000 nm (Figure 1). The camera response is maximum at 690 nm. The cameras are connected to an electronic box and to one Experiment Processing Computer which is only dedicated to the camera programs and data archiving. The digital space micro-cameras have been developed by CSEM (Centre Suisse d'Electronique et de Microelectronique, now Space-X). The objectives have a focal length of 14 mm, an aperture of f/3.5 and a field of view of 70°. The images are taken on 1024×1024 pixels with 10 bits dynamic range but only the central part of the CCD (512×512 pixels) is used (the effective field of view is then 39.8°). The pixel length is 14 $\mu$m with a pixel aperture ratio of 0.71 due to the anti-blooming system. The images of both cameras are taken simultaneously. Because of the very rapid development time of the experiment (3.5 months), it has not been possible to lower the data transmission time of both images time below 5.5 s. The time exposure is 1 s. The precision in time is one second. The cameras are fixed on an ISS window. Both cameras were calibrated for quanti-

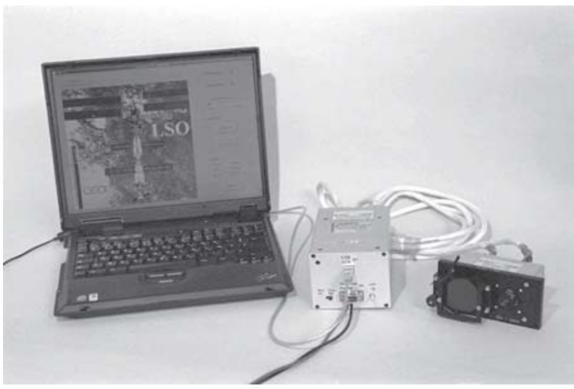



*Figure 3.* LSO experiment

tative measurements of brightness (Blanc et al., 2004). The spectral sensitivity of both cameras is 45 $\mu$J/m$^2$/sr at 765 nm for 1 LSB (least significant bit) or about $2{\cdot}10^{-4}$ft candles ($\sim$2 mLux), which is comparable with the sensitivity of the camera used for the first sprite measurements from space (Vaughan, 1994).

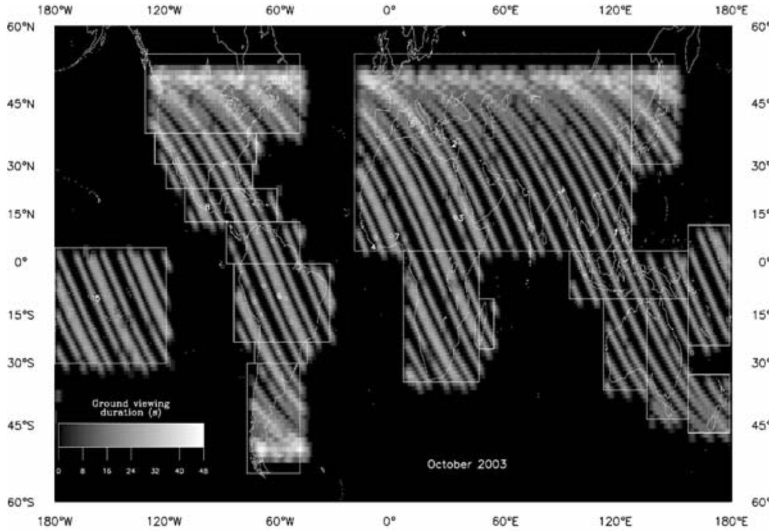
The measurements are automatic. The astronaut enters the dates of the beginning and of the experiment and the two lines norad elements needed by the on board computation program. Data are archived on a removable disk which is brought back to the ground by the astronaut.

Observations are performed during the night and mainly over continents, were most of the storms are expected according to the TRMM (Tropical Rainfall Measurement Mission) satellite observations (Christian et al., 2003). One observation area has been selected over the Pacific Ocean to represent ocean conditions. The observation areas covered during the Cervantes mission are shown in Figure 4.

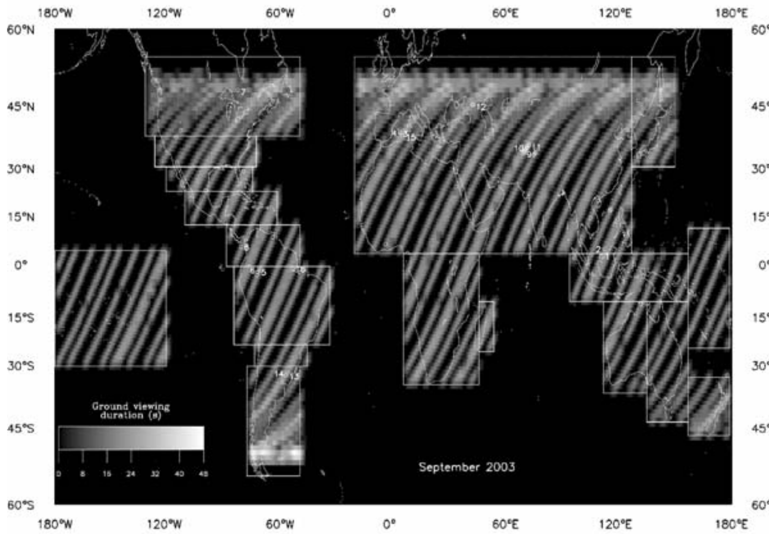
## 7.4 Observations

At the end of the Odissea mission, LSO observed 60 transitory events with the camera in the visible and 13 events with both cameras. The first class of events observed by both cameras corresponds to sprites. It is defined by a ratio of both cameras' intensities higher than 3% (Figure 5, left and middle). These events are characterized by a complex spatial response and the ratio is variable inside a same event. Also the response is variable from one event to another. Ten events belonging to this class were identified in this first experiment set (Blanc et al., 2004). The second class of events, observed by both cameras, is characterized by a lower intensity ratio of about 1% (Figure 5, right), the ratio is quite stable over the event spatial coverage, in addition the response is comparable from one event to another. They have been identified as very intense lightning called superbolts with a power from $3{\cdot}10^{11}$ to $7{\cdot}10^{12}$ W (Turman, 1977). Only about 1% of lightning belongs to this lightning class. The LSO filter suppresses the response of most lightning, but the intensity of the superbolts is sufficient to provide a response in the filter.

The analysis of the new data obtained in the frame of the Cervantes mission confirms the first results about these two classes of events. An example of a sprite event observed in this data set is shown in the Figure 6 with the same color scale as in Figure 5. The complexity of this event arises from the presence of three different flashes, observed in the same image because of the 1 second of integration time of the observations. The three events are differentiated by the ratio of both cameras. The sprite appears in red in the picture of the ratio of the cameras' intensities, indicating a ratio value higher than 6%. Differently the two other emissions appear in blue with a ratio of about 1% or in yellow and green with a ratio of 2 or 3%. As a superbolt is characterized by a ratio of




(a)




(b)

*Figure 4.* Duration and areas observed by LSO for the Cervantes mission.

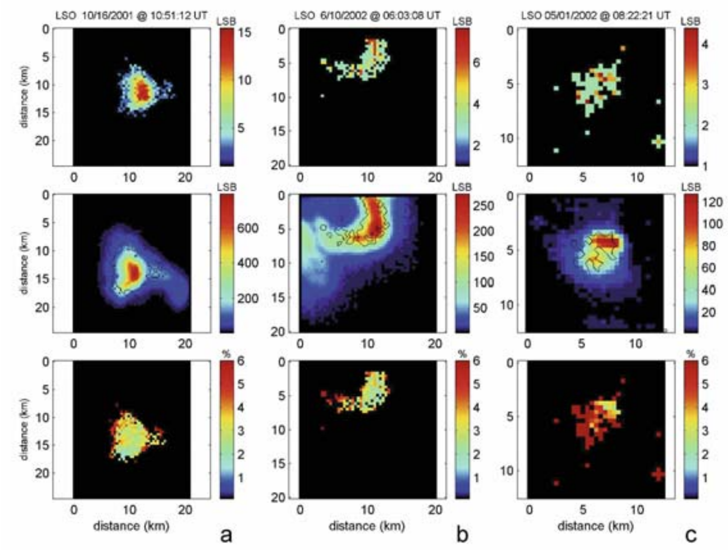



*Figure 5.* First observation of sprite from the nadir by LSO. 1. Top filtered images 2. Middle: images in the visible, 3. Bottom: ratio of both intensities. The event at the right is a superbolt while both events on the left are sprites. They are differentiated by the ratio of the intensities measured by both cameras, most intense for sprites than for lightning.

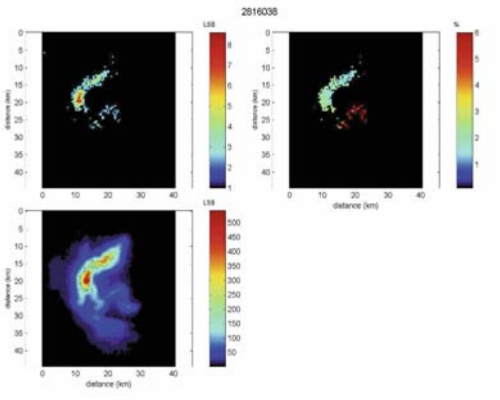



*Figure 6.* Simultaneous observation of a sprite and a superbolt performed on October $3^{rd}$, 2003, at 19:19:31 UT at 35.58°N 36.18°E. The ratio of both cameras is higher than 6 for the sprite. It is about 1% for the superbolt. The most intense event in the visible and in the filter corresponds to a ratio of 2 to 3% and could be explained by the presence of a halo.

1%, the ratio increase could indicate the presence of an halo superposed with the lightning. When isolated, halos have been identified by a ratio comparable or slightly lower than the sprite ratio, but with a larger geometric extension and a response more flat.

During the 19 hours of observations, 40 events were observed with both cameras. The first 13 hours correspond to the first data set analyzed by Blanc et al. (2004). Table 1 provides the characteristics of the additional events observed during the Cervantes mission. In total, 17 sprites were identified with 3 isolated halos. Three sprites, not clearly identified are not taken into account in this number. Also 9 superbolts were identified. The three, indicated in bold, are among the most intense events observed by LSO. The sprite observation frequency is then about 1.7 per hour. The number of sprites observed by MEIDEX onboard of the Space shuttle is 2.6 sprites per hour, and 4 TLE per hour (Yair et al., 2004). This number is higher but the cameras were oriented to observe the regions of interest according to the probability of lightning activity and the astronaut adjusted the camera pointing angle for lightning observations, increasing the probability to observe TLEs.

Figure 7 shows the local time distribution of the 40 events observed by both cameras of LSO. The local time is deduced from the universal time taking into account the position of the ISS at the measurement time. The maximum of activity is observed near midnight. The distribution is not related to the lightning nighttime distribution which is decreasing regularly from 18-7 LT (local time), the maximum being at about 14 LT (MacGorman and Rust, 1998).

LSO observed 180 flashes corresponding to the most intense lightning. The number of lightning flashes which effectively occurred during the 19 h of the LSO measurements can be estimated by using the LIS data measured on board of the TRMM satellite in the same period of observation (LIS/OTD webpage, 2002; Christian et al., 2003). This number of lightning flashes is estimated about 1100. This estimation takes into account the respective observation areas of LIS and LSO and the fact that LSO measures only over the continents, where 88% of the lightning occur. The occurrence of sprites is then 1.4 sprites for 100 lightning flashes. Taking into account that the global number of lightning determined from LIS observations is 44 flashes per second (Christian et al., 2003), the global number of sprites per minute could be about 37. This number is more important than the global number of sprites estimated by (Yair et al., 2004) which is 7.5 sprites per minute. The reason is that the LSO observations are performed over continents where most of the lightning flashes occur. This increases the probability to observe sprites.

Figure 8 shows the intensity distribution of the 203 events observed by LSO in the visible. This include sprites, lightning and superbolts. The superbolts correspond to the most intense events observed by LSO. Among the 5 most intense events, 4 are superbolts and 1 is a sprite.

## 7.5 Perspectives

The results obtained by LSO show that sprites and lightning flashes observed from space at the nadir can be differentiated by using adapted filters. This differentiation has been performed by the comparison of the response of two cameras, one in the visible and the other in the $N_2$1P sprite emission band, which partly coincides with the dioxygen absorption band. Sprites are also separated spatially from lightning. It is expected that the mean distance between sprites and lightning is about 40 km in agreement with ground based observa-

*Table 1.* Characteristics of the events observed by both cameras during the Cervantes mission.

| Date | Universal Time | Longitude | Latitude | Event identification |
|---|---|---|---|---|
| 01/09/2003 | 17:41:43 | 111.0 | 3.3 | Lightning |
| 01/09/2003 | 17:42:25 | 112.6 | 5.5 | Sprite (?) |
| 02/09/2003 | 03:06:58 | 4.0 | 38.8 | Sprite |
| 02/09/2003 | 03:07:03 | 4.3 | 39.0 | Lightning |
| 03/09/2003 | 04:59:07 | -71.2 | -1.7 | Sprite (?) |
| 03/09/2003 | 04:59:18 | -70.8 | -1.1 | Lightning |
| 03/09/2003 | 09:54:35 | -82.0 | 0.5 | Superbolt |
| 04/09/2003 | 05:35:45 | -80.3 | 6.2 | **Superbolt** |
| 04/09/2003 | 21:06:26 | 69.7 | 33.5 | Lightning |
| 04/09/2003 | 21:07:05 | 71.8 | 35.2 | Sprite |
| 04/09/2003 | 21:07:10 | 72.1 | 35.4 | Sprite |
| 05/09/2003 | 00:15:51 | 42.8 | 45.3 | Halo |
| 05/09/2003 | 01:20:23 | -56.4 | -32.5 | Superbolt |
| 05/09/2003 | 01:20:39 | -55.5 | -31.8 | Sprite |
| 05/09/2003 | 01:44:37 | 5.6 | 38.0 | Sprite (?) |
| 05/09/2003 | 03:03:18 | -53.0 | -0.7 | **Superbolt** |
| 01/10/2003 | 22:58:38 | 23.6 | 4.0 | Lightning |
| 02/10/2003 | 15:50:06 | 121.7 | 11.0 | Lightning |
| 03/10/2003 | 19:19:31 | 36.2 | 35.6 | Sprite |
| 03/10/2003 | 20:59:08 | 33.5 | 14.4 | **Superbolt** |
| 03/10/2003 | 22:36:45 | 22.2 | -2.4 | Lightning |
| 04/10/2003 | 10:56:27 | -159.2 | -10.7 | Sprite |
| 04/10/2003 | 17:02:53 | 102.6 | -4.3 | Lightning |
| 04/10/2003 | 19:51:26 | 13.8 | 40.6 | Halo |
| 04/10/2003 | 23:07:10 | -0.3 | 8.7 | Superbolt |
| 05/10/2003 | 02:02:09 | -71.8 | 35.3 | Lightning |
| 05/10/2003 | 05:12:38 | -101.0 | 17.8 | Sprite + Halo |

tions (São Sabbas et al., 2003). In total, 17 sprites, 3 halos and 9 superbolts were identified in the LSO dataset available up to now.

This differentiation could be improved by increasing the time resolution of the measurements. The mean time difference between sprites and lightning

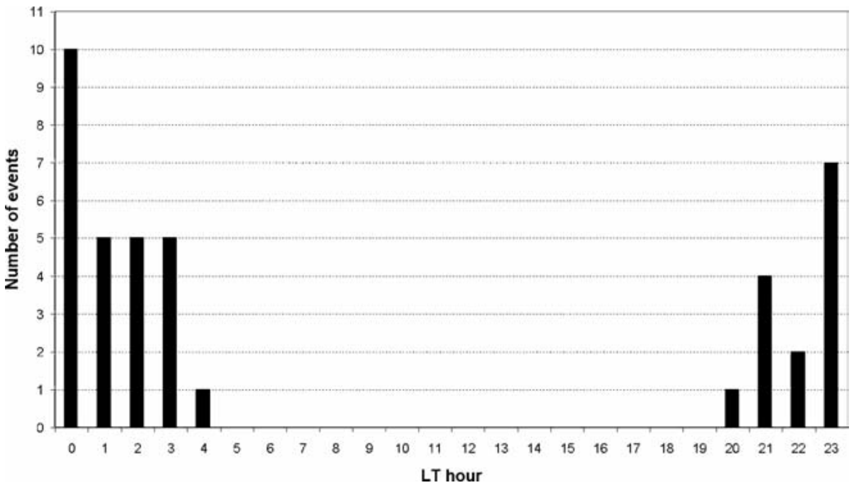



*Figure 7.* Local time distribution of the events observed by LSO.

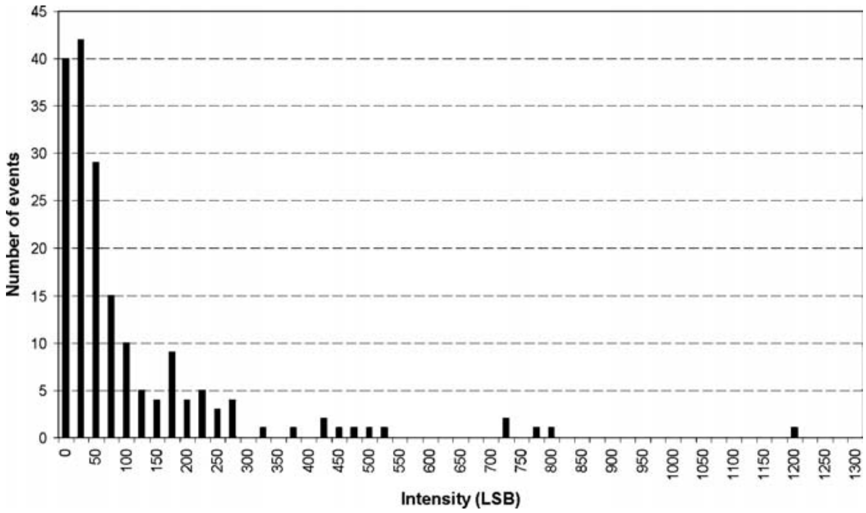



*Figure 8.* Distribution of all the LSO events.

flashes measured by the National Lightning detection network is about 20 to 30 ms (São Sabbas et al., 2003). Other observations using ELF-ULF measurements found that the difference can be smaller or larger, varying from an event to another (Bell et al., 1988). Cummer and Füllekrug (2001) showed that the time delay depends on the charge moment.

In addition to the spectral differentiation realized by LSO in the red part of the spectrum, measurements can be performed in the violet and ultraviolet part of the spectrum. The first results of ISUAL showed that the lightning lights completely disappeared in the 150-280 nm wavelength range and in the $N_2$2P sprite emission band at 337 nm (Chapter 6).

The measurement concept studied by the LSO experiment will be used by the microsatellite TARANIS (Tool for the Analysis of RAdiation from lightNIng and Sprites) dedicated to measure simultaneously the optical, X and $\gamma$ emissions, the electric and magnetic field from ELF up to HF, and the high energy electrons associated with sprites for a better understanding of the implied mechanisms. The final goal is the study of the coupling between atmosphere, ionosphere and magnetosphere associated with thunderstorm activity and the effects of these phenomena on the Earth's environment (Blanc and Lefeuvre, 2003) .

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