AN OVERVIEW OF THE STRATELEC PROJECT (STRATÉOLE-2 ATMOSPHERIC ELECTRICITY)

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ABSTRACT

The STRATELEC (STRatéole-2 ATmospheric ELECtricity) project, funded by the French Space Agency CNES, aims at deploying new atmospheric electricity instrumentation during the last Stratéole-2 balloon campaign [1]. The multidisciplinary STRATELEC project focuses on i) measuring the electrical state of the atmosphere and the production of high-energy radiation through in situ and remote sensing measurements, ii) identifying state-of-the-art and emerging technologies to populate and build the STRATELEC instrumentation package, and iii) contributing to additional scientific returns on any international space mission dedicated to lightning detection and more generally to the study of electrodynamic couplings in the terrestrial atmosphere-ionosphere-magnetosphere system.

The STRATELEC scientific and technical objectives are first presented. The current status of the key technical STRATELEC tasks is then discussed with an emphasis on the analysis of the West Hemisphere lightning activity as recorded during the first Stratéole-2 campaign.

1. INTRODUCTION

A thunderstorm is a very complex phenomenon where dynamical, microphysical, electrical, chemical and radiation processes compete. Based on measurements collected by low-orbit lightning optical detection OTD (Optical Transient Detector) and TRMM-LIS (Tropical Rainfall Measuring Mission Lightning Imager Sensor) missions, about 45 flashes occur per second all around the Earth [2] with a predominant distribution over the continents, with a maximum yearly activity located in Central Africa, and along the inter-tropical band (Fig. 1).

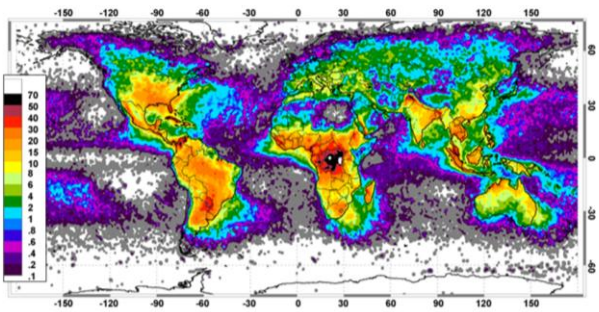

Figure 1. Annual average number of lightning flashes per km^2 from NASA low orbit LIS and OTD missions, adapted from [2].

Lightning flashes are triggered when the ambient electrostatic field inside the parent thundercloud exceeds an altitude-dependent threshold (e.g. [3]). Electrostatic field up to 3 kV.m^{-1} has been measured at 20-km height above a convective cloud by [4] based on dedicated airborne measurements during the CAMEX (Convection And Moisture Experiment) experiment. Additionally solar radiation, thunderstorm occurrence, and fair-weather conditions impact the global atmospheric electrical circuit and its continual electrical current still needs to be better documented at different altitudes of Earth atmosphere.

Different types of TLEs (Transient Luminous Events) can be produced during thunderstorms (Fig. 2). TLEs are usually documented with cameras either from the ground or from space. For instance, based on 4 years of ISUAL (Imager of Sprites and Upper Atmospheric Lightning) measurements the ratios of elves, sprites, halos, and gigantic jets are derived to be 3.23, 0.50, 0.39, and 0.01 events per minute [6].

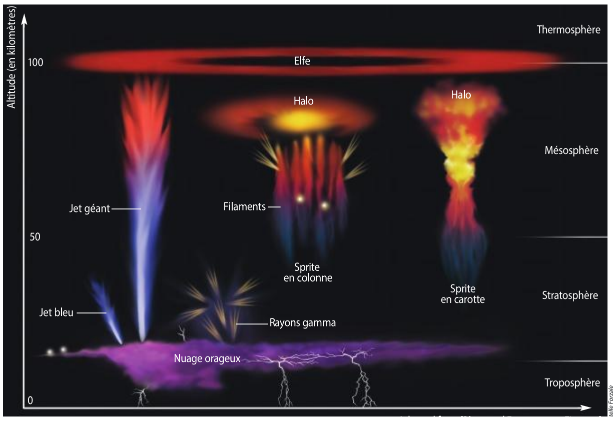

Figure 2. Illustration of typical lightning flashes, Transient Luminous Events and gamma ray emissions from thunderclouds adapted from [5].

Terrestrial gamma ray flashes (TGFs) are bursts of high-energy photons originating from the Earth's atmosphere in association with thunderstorm activity (Fig. 2). TGFs were serendipitously discovered in the 1990s by NASA's CGRO (Compton Gamma Ray Observatory), which had been originally launched to perform observations of celestial gamma ray sources. Later on, the detection of these events has been reported and analyzed using various space-borne instruments. It is worth mentioning that the great majority of TGFs occurs in the inter-tropical region. Moreover, measurements have correlated TGFs with initial development stages of normal polarity intra-cloud (IC) lightning that transports negative charges upward (+IC). In addition to radiation bursts, another type of high-energy emission has been observed inside thunderstorms using detectors on board balloons and airplanes. These events, so-called gamma ray glows, correspond to significant enhancements of background radiation that last for more than a few seconds. Recently, high-altitude gamma ray glows have been observed above thunderstorms at 20 km altitude during high altitude airborne campaigns [7].

All those connected phenomenon need to be documented both remotely and in situ. The TARANIS (Tool for the Analysis of Radiation from lightNIng and Sprites) mission aimed at documenting on a unique way the impulsive energy transfers between the atmosphere of the Earth and the space environment (ionosphere-magnetosphere) [8]. The failure of TARANIS launch dramatically ended any analysis of such phenomenon planned with a dedicated package of cameras, photometers, and instruments to simultaneously measure gamma emissions, energetic electrons, electric and magnetic fields designed to detect, localize, and characterize the lightning discharges, associated TLEs, and high energy particles. On the European side, ESA and DTU have installed the ASIM (Atmosphere–Space Interactions Monitor) mission on board the ISS in April 2018. ASIM carries cameras and X-ray/γ-ray sensors to document TLEs (e.g. sprites, jets and elves) and terrestrial gamma-ray flashes respectively [9].

Geostationary lightning imagers like the American GLMs (Geostationary Lightning Mappers; [10]), the Chinese LMI (Lightning Mapping Imager; [11]), and soon the European LI (Lightning Imager; [12]) will offer a unique almost global coverage of the Earth and more specifically the inter-tropical band. Combining those lightning observations with in situ ad-hoc high-altitude balloon measurements will definitively understand and, hopefully, model the lightning-induced interactions in the terrestrial atmosphere-ionosphere-magnetosphere system.

2. THE STRATELEC PROJECT

The STRATELEC (STRatéole-2 ATmospheric ELECtricity) project, funded by CNES, is an opportunity project for a potential deployment of new atmospheric electricity instrumentation on several Stratéole-2 (ST2) balloon flights [1]. The balloon-borne ST2 program aims at studying the dynamics of the atmosphere at the interface between the troposphere and the stratosphere. On its side, the STRATELEC multidisciplinary project focuses on

i) Documenting the electrical state of the atmosphere and the production of high-energy radiation through in situ and remote sensing measurements to reach a better understanding and better modeling capabilities of the processes occurring during thunderstorms through opportunity balloon flights like the ST2 mission or specifically designed airborne or/and balloon-based campaigns;

ii) Identifying state-of-the-art and emerging technologies to populate and build the STRATELEC instrumentation package with new sensors in the perspective for implantation on stratospheric balloons, high altitude aircraft and even low-level drones to eventually propose new mission concepts to space agencies and Europe;

iii) Contributing to additional scientific returns on any space mission dedicated to lightning detection (e.g. ISS-LIS, ISS-ASIM, MTG-LI, GOES-GLM, FY4-GLI) and more generally to the study of electrodynamic couplings in the terrestrial atmosphere – ionosphere – magnetosphere system.

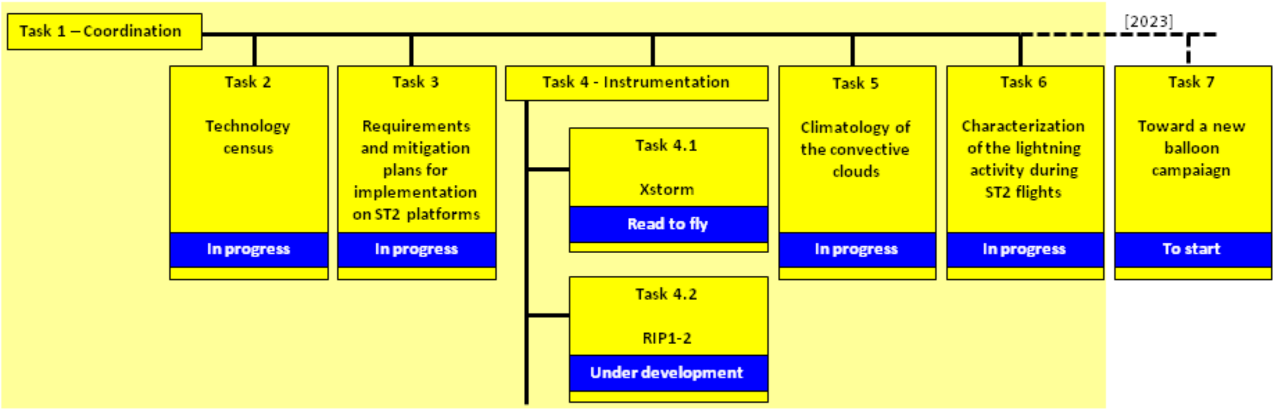

Figure 3. STRATELEC work breakdown structure (as of August 2022).

The STRATELEC consortium is currently composed of CEA (France), CNES (France), IAP (Czechia), IRSN (France), LAERO (France), LMD (France), and LPC2E (France). The project is supported by the French space agency CNES. The STRATELEC project is composed of 6 technical and scientific tasks (Fig. 3) with a new task expected to start in 2023 on the definition and the design of a new balloon campaign, with a comprehensive science and instrumentation plan, based on the lessons learned during the STRATELEC project and the last ST2 balloon campaign.

The STRATELEC project includes the census of state of the art and emerging technologies to populate and design the STRATELEC instrumentation package (Task 2, Fig. 3), the analysis of the requirements and the design of mitigation plans to implement STRATELEC instruments according to the specifications of the ST2 science and service gondolas (Task 3), the instrumentation design and making, laboratory testing and flight campaigns (Task 4), and a series of scientific studies on i) the characterization of the convection and lightning activity along the intertropical band covered by the ST2 program (Task 5), and ii) the study of the lightning activity along the Stratéole-2 flight trajectories (Task 6). A 7th task will start in 2023 on the design of a new balloon campaign combined with a specific science and observation plan based on the lessons learned during the STRATELEC project.

2.1. Focus on STRATELEC instrumentation package

As stated earlier, the STRATELEC project will benefit of several stratospheric balloon flights of the ST2 program. So far, the STRATELEC instrument package consists in a series of passive sensors such gamma ray spectrometers and broad band VHF receivers.

The XStorm sensor [13] is a gamma ray spectrometer inherited from that developed within the CNES OREO (Observation du Rayonnement Energétique dans les Orages) project [14]. XStorm has reached a sufficient maturity level for flying during the last ST2 campaign planned for winter 2024-2025.

The RIP1-2 (Radio Instrument Package for 1-2 component measurements) will measure the radio-frequency signal in the frequency band from ~1 kHz up to 40 MHz [15]. RIP1-2 is dedicated for measurements of broadband signals emitted by different lightning phenomena and for recordings of narrowband signals from radio transmitters modified by the lightning activity. This equipment will be the balloon-borne version of the BLESKA/SLAVIA instrument operated in Corsica (e.g. [16]) within the CNES SOLID (Space-based Optical Lightning Detection) project. A precise synchronization of broadband electric field measurements with a gamma-ray detector will allow us to correlate individual photon detections with electromagnetic pulses observed during the leader propagation. These simultaneous measurements may not only help us to investigate the place of TGFs in the lightning evolution processes but also to reveal the nature of the gamma glows.

The deployment of optical sensors (imagers and photometers) was initially considered. But because of the rather short period before the last ST2 campaign for development and testing, and because of limited telemetry bandwidth to transfer the scientific observations, no optical sensor will be operated during the 2024-2025 ST2 campaign. Note that the implementation of other sensors, like electrostatic field sensors, is still under evaluation.

2.2. Stratéole-2 flights and lightning activity

Two Stratéole-2 campaigns have already been conducted, one during the winter 2019-2020 (Fig. 4), the second during the winter 2021-2022. The flights of the 1st Stratéole-2 campaign have been used to design specific extraction methodologies of lightning and cloud data to investigate the lightning and cloud properties along the balloon trajectory.

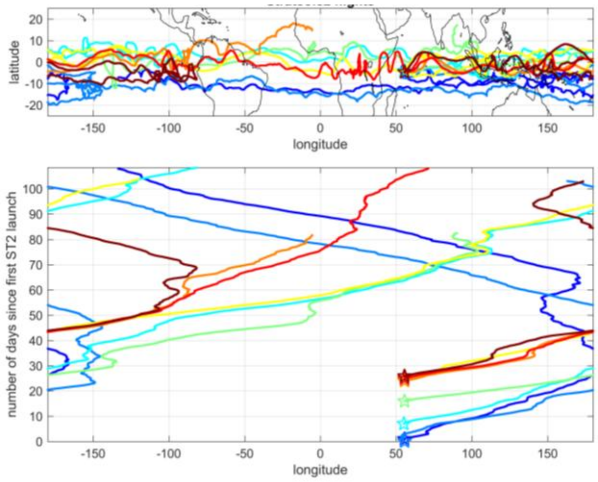

Figure 4. Balloon trajectories during the first ST2 campaign during winter 2019-2020.

Fig. 5 shows a typical overlay of the ST2 balloon track on cloud coverage as measured by the infrared geostationary ABI (Advanced Baseline Imager) imager during one flight of the first ST2 campaign. As the ST2 balloons are transported by the high-altitude air masses, thunderstorm development can be, totally or not, documented according to the location of the balloons relative to the convective clouds underneath. The use of sensors with wide angle field of view could mitigate the risks of partially documenting or missing thunderstorms. Side viewing sensors should also be considered but it would require the attitude of the gondola to be controlled or at least to be well characterized.

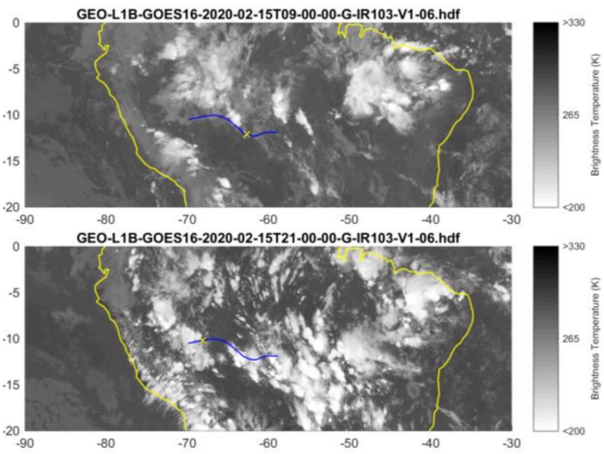

Figure 5. ST2 balloon location (yellow cross), daily track (blue) and infrared 10.3-µm cloud imagery on 14 Feb 2020 at 09:00 (top) and 21:00 (bottom) UTC.

Fig. 6 presents an example of a lightning flash detected by GLM over South America. GLM is a 777-nm camera operated with a 2-ms time frame. A lightning flash is detected as a succession of frames, not necessary contiguous, composed of illuminated pixels. Note that the GLM pixels are adjacent and are not plotted at their actual scale in Fig. 6. Fig. 6b shows that the ST2 balloon at 21:50:07 UT on 14 Feb 2020 was located above the cloud region where the maximal strength of the optical signal emanating from the cloud top has been detected. Fig. 6a shows a spatial shift of the lightning pixels relative to the cold cloud top region because of i) the motion of the storm (there is one ABI image every 10 minutes), ii) no parallax correction on the brightness temperatures, and iii) the possibility of the flash light to emerge from the north-east side of the storm in cloud region with low cloud top height.

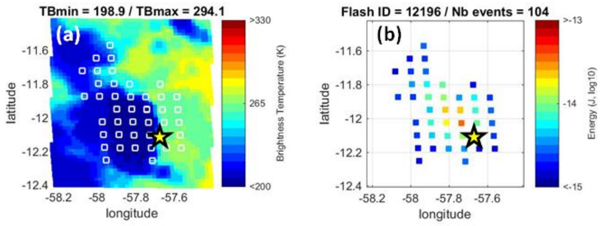

Figure 6. A lightning flash (14 Feb 2020 21:50:07 UT) as mapped by GLM below the ST2 balloon location (yellow triangle) overlaid on ABI 10.3 µm brightness temperatures (a) and mapped according to the strength of the optical signal emanating from the cloud (b). GLM pixels are not at the scale. ABI cloud observations are not parallax corrected.

Fig. 7a details few days of lightning observations collected along one ST2 flight over South America. Fig. 7b presents the lightning activity along the balloon track considering 3 different spatial windows, i.e. squares of ±3°, ±1°, ±0.1 side centered at the balloon location but with the same time window (±5 min). As expected the number of flashes decreases (for the present case : ±3° : 162971 flashes; ±1° : 16547 flashes; ±0.1° : 193 flashes) as the field of view of the instrument decreases. Fig. 7c also shows that the on-board data acquisition, processing and storage should be able to handle large rate of lightning activity according to the field of view of the instruments, the time window, the storm occurrence at (relative) close range to the balloon track, and the storm severity.

A tactical flight strategy where flight parameters are modified according to the weather nowcasting and weather forecast in the region of interest would definitively provide the observation basis to enhance the chances to record the properties of a storm during its entire lifecycle and to mitigate the probable challenges of building large field of view instruments. Additionally, commands sent to the instruments should be considered to trigger the data recording based on real time worldwide ground-based and space-borne lightning records.

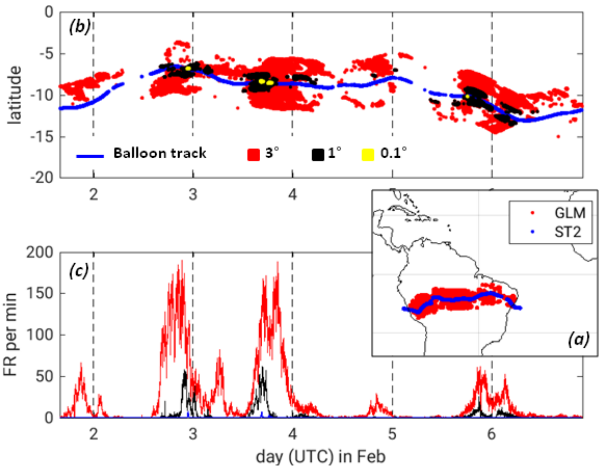

Figure 7. (a) ST2 balloon location and lightning activity, (b) time-latitude of ST2 balloon and lightning activity, (c) flash rate (FR) per min for 3 spatial windows (±3°, ±1°, ±0.1°) for 2nd ST2 flight (01 Feb18:00 UTC to 07 Feb 2020 00:00 UTC).

2.3. Thunderstorm distribution along ST2 coverage area

As ST2 balloon trajectories cover the Tropics (Fig. 4), the occurrence, strength and diurnal cycle of the lightning activity and the convection have been assessed using available satellite observations in order to consolidate the STRATELEC Science/Instrumentation Plan. Indeed, over the West hemisphere, 2 years of GLM-16 and GLM-17 data were used to document the lightning activity, while 10 years of 10.6 µm infrared SEVIRI (Spinning Enhanced Visible and InfraRed Imager) observations were used to quantify the occurrence of deep convective clouds over Africa. Comparisons with existing published cloud/lightning climatology built from low orbit passive/active remote sensing missions have also been conducted (not shown here).

Fig. 9 presents the lightning distribution recorded in 2020 and 2021 by the two GLM sensors over the Western hemisphere. Fig. 9a shows that the lightning activity starts increasing just after noon Local Time (LT) to peak between 18:00 and 19:00 LT. Most of the lightning activity is recorded over the South Hemisphere, mainly over the South American continent as shown in Fig. 9b and Fig. 9c. Even if only two years of data have been used to document the lightning activity over that region of Earth, the results obtained are consistent with what has already been discussed in the literature except that the data used here provide a continuous monitoring of the lightning activity as mapped from geostationary locations compared to low orbit space missions.

Data processing is underway to document the convection over Indian Ocean, Asia and Australia.

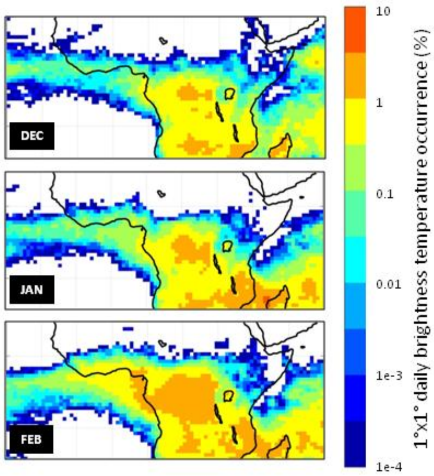

Figure 8. 10-year (2011-2020) monthly 1° latitude x 1° longitude deep convective cloud occurrence for December, January and February over the Tropics in Africa. Deep convective clouds are identified for SEVIRI 10.8 µm brightness temperatures below 200 K.

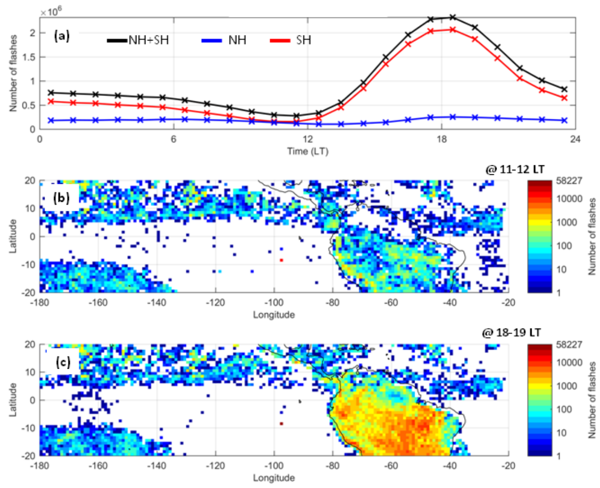

Figure 9. 2-year (2020-2021) December lightning distribution recorded by the two GLM sensors with (a) total number of flashes recorded between 20S and 20N latitudes, (b) distribution of flashes between 11 and 12 Local Time (LT), and (c) same as (b) but for 18-19 LT.

3. SUMMARY AND WAY FORWARD

The STRATELEC, supported by CNES, is an opportunity project taking advantage of the possible stratospheric balloon flights of the Stratéole-2 mission. Currently the XStorm gamma ray spectrometer is ready to fly while the RIP1-2 VHF receiver is under development. While optical imagers and photometers have been discarded from STRATELEC instrument package, other sensors like electric field mills are currently under evaluation for a possible deployment during the last ST2 campaign planned for winter 2024-2025.

Several studies have been conducted to quantify the climatology of thunderstorms over the West hemisphere Tropics and Africa based on satellite measurements. The same studies are underway over the rest of the tropical band. In addition, several software packages have been developed and used to extract and analyze the lightning and cloud information along ST2 flight path with adjustable time and space windows.

Thunderstorms are expected to be documented during the November-to-February period of the 2024-2025 ST2 campaign over the South Tropical band with a higher probability of occurrence over land. Analysis of the lightning activity recorded during the 1st ST2 campaign reveals that observations over ocean are also of interest as lightning flashes exhibit a stronger optical signal, and potentially stronger electrical currents.

The convection/lightning climatology suggests that the mapping instrumentation should be pointing mainly at nadir (lightning), on the side or upward (TLEs) with a sufficient knowledge of the gondola attitude required if imagers would be deployed.

A tactical flight strategy could be applied to increase the chance of collecting scientifically interesting observations with flight parameters modified according to the weather nowcasting and forecast in the region of interest. A mitigation plan would consist to operate instrumentation with large field of view. In addition, observations of operational satellite or ground-based lightning locating systems could be used to trigger on-board recording with a delay between a few seconds to <1 minute to optimize on-board storage and energy consumption.

The preparation for the opportunity ST2 flights will continue during the next years: it includes instrument design, laboratory and flight tests, and scientific exploitation of the measurements. The methodology to analyze the data will be refined as well to be applied almost in real time during the last ST2 balloon campaign scheduled for winter 2024-2025. Finally, the Consortium will start investigating a new balloon campaign by designing a (updated) comprehensive scientific and observational plan to address the STRATELEC objectives based on the experience gained during the 3 ST2 campaigns.

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