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What Happens Above Thunderstorms: First Operational Concept and Lessons Learned from the THOR Experiment during the Short Duration Mission on-board the International Space Station.

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Abstract

THOR, a European Space Agency experiment on the International Space Station (ISS), aims at imaging atmospheric and electric activity above thunderstorms, using optical cameras. More specific, the focus is on Cloud Turrets, mesospheric Gravity Waves, and Transient Luminous Events.

This paper describes the operational concept applied for the first series of observations. The lessons learned from this first series of observations are presented, and improvements for future observation campaigns are suggested.

The THOR experiment was firstly conducted during the Short Duration Mission (SDM) of Andreas Mogensen in September 2015. The observations were made using standard ISS camera equipment, following the instructions provided by ground on the targets of interest and camera settings to use.

The development of the operational concept for the SDM was challenging due to the different International Partners involved, the time constraints limiting the options for technical feasibility studies and the shipping and budgetary constraints allowing only available on-board equipment to be used. Consequently, compared to the initial scenario the experiment was strongly restricted in terms of the operational setup and scientific observations.

Despite these challenges the results obtained were above expectations. Among many observations of CTs and regular lightning, Andreas Mogensen managed to capture on film Sprites and for the first time a pulsing Blue Jet. Even with limited resources and non-specialised equipment, interesting observations could be made.

Keywords: International Space Station; atmospheric physics; observations; operational concept

Acronyms/Abbreviations

B.USOC	Belgian User Support and Operations Centre
CEO	Crew Earth Observation
Col-CC	Columbus Control Centre
CT	Cloud Turret
DOY	Day Of the Year
DTU	Technical University of Denmark
ESA	European Space Agency
ESR	Experiment Scientific Requirements
GMT	Greenwich Meridian Time
GW	Gravity Wave
IP	International Partner
ISS	International Space Station
NASA	National Aeronautics and Space Administration
PI	Principal Investigator
RSC	Rocket and Space Corporation
TLE	Transient Luminous Event
SDM	Short Duration Mission
USOC	User Support and Operations Centre
UV	Ultra Violet

1. Introduction

The European Space Agency (ESA) experiment, THOR, named after the god of thunder, lightning and storms in Norse mythology, was proposed by the National Space Institute of the Technical University of Denmark (DTU Space). It aims at imaging atmospheric and electric activity happening above thunderstorms from aboard the International Space Station (ISS) using optical cameras. The events of interest are Clouds Turrets

(CTs), Gravity Waves (GWs), and Transient Luminous Events (TLEs).

The first THOR observations were conducted in September 2015 by the Danish astronaut Andreas Mogensen during his Short Duration Mission (SDM), also called IrISS mission. The Belgian User Support and Operations Centre (B.USOC) was contracted by ESA to develop the THOR operations concept and was responsible for the operations preparation and execution of the experiment.

After describing the scientific objectives of the THOR experiment and the role of B.USOC, this paper is presenting the operational concept adopted during the SDM, the challenges encountered, the results and the operational lessons learned from the activities. Finally this paper investigates on alternate operations concepts as for future use of THOR.

2. Scientific Objectives

The scientific motivation for the THOR experiment is driven by the importance of water vapour as a greenhouse gas. The original scope of the experiment covered the investigation of water vapour transport from the troposphere to the stratosphere by thunderstorm convection on one hand, and the circulation in the stratosphere and mesosphere driven by internal gravity waves generated by thunderstorms on the other hand.

As a diagnostics for water vapour transport into the stratosphere the experiment focuses on so-called Cloud Turrets (CTs), which are formed in cumulonimbus clouds as a result of a strong, updraft motion in the cloud. Occasionally, the updraft motion in cumulonimbus clouds gets so strong that the cloud turret penetrates the tropopause for short period of time (typically less than an hour) [1, 2, 3].

Gravity Waves (GWs) driven by severe thunderstorms, may travel to the stratosphere and mesosphere, where they can be detected as wave-like patterns in the airglow layer [4]. GWs have an important role in the transfer of energy, momentum, and chemical species between the different atmospheric layers and in the subsequent influence on upper atmosphere winds, turbulence, temperature, and chemistry. As such they are of importance for the water vapour circulation in the upper layers of the atmosphere [5,6].

The lightning activity, the formation of CTs and the mesospheric GWs intensity increase with increasing convection in the thunderstorm cell [7, 8]. A reliable correlation between lightning activity on one hand and CT and GW formation on the other hand could allow global observations of lightning activity to be used as a proxy for quantifying water transport to the upper layers of the atmosphere. This proxy could be included in climate models, increasing their accuracy.

The ISS offers a platform to observe thunderstorm regions with optical cameras, allowing to better understand how lightning activity correlates to CTs formation and mesospheric GWs. Additionally, it is well known that large thunderstorm cells are the origin of electrical discharges in the stratosphere and mesosphere, also referred to as Transient Luminous Events (TLEs) [9, 10, 11]. TLEs cover various types of electrical-discharge phenomena in the upper atmosphere, high above large thunderstorms, with a lifetime varying between 1ms and 300ms. Different types of TLEs have been identified (Figure 1), including relatively slow-moving fountains of blue light, known as ‘blue jets’, which emanate from the top of thunderclouds up to an altitude of 40km; ‘sprites’ that develop in the mesosphere with bottom tendrils moving downward at speeds up to 10000kms^{-1}; ‘elves’, which are lightning induced ionospheric light emissions that can spread over 300 km laterally; and upward moving ‘gigantic jets’, which electrically connect thundercloud tops and the lower ionosphere. Blue Jets occur much less frequently than sprites and are also believed to be more difficult to observe from ground due to the severe Rayleigh scattering of blue light in the atmosphere [12]. The optical observations of thunderstorms from the ISS offers the opportunity to quantify the occurrence of TLEs within thunderstorms [13], and more specific the Blue Jets and Gigantic Jets which are rarely observed from ground.

The most severe thunderstorms occur over the tropical and subtropical regions, which are not always easy to access from ground (see TLE and GW captured from the ground in Figure 2). The ISS orbit offers an almost complete coverage of these regions; moreover, the ISS is the lowest orbit observational platform available, which makes it suitable for the type of observations the THOR experiment is interested in. The ISS also offers the opportunity to study these events in optical bands that are much less absorbed when seen from space than from ground.

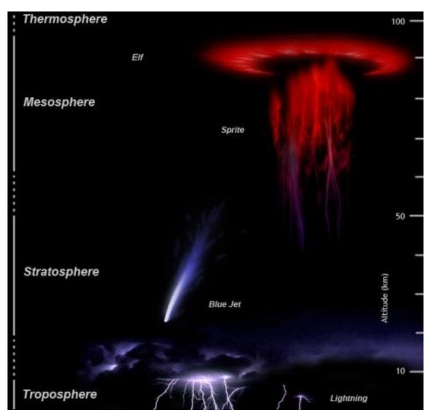

Figure 1: Classification of the different types of TLEs, their structure, and their altitude. [Credit: Abestrobi]

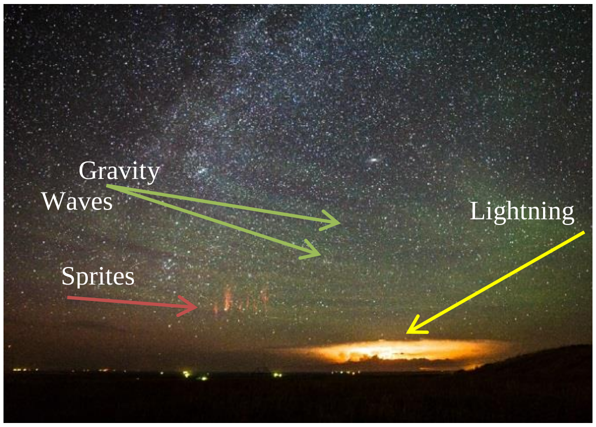

Figure 2: Observation of large thunderstorm from South Dakota, showing lightning, sprites, and gravity waves. [Credit: Tom A. Warner]

3. Role of the USOC

A network of seven USOCs, spread around Europe, is a decentralised concept adopted by ESA in the nineties to operate European payloads aboard the ISS. The mission of the USOC network is to provide operational services for scientific institutions and space agencies. They constitute a link between the scientists and the space station world. Starting from the scientific requirements, the users centres establish an operational concept in close collaboration with the Principal Investigator (PI) and the Payload Developer (if any), this within the ISS constraints and in coordination with the International Partners (IP). In practice, the USOC develops crew and ground procedures, supports the crew training, and prepares all the operational products. Once the payload or the experiment is onboard, USOC operators monitor and control the instruments in real-time, plan the scientific activities and troubleshoot anomalies. Finally the USOC is responsible for the distribution and archive of the data.

Most of the USOCs are connected to the Columbus Control Centre (Col-CC) in Munich, the operations centre of the European Laboratory Columbus.

4. Preparation Phase

ESA assigned the THOR mission to B.USOC in October 2014, at a time when the Experiment Scientific Requirements document was under development [14]. The THOR experiment was to be conducted during the 10 days flight of Andreas Mogensen in September 2015, with the objective of demonstrating its technical feasibility. Andreas Mogensen's time onboard was to be allocated to many experiments, and crew time allocation to THOR was undefined.

No budget and time was available for payload development, and the upload capability was limited in weight, therefore the experiment had to be performed with equipment available onboard.

The scientific requirements were very challenging to be implemented in less than a year. The original ESR required high accuracy of the pointing direction (< 5 degree in the reference system), a mounting device to ensure good stability of the camera system for limb observation, a telescopic lens to catch CTs, and a high speed and resolution camera for the TLE observation (>20 frames/s at >2000x2000 pixels).

THOR can be seen as three experiments in one. The three types of events to be observed, CTs, GWs and TLE's, have different characteristics and specifications for observation, as shown in Table 1. Therefore different hardware requirements and constraints were to be considered.

Table 1: Events characteristics and observation specifications

	CT	GW	TLEs
Pointing Direction	Limb – no Sun in FOV - 90°-60° from Nadir	Nadir 0°-30° from Nadir	Limb 90°-60° from Nadir
Observation bands	428 nm 630 nm	630 nm	Broad optical range
Time of observation	Afternoon (630 + 428nm) Night (428 nm)	Night	Night
Event duration	< 1 hour	Continuous	1ms - 300ms
Altitude	10 km - 15 km	90 km - 95 km	10 km - 80 km
Shape and orientation	Vertical extended cloud	In the airglow layer; Wavelengths from 10 km - 100 km	Vertical, funnel, or carrot shape
Dimension	10 km x 5 km	500 km x 500 km	50 km x 50 km

Cloud Turret observations of interest focus mainly on the top of the clouds (8-20km altitude) to observe their vertical extent. CTs are therefore best observed near the limb, ideally in two different optical bands: one near the UV at 427.8nm during the night and a red band at 630nm during the day, to yield information on the distribution of ice crystals extending into the stratosphere.

Gravity Waves are observed only during the night time, looking toward nadir in a red band filter (630nm).

The TLE observations are made limb-viewing, covering a broad spectral band in the visible spectrum.

The preparation phase started with a technical feasibility assessment. Two locations permitting Earth observation were looked at: the Cupola and the Pirs module.

The Cupola, the panoramic observation dome looking down to the Earth, allows for nadir and limb observation. The 2 windows (port and starboard) of the Pirs module offer a good spot for limb view. (See Figure 3).

Figure 3: The Cupola (foreground) and Pirs module with the port window (background). [Credit: ESA/NASA]

The Pirs module on the Russian segment is providing a docking port for Soyuz and Progress vehicles, and is sometimes used by the crew as a sleeping compartment. Very little information was known about the module and no direct contact with the Russian space agency (RSC Energia) was possible.

In November 2014, ESA met RSC Energia and discussed the implementation of some experiments of Mogensen's flight. For THOR, RSC Energia granted access to the Pirs module, and stated that some crew time will be necessary to clear-up spaces in front the windows.

The Cupola, on the American segment, is a dedicated module for the observation of the Earth, the ISS exterior and the visiting vehicle. It hosts the robotics workstation to control the space station's robotic arm. The use of the Cupola is ruled by several flight rules such as the windows having to be covered by the shutters during thruster firing, which occurred regularly on the station. In addition, the use of a telescopic lens required by the original ESR, was not permitted inside the Cupola.

Since THOR was not included in any increment requirements documents ESA and NASA shared, limited technical support could be requested to NASA in the preparation phase, i.e. with regards to the utilization of the Cupola, or on the on-board media equipment.

For what concerns the selection of cameras, the Nikon D4, the highest quality camera on-board, was selected to catch CTs and TLEs.

For GW, the Nightpod with the Nikon D3S was suggested. The Nightpod stand installed on the inside structure of the Cupola with the camera pointing nadir, can take sharp pictures of Earth at night. The movement of the ISS with respect to the target of interest is automatically compensated. As such, the subject stays centred in the frame so the final image is in focus. By using NightPod, an accurate pointing direction can be obtained to observe GW. The NightPod infrastructure can only be used in the Cupola and is not compatible with the Nikon D4 camera, and therefore was not suitable for CT and TLE observations.

For limb observation, no mounting structure offering a pointing accuracy is available onboard and at the Russian SDM meeting in November it was advised to perform the activity free floating.

Hardware available onboard did not match the required specifications precisely. Therefore ESA and the PI agreed on the relaxation of several requirements such as the suppression of the telescopic lens, reduction of the pointing accuracy, increase of filter bandwidth, or reduction of the pixel size for TLE observation.

End of 2014, BUSOC proposed to drop one objective: the observation of GW. By focusing on the limb observations, the observation could be performed in one location with a single camera, and the chances of achieving readiness on time were augmented.

Finally it was decided to observe CT and TLE with the D4 camera from the Pirs module, and this in free-floating position. The transmission properties of the Pirs windows were known to be very good, and the module appears to have very few operational constraints.

ESA negotiated with NASA the use of one D4 camera dedicated to THOR during the whole SDM mission. After which the support from NASA photo-TV Group was granted.

The camera settings were discussed and defined with the science team and further fine-tuned in collaboration with the experts from the NASA Photo-TV Group responsible for the D4 camera on the station.

Then B.USOC established an operational concept in coordination with all parties involved: Science Team, the ESA planning team, the ESA Mission Directors and the ESA Mission Science Office.

Crew procedures were developed to set-up the D4 camera, and provide the different steps required for each CTs and TLEs observation sessions. These steps are summarized as follow:

- Synchronise camera time with GMT time (time of observation was required with a desired accuracy of 10ms).
- Installation of the lens (24-70mm for CT, 58mm nocturnal lens for TLE).
- For CTs:
    - o Apply settings: shutter speed 1/1000s, ISO sensitivity 200, RAW quality.
    - o Point on the thunderstorm and center the image on a Cloud Turret, take a picture.
    - o Zoom in on the CT, take images at a rate of 1 image per second, and follow the CT as long as possible.
- For TLEs:
    - o Apply settings: shutter speed 1/25s, ISO sensitivity 6400, RAW quality. Movie settings: Frame size 1920x1080, frame

rate 24fps, ISO Sensitivity Range A12800.
- o Before the thunderstorm is observable take one image of the star field (for on-ground calibration).
- o When the thunderstorm is observable, go to movie mode, point and focus on an active storm region as long as possible.

- Downlink imagery files right after the session.

Before the launch, Andreas Mogensen received a THOR dedicated training, to help him recognise and image thunderstorms and CTs from the ISS, and to familiarize him with the procedures.

5. Execution and Scientific Results

During the mission, a team of scientists associated with the PI performed, on a daily basis, a thunderstorm forecast to maximize the chances of successful observations. Due to the long lead-time needed by astronaut activity planners, a target list was produced every day for the next three days. The target list included prediction of storm position, time of overflight, pointing angle relative to the ISS and a priority flag indicating the importance of convection in the storm [15].

At B.USOC, an operator was sitting on console 16 hours per day (divided in 2 shifts) to prepare the planning inputs, support – in case needed - the crew while performing THOR, and to keep a situational awareness of the mission. Every day the operator verified the targets list sent by the science team, specified which targets had the best relay satellite coverage (in case crew would request support from ground), and sent the list to the ESA planning team at Col-CC. The original operational concept foresaw the inclusion of the targets list on a daily basis, into the so called “Tasks List”. The crew selects a task from the Task List and performs it during his free time at his best convenience. Since Andreas Mogensen’s free time was scarce, a more secured option was to hard-schedule an observation session in his timeline.

The execution of the experiment in real time was somewhat different to the pre-defined operational concept. This was mainly due to real-time organisational decisions and the reshuffling of the SDM on-orbit planning due to the 2-day delay of the start of the mission following the obliged change of the Soyuz vehicle approach from a 4-orbit approach to a 34-orbit approach. The main changes to the THOR operational concept and the actions making the mission more challenging were the following:

- No target lists would be provided as crew message to the crew before the crew had performed the setup activity for the dedicated camera to be used, had had a familiarisation tour of the PIRS module by their Russian colleagues and had had their first hard-scheduled THOR observation. The first hard-scheduled observation was only scheduled on Flight Day 7.
- The whole list of THOR targets observable each day would not be put on the Task List anymore. Andreas Mogensen would only execute hard-scheduled THOR activities.
- A daily reshuffling of planning due to the nature of the mission.
- No daily downlink of the obtained data during observations.

Despite the challenges and changes in operational concept, the high level achievements of THOR on a best effort basis were set as completed [16]. Two hard-scheduled THOR sessions with successful observations and two other THOR related target observations were performed outside scheduled slots. A summary of the performed observations for THOR with the day of observation, the type of target observed and the amount of images or video duration obtained is represented in Table 2.

Table 2: Summary of the obtained files for the performed THOR observations during the SDM, sorted by date and by target type.

Day of Observation (2015)	Target Type	Images count	Video duration
Day Of the Year 249	Time Sync	3	
DOY 250	Calibration	176	
DOY 251	CT	160	
DOY 251	Calibration	3	
DOY 251	TLE		2’40’’
DOY 252	Calibration	59	
DOY 252	TLE		6’30’’
DOY 254	Calibration	26	
DOY 254	TLE		6’20’’

One CT session and three TLE sessions were obtained. The amount of required sequences to proof the technical demonstration of the THOR experiment during the SDM was achieved (the requirement was to obtain a minimum of two observations of both CTs and TLEs).

Andreas Mogensen performed several observations from the Cupola instead of the requested Pirs module. As reported by Andreas Mogensen after the mission, the Pirs module is not convenient for TLE/night observations as there is a lot of light from the neighbouring modules (Zarya and Rassvet) which contaminates the observation and the inner lights cannot be switched off as other crew is present.

In addition the Cupola offers a wider view, facilitating observations. The Cupola allows to have a lookout next to the camera to pinpoint the location of the main thunderstorm, interesting details and targets while filming.

The data down-link requirements specifically for the SDM were only partially fulfilled. As per requirement, the whole set of frames should have been downlinked within a few hours after the performed observation. Despite BUSOC efforts in setting-up a good and efficient data downlink process, the process was not fixed or known by all involved parties at the start of the SDM and the whole downlink concept had to be reset in real-time. This delayed the downlink of the data of the performed THOR TLE session and some data was only retrieved after the end of the SDM.

Considering the short duration of the mission and the few number of observation attempts, the results of the mission was globally good scientifically. Unfortunately, the successfully recorded pictures of CTs during daytime were of too poor resolution to be exploited scientifically (see Figure 4). Fortunately, among the 3 successful observations performed during night time, the one performed on DOY251 has reached scientific interest above expectations. The observation was made from the Cupola, while tracking the thunderstorm activity over the Bay of Bengal. It contains clear imaging of the CT lightened by lightning flashes, a Sprite, a Blue Jet (see Figure 5) and numerous blue discharges at the top of the cloud [17].

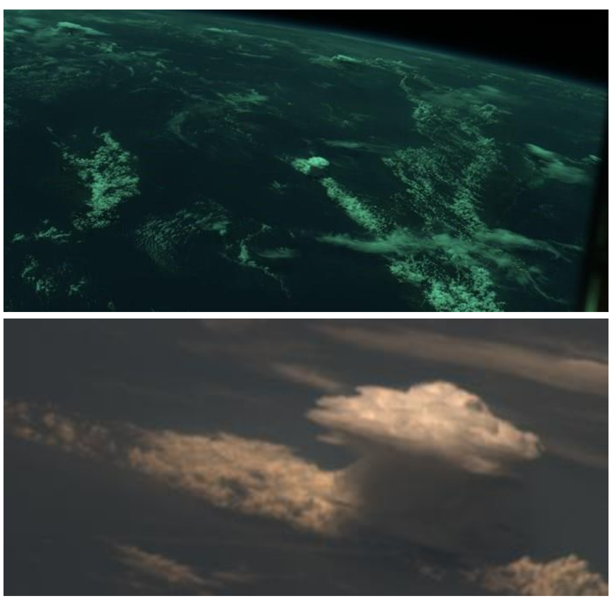

Figure 4: Images of a Cloud Turret taken from the ISS/Pirs module (wide view and zoom) (Credit : ESA, DTU Space)

Figure 5: Image of CT lighten by lightning flashes (top panel), of a Sprite (middle panel), and of a Blue Jet (bottom panel) taken from the Cupola. (Credit : ESA, DTU Space)

6. Lessons Learned

A list of operational lessons learned from the SDM mission preparation and operations execution is provided below:

- In case the transmission properties of the Cupola is, after technical investigation, deemed good enough, it would be recommended to use the Cupola for TLE observations. The Cupola

has a wider view which makes it possible to have a lookout next to the camera to see where the main thunderstorm, interesting details and targets are while filming.
- Use technical reports to support decision, such as the choice of windows for limb observation.
- Using on-board nominal materials reduces the cost obviously, but also the crew training required. All crew are trained to use the onboard cameras equipment.
- Support from ground during the observation was not needed, most of the operator tasks on console were focused on planning activities.
- A clear and regular downlink of images should be set up and agreed with IPs.

7. Alternate Operational Concepts

The experience of the SDM showed that even though we reached the main objectives of the THOR activities, the operational concept could be improved to have a smoother run in possible future missions.

The main problem that was encountered is that as thunderstorms are changing phenomena and cannot be temporally fixed a long time in advance, it is difficult to hard-schedule these events within the ISS on-orbit planning. We would recommend to follow a similar approach as for the Crew Earth Observations (CEO) activity, or even to collaborate with the CEO team as they have plenty of experience in Earth photography. If so, the THOR targets could be displayed in the crew daily timeline where the crew would find all the necessary information to perform the observation (procedure, additional target information). The Cupola is a very popular module offering a spectacular view, if the crew would know about THOR they might take the opportunity to chase CTs and TLEs while chilling in the dome.

Another issue that would ask for a concept change was the difficulty of performing limb observations and taking videos from the Pirs window. Crew stated that the Cupola was much better adapted for this. However, the videos taken from Cupola were of medium quality since the astronaut was free floating which made it difficult to maintain a storm in a fixed position in the video. The used equipment could also influence this. For TLE observations, a standard optical camera might not be the best choice. Although some Sprites and Blue Jets were captured, a more dedicated equipment could provide a higher scientific return. In case this experiment is continued on the long run, the PI might want to invest in a high speed camera, a filtered one and/or a mounting structure.

8. Conclusion

The technical study of the available equipment onboard and the development of the operational concept was challenged mainly by the time constraint and the lack of support agreements with the IPs. The ten days flight of Andreas Mogensen were fully packed with many ESA experiments, in which THOR was conducted on best effort basis. Nevertheless, the teams involved in THOR managed to proof technical feasibility of the experiment. CTs were caught successfully from the Russian segment, and thanks to Andreas Mogensen’s initiative, fortunate movies of thunderstorms were taken from the Cupola including nice shots of different types of TLEs.

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