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Low-Latitude Ionosphere/Thermosphere Enhancements in Density Mission (LLITED): Results and Challenges

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ABSTRACT

The Low-Latitude Ionosphere/Thermosphere Enhancements in Density (LLITED) mission, a two 1.5U CubeSat mission to study nighttime ionosphere/thermosphere coupling, was successfully launched in the spring of 2023. While the CubeSats successfully reached orbit, the final orbit differed from the planned orbit. Both LLITED-A and LLITED-B spacecraft completed early orbit check out and commissioning, but due to a solar cell anomaly are operating with a significant reduction in power. This has resulted in a much lower duty cycle for each of the three science payloads: an ionization gauge (MIGSI) to observe neutral density, a planar ion probe (PIP) to observe plasma density, and a GPS radio occultation sensor for observing (CTECS-A) total electron content. The combination of the operating orbit and power budget has required a refocusing of the mission science goals and a highly tailored ConOps. Despite these challenges, LLITED-A/B has provided exciting observations of small-scale density structure evolution, neutral atmospheric variability across the cusp boundary, and neutral and plasma density structure coupling.

MISSION OVERVIEW

The NASA Heliophysics funded Low-Latitude Ionosphere/Thermosphere Enhancements in Density or LLITED (pronounced as "lighted") mission consists of two 1.5U CubeSats. Each CubeSat host three science payloads: 1) Miniature Ionization Gauge Sensor (MIGSI), 2) Planar Ion Probe (PIP), and 3) GPS radio occultation sensor known as the Compact Total Electron Content Sensor-Aerospace (CTECS-A). The LLLITED team consists of The Aerospace Corporation, (lead institution and CTECS-A lead), Embry-Riddle Aeronautical University (PIP lead), and University of New Hampshire (MIGSI lead).[1]

Figure 1 shows different aspects of one of the LLITED flight CubeSats prior to its delivery to Momentus in February 2023. The two primary sensors, PIP and MIGSI, are located on the ram face (Figure 1, right panel). Following their delivery, the CubeSats were integrated into the Momentus orbital transfer vehicle, Vigoride-6, which was subsequently integrated onto Space-X's Transporter-7 mission which was successfully launched 16 April 2023 at 0647 UTC from Vandenberg Space Force Base. LLITED was one of 15 missions deployed from Vigoride-6 and it was released into orbit on 15 May 2023 at 2324 UTC into a 513.8 km x 495.7 km orbit at a 97.4° inclination. Early orbit commissioning began in late June and nominal operations began in September 2023. A one-year operational mission life is planned with a current estimated date of re-entry for late fall of 2024.

Originally, LLITED planned on operating all three science payloads on the nightside for approximately 5-7 orbits a day to study the Equatorial Temperature and Wind Anomaly (ETWA) and the Equatorial Ionization Anomaly (EIA). However, there were many technical and programmatic challenges during the development and deployment of the LLITED mission which has been described in-depth along with how they were addressed or mitigated, and the lessons learned.[2] The two most significant challenges that affected the ability to achieve the proposed science mission was insertion into the incorrect orbit and the solar cell anomaly resulting in the substantial loss of power generation capability. These together prevented LLITED from addressing the originally proposed

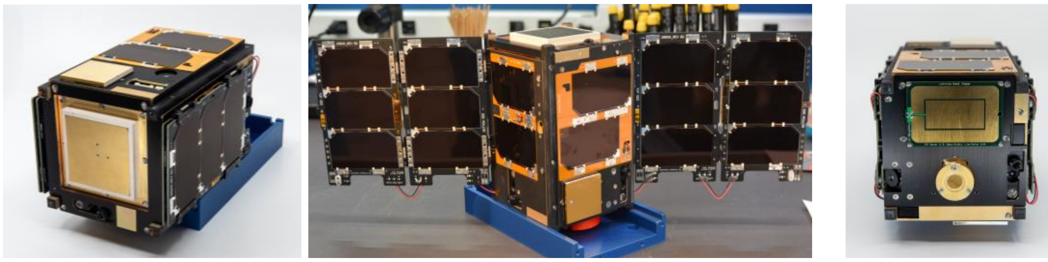

Figure 1. Fully assembled LLITED CubeSat prior to delivery showing the stowed configuration with the CTECS-A antenna on the top side (left), bifold solar panels deployed (center), and the ram face displaying the collection plate of PIP and circular aperture of MIGSI (right).

science questions. The overall focus of the mission shifted to investigating the nightside feature of the Midnight Density Maximum (MDM)[3,4]. The revised mission objectives are:

1. What is the short-term (<45 min) mesoscale variability of the Midnight Density Maximum during elevated solar cycle conditions as a function of season, and longitude/latitude as well as its relationship to EIA?

2. What is the relationship between neutral winds (i.e., tides) and the pre-midnight EIA zonal structure?

3. Are the small-scale wave fluctuations in neutral atmosphere quantities, such as those observed by earlier missions exhibited in the ionospheric density closer to midnight?

The above science questions were developed immediately following LLITED's orbit insertion into a sun-synchronous orbit with the local time of the ascending node (LTAN) of 1030, which was unsuitable for studying the ETWA and EIA but appropriate to study the MDM. Unfortunately, the solar cell anomaly and subsequent degradation in power, which began approximately 3-weeks after initial turn-on, required further tailoring of the science mission. The priority was to maximize the science returns from LLITED, and a strategy of focused studies interleaved with on-going MDM observations was adapted.

To-date, 10 focused science studies or campaigns have been planned in addition to the core MDM study:

1. October 2023 partial solar eclipse. Data collection occurred over three orbits over the eclipse path. Both MIGSI and PIP collected observations on LLITED-B.
2. Investigate neutral density variations over a solar rotation. Observations over two rotations completed and more planned. Special emphasis was given to high latitudes beneath the magnetospheric cusp.
3. Support for the Dissipation Rocket Campaign. In November 2023, LLITED provided observations of the neutral and plasma density during launch window to provide contextual information.
4. Differential drag experiment. An experiment that will collect position data with one vehicle in a high drag orientation and the other in a low drag orientation when the vehicles are in close proximity. Will test a new technique to extract neutral density observations.
5. April 2024 Full Eclipse. MIGSI and PIP completed observations before, on the edge of totality, and after along the path of the solar eclipse.
6. Coincident neutral density observations between LLITED-B MIGSI and the PIANO sensor on the ISS. Six coincident observations collected and are under analysis.
7. Small-scale density structures. Concurrent LLITED-A/B PIP observations. LLITED-A observes three concurrent orbits to examine evolution. LLITED-B PIP collects during one of the orbits to provide spatial information.
8. Coincident PFISR observations. Utilizing the PFISR 11 beam mode, compare ionospheric density structure and drifts to density structures observed by LLITED-A/B sensors.
9. Coincident EISCAT observations. Through an accepted EISCAT proposal, 24 hours of EISCAT observations coincident with LLITED will investigate spatial and temporal

relationships between the cusp and upwelling events.

10. Coincident MIGSI and all-sky image comparison. Obtain dayside cusp observations from Kjell Henriksen Observatory on Svalbard for comparison to cusp density structures observed by LLITED overflights. Utilize APL Alaskan all-sky imagers in the auroral zone.

CONOPS

Prior to launch the ConOps plan was to complete early orbit checkout and commissioning of both CubeSats and all science instruments within 8-weeks. As part of the payload checkout, the sensors would be cross validated when the separation between the two CubeSats was minimal. LLITED-A/B would be separated over several months using differential drag until they were between ¼ to ½ orbit separated. Based on the designed power-budget and requested orbit, there would be two operational modes: sun-safe and mominal payload operations. The sun-safe or solar inertial would be 24-hours long and the vehicles would orient the bi-fold panels for maximum power collection. This mode would last 24 hours. During the nominal payload operational mode, the vehicles would maintain local-vertical-local horizontal (LVLH) pointing over 24-hours with the exception of a minor orientation change to point the panels towards the sun on the dayside. The payloads would operate and collect data between $\underline{+}$45 latitude. Payloads would operate for 2-3 consecutive orbits followed by 1-2 orbit with the payloads powered off to maximize the length of time between required solar inertial modes. Three ground contacts were planned per day with a nominal contact time of six-minutes each. The regular ConOps plan would enable utilization of the ground-station automation. At the time of launch, there were six ground stations located in Maine, Texas, Michigan, Vandenberg Air Force Base, and Hawaii.

Because of the different orbital configuration and power limitation, the LLITED ConOps plan was significantly modified and continues to evolve. The realized power is less than 50% than planned for. Thus, the two primary instruments, PIP and MIGSI, have been prioritized. MIGSI requires the most power and limits the amount of time payloads can operate. Further, while both MIGSI sensors are operational, MIGSI on LLITED-A is not as stable and the resulting data has more artifacts. It was decided that LLITED-B would focus on simultaneous collects of MIGSI and PIP, and LLITED-A would utilize PIP only. LLITED-B collects data 1-2 times per day. Collection times range from 23 minutes to 40 minutes. The remainder of the time the attitude control system is turned off to conserve power and the CubeSat tumbles and charges the batteries. LLITED-A schedules three consecutive PIP collects of 35 to 45 minutes in duration before battery charging is required.

Another consequence of the reduction in available power involved maneuvers and ground contacts. The power reduction has prevented undertaking any differential drag maneuvers to separate the CubeSats. The separation between spacecraft has been allowed to occur naturally. This has complicated ground contacts. For both CubeSats to utilize the same ground station on a given orbit, they must be separated by at least 15-minutes. That separation occurred approximately five months into nominal operations. Prior to that, priority was given to LLITED-B in order to obtain simultaneous MIGSI and PIP collects.

In addition to the on-orbit challenges, there has been several ground station issues. The two stations that provided the most reliable contacts for LLITED, Maine and Hawaii, went off-line in April. The Hawaiian station was permanently removed because of site limitations while a hardware issue caused Maine to go off-line. Maine will be coming back on-line early summer, but the loss of those stations has impacted the scheduling and downlink cadence, further reducing the number of science data collects.

All of these challenges have required a much more hands-on effort by ground operators than originally planned. They have worked to modify the automation capabilities of the system to accept asynchronous scheduling. They have also worked to optimize the power usage of the various CubeSat subsystems to maximize the available power for science operations.

FIRST LOOK SCIENCE RETURNS

Despite the challenges described in the previous sections, the LLITED CubeSats have obtained exciting observations of the thermosphere and ionosphere. This section presents initial observations of phenomena at various latitudes.

Low-Latitude Plasma structures

The PIP sensor is capable of a changing the sampling rate through commanding up to a maximum sampling rate of 100 Hz. Over the course of the mission the PIP sampling rate varied between 100 Hz, 50 Hz, and 16 Hz depending on the science focus and available ground station resources. During the early portion of the mission 100 Hz was utilized. Currently both PIP sensors are using a 50 Hz sampling rate. Figure 2 shows two examples of ion density data at the 100 Hz sampling rate for 22 December 2023 (top) and 12 February 2024 (bottom). The small panel below each observations shows the ram angle of LLITED-B with the red lines indicating the ACS activation.

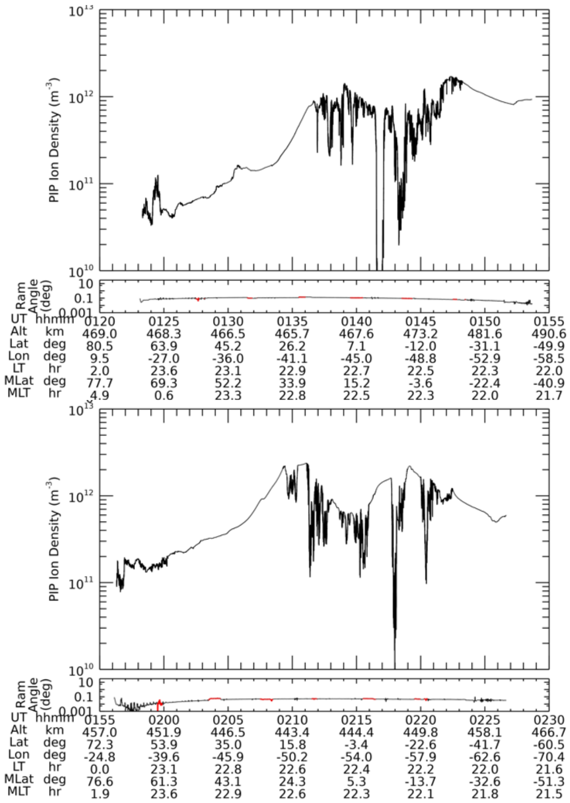

Figure 2. Examples of small-scale plasma depletion structures at low latitudes as observed by LLITED-B PIP on 22 December 2023 (top) and 12 February 2024 (bottom).

Both panels of Figure 2 show significant ion density depletions at low latitudes. Large depletions greater than $6x10^{11}m^{-3}$ occurred on both sides of the magnetic equator for both collections. Small spatial scale depletions are observed beginning ~20 mlat and extend across the magnetic equator into the southern hemisphere.

Auroral Zone

At the beginning of nominal operations LLITED-A & B were separated by a few 100 km. Figure 3 shows simultaneous LLITED-A/B PIP collects when the CubeSats separated by less than 30 seconds or ~220 km. The LLITED-B PIP data has been shifted in time to be coincident in space to the LLITED-A PIP data. The data is interesting for several reasons. First, the features in the ion density profiles are nearly identical in space with minor variations. This is the first-time orbital ion density has been observed at such fine temporal and spatial scale and it captures the relative stability of the plasma features. Second, the orbit crosses the cusp region, shown in yellow. The data to the left of the green dotted line in Figure 3 was collected as LLITED crossed the auroral zone. The PIP data shows the expected ion density ion density variations that are relatively stable. The cusp region generally sees an increase in plasma density. However, the large variations containing sudden increases in density that are quickly moving within the cusp is surprising.

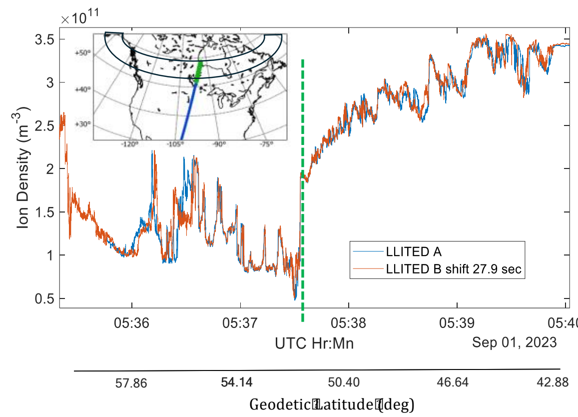

Figure 3. PIP ion density observations from LLITED-A/B showing small-scale relatively stable structures as they traverse the cusp region.

HIGH LATITUDE

Figure 4 shows observations from both MIGSI (top) and PIP (bottom) as LLITED-B traverses the northern hemisphere high latitude from the dayside to night. The cusp region is observed twice. As expected on the dayside, the thermosphere and ionosphere are varying smoothly with small variation in pressure and density. Once the dayside cusp is entered, the regions begin to exhibit significant variability. The MIGSI pressure data, which is proportional to neutral density, experiences a sudden increase. Further, there are wave like pressure variations with ~500 km wavelengths observed across the entire polar cap. While these wave-like structures were not common earlier on in the mission, they have been more routinely observed as the CubeSats descend below 440 km and geomagnetic activity has increased. At the same time there are small-amplitude density structures and some larger-scale variations. Further analysis is required to understand the extent of coupling between the neutral and plasma density.

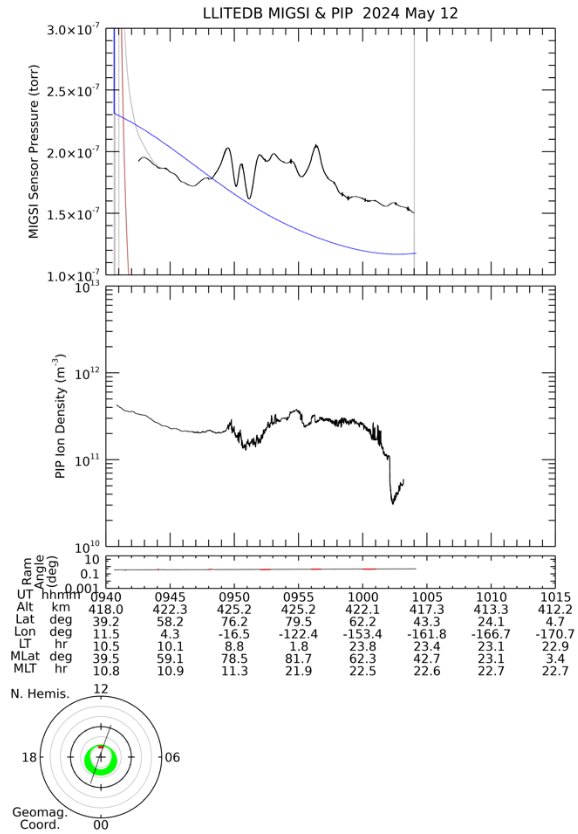

Figure 4. Observations from LLITED-B as it traverses the southern hemisphere cusp region. Top: MIGSI pressure (black), MSIS (blue). Center: PIP ion density. Bottom: LLITED-B orbit crossing cusp (green).

SUMMARY

The LLITED CubeSats are stable and routinely collecting thermosphere and ionosphere observations. Despite the orbital, power, and ground system challenges LLITED has provided new and intriguing observations of density structures. The challenges experienced have required flexibility both in terms of ConOps and science focus. In addition to the core MDM observations, LLITED science returns are being maximized through focused observational campaigns, such as the two solar eclipse events.

The science data from the LLITED mission will be publicly available this summer in netcdf format. A more detailed mission paper and individual instrument papers are in preparation and are planned to be submitted later this year.

Acknowledgments

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