The Limb-Imaging Ionospheric and Thermospheric EUV Spectrograph: Design and First Results

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# The Limb-Imaging Ionospheric and Thermospheric EUV Spectrograph: Design and First Results

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**SUPPLEMENTARY NOTES**

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**ABSTRACT**

This report presents the design, implementation, and performance of the LITES experiment. LITES is a high-throughput, compact, ultraviolet imaging spectrograph that collects altitude profiles of the ionosphere and thermosphere above the limb of the Earth. LITES was flown as a demonstration experiment to the International Space Station as part of the DoD Space Test Program STP-H5 experiment pallet. This flight represents the first application and demonstration of this sensor design to ionospheric and thermospheric imaging and has advanced the TRL of this sensor concept from 4 to 7.
CONTENTS

1. MOTIVATION ................................................................................................................. 1
   1.1 Background .............................................................................................................. 1
   1.2 Measurement Objective 1: Nighttime Ionosphere .................................................. 4
   1.3 Measurement Objective 2: Daytime Ionosphere ...................................................... 5
   1.4 Measurement Objective 3: Daytime Thermosphere .................................................. 5

2. EXPERIMENT DESCRIPTION AND APPROACH .......................................................... 6
   2.1 Optical Design and Development ........................................................................... 6
   2.2 Mechanical Development ....................................................................................... 9
       2.2.1 Wedge Mount ..................................................................................................... 9
       2.2.2 Door Mechanism ............................................................................................. 10
       2.2.3 Spectral alignment ......................................................................................... 12
   2.3 Concept of Operations ............................................................................................ 12
   2.4 Power and Data Interface ....................................................................................... 13
   2.5 Command and Data Handling ............................................................................... 15
       2.5.1 Raw Mode data format .................................................................................... 17
       2.5.2 Image Mode data format ................................................................................ 17
       2.5.3 Pulse Height data format ............................................................................... 18
       2.5.4 Pinpuller data format ...................................................................................... 18
   2.6 Safety and Mission Assurance Considerations ....................................................... 18
   2.7 Validation ............................................................................................................... 20

3. TECHNICAL RESULTS ................................................................................................. 21
   3.1 Optical Performance ............................................................................................... 21
   3.2 In-Flight Calibration Concept .............................................................................. 21
   3.3 In-Flight Alignment Determination ....................................................................... 23
   3.4 Thermal Effects ...................................................................................................... 25
   3.5 Ion Mitigation ......................................................................................................... 25

4. PRELIMINARY SCIENTIFIC RESULTS ....................................................................... 27
   4.1 Nighttime Ionosphere ............................................................................................ 27
   4.2 Daytime Ionosphere .............................................................................................. 33
   4.3 Daytime Thermosphere .......................................................................................... 34

SUMMARY ..................................................................................................................... 36
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EXECUTIVE SUMMARY

This report presents the design, implementation, and performance of the Limb-imaging Ionospheric and Thermospheric Extreme-ultraviolet Spectrograph (LITES) experiment. LITES is a high-throughput, compact imaging spectrograph that collects one-dimensional altitude profiles of the ionosphere and thermosphere above the limb of the Earth over the ultraviolet (UV) spectral range 600-1400 Å. The optical design is advantageous over modern operational sensors in that it uses a toroidal grating as its lone optical surface, which minimizes inefficient reflections and eliminates the need for scanning, moving parts. By continuously measuring the full altitude profile all the time, LITES also gains an effective cadence and sensitivity advantage over scanning sensors that collect light from only a portion of altitude profile at any given time. The vertical spectrographic imagery of UV airglow is used to create high-fidelity images of ionospheric structures. LITES was manifested and flown as a demonstration experiment to the International Space Station as part of the DoD Space Test Program – Houston 5 (STP-H5) experiment pallet that launched on 19 February 2017. This flight represents the first application and demonstration of this sensor design to ionospheric and thermospheric imaging and has advanced the technology readiness level (TRL) of this sensor concept from 4 to 7. In addition, it has provided insight into global ionospheric structures that are of high interest to the ionospheric research community. As such, LITES has successfully demonstrated a new and improved capability to observe low- and mid-latitude ionospheric structures on a global scale.
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1. MOTIVATION

1.1 Background

The ionosphere is a complex and dynamic region of the terrestrial space environment that has long been critical to the operation of the U.S. Department of the Navy (DON) and Department of Defense (DoD). This layer of sparse plasma embedded within the neutral atmosphere between altitudes 80-1000 km can absorb or transmit radio wave signals that are a vital lifeline to military operations around the globe. The transient cascade of structures embedded within the plasma can also scatter these radio waves and cause detrimental effects on satellite communications, over-the-horizon radar (OTHR) systems, geolocation, and space situational awareness.

Dynamical processes such as solar and auroral heating, waves, tides, and electric fields drive ionospheric climatology, global scale structure, and gradients. The “F-region” layer of the ionosphere spans altitudes 200-600 km and includes the point where the plasma density is highest. In this region, especially high electron density enhancements form north and south of the magnetic equator. These persistent equatorial arcs are also referred to as the “equatorial anomaly” or “Appleton anomaly”, in reference to nomenclature from some of the first reported ionospheric measurements.[1] These early mappings found the unexpected appearance of a density trough near the magnetic equator, in contrast to a single-peaked distribution that could be expected from solar-controlled photoionization production mechanisms. The arcs are now recognized as enhancements in density that form when an eastward electric field and the northward terrestrial magnetic field generate an upward electromagnetic (ExB) plasma drift. The plasma fountain this creates is eventually countered by gravity that forces the return flow of the charged plasma along the magnetic field to the north and south. Inter-hemispheric winds in the thermosphere can modify this return flow, impeding or enhancing the transport of plasma along the magnetic field and thereby generating asymmetries in the separation, heights and densities of the crests of the arcs. Recent observations have also found longitudinal periodicities in the densities within the arcs, suggesting a connection to atmospheric waves and tides in the mesospheric region below.[2,3]

Within this climatology, several flavors of transient phenomena and irregularities exist. At high and middle latitudes, for example, large scale and medium scale traveling ionospheric disturbances (LSTIDs and MSTIDs) appear in response to acoustic gravity waves. At middle and low latitudes, plasma perturbations create large-scale plasma depletions, or bubbles, that percolate and grow from the lowest altitudes up through the peak in the F-region layer. These large- and medium-scale plasma irregularities can span hundreds or even thousands of kilometers and can cause errors in differential navigation solutions. The gradients in ionospheric density caused by bubble structures can subsequently cascade into small-scale secondary instabilities and perturbations that create scintillation on radio waves that propagate through these regions, affecting the fidelity of all frequencies below ~1 GHz and causing interference and outages of communication and navigation signals. In part because of this visceral impact on operational navigation and communication systems and OTHR systems, the U.S. Naval Research Laboratory has long had an interest in understanding, specifying, and forecasting the state of the ionosphere and thermosphere,

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and the formation and evolution of ionospheric irregularities that are now an important part of modern space weather forecasting.

As part of our ongoing research into advanced methods for observing ionospheric space weather events, we have developed a new experiment to collect data on the ionosphere and thermosphere call the Limb-Imaging Ionospheric and Thermospheric Extreme-Ultraviolet Spectrograph (LITES). LITES builds on the long and unique heritage of NRL experiments that observe the near-Earth space environment at extreme- and far-ultraviolet (EUV and FUV) wavelengths. This part of the spectrum is useful for space-based ionospheric sensing because Earth’s lower atmosphere strongly absorbs radiation with wavelengths shorter than about 2000 Å, meaning that there is no background terrestrial emission to contaminate or overwhelm the measurement or otherwise hinder interpretation of the airglow emissions.

LITES is an imaging spectrograph that consists of three main components: a slit assembly, a toroidal-shaped grating, and an imaging detector. The wide field of view (approximately 10° x 10°) images vertical (altitude) profiles of 600-1400 Å airglow from Earth’s limb. The overarching goals of the LITES experiment are to (1) demonstrate a compact next-generation sensor for operational near-Earth space weather remote sensing in the EUV and FUV, and (2) obtain measurements of the density and composition of the global ionosphere and thermosphere that can be used to further the development of space weather models that are needed to meet space environment specification and prediction requirements for the DoD. The LITES instrument design is cutting-edge technology in that it is compact, lightweight, and can be easily customized in field of view, passband, spectral resolution, and sensitivity for a specific application, orbit, or measurement objective. More importantly, the sensor collects data without the need for scanning mechanisms or other moving parts. The flight of this sensor is timely in that it uses lessons learned from the NRL Remote Atmospheric and Ionospheric Detection System (RAIDS) flown by the DoD Space Test Program (STP) on the International Space Station (ISS) as part of the HICO-RAIDS Experiment Payload (HREP), most significantly by expansion of the nominal wavelength passband to obtain specific measurements needed for higher-accuracy daytime ionosphere specification.

The sensor concept and original flight hardware were developed by a team of researchers at Boston University in the late 1990s that included several members now leading the current LITES experiment team (A. W. Stephan, S. Chakrabarti, and T. A. Cook). The LITES experiment is a new collaborative effort between the U.S. Naval Research Laboratory and the University of Massachusetts Lowell. This demonstration sensor leverages flight-proven hardware previously used on astronomical sounding rocket experiments flown by the University of Massachusetts Lowell research group, who refurbished an existing flight unit and optimized the optical configuration to provide these ionospheric and thermospheric measurements for the first time. LITES has been integrated and flown by the DoD Space Test Program as part of the Space Test Program – Houston 5 (STP-H5) experiment pallet on the International Space Station, ExPRESS Logistics Carrier (ELC-1). It is flying jointly with the GPS Radio Occultation and Ultraviolet Photometry – Colocated (GROUP-C), another ionospheric remote sensing experiment developed in the Space Science Division at the U.S. Naval Research Laboratory. LITES was flown under Class-D guidelines commensurate with this rapid technology development and demonstration mission. The mission success criteria and achievements as of the writing of this document are outlined in Table 1.
Figure 1 – The LITES experiment, prior to integration onto STP-H5.

Figure 2 – The STP-H5 experiment pallet prior to launch, including the LITES sensor visible immediately to the left of the triangular-shaped antennal plane containing the three patch antennae of the NRL GROUP-C experiment. In orbit, the right side of the payload is oriented to the nadir such that the length of the LITES aperture is oriented vertically in altitude. (Photo credit: STP)
Table 1 – LITES mission success criteria and accomplishments

<table>
<thead>
<tr>
<th></th>
<th>Minimum Goal</th>
<th>Comprehensive Goal</th>
<th>Accomplishment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lifetime</strong></td>
<td>30 days of routine science data collects</td>
<td>1 year of science data collects</td>
<td>Comprehensive (14 months)</td>
</tr>
<tr>
<td><strong>Duty cycle</strong></td>
<td>30% average duty cycle over lifetime, entire field of view with tangent altitudes higher than 50 km and lower than ISS orbit altitude</td>
<td>30% average duty cycle over lifetime, entire field of view with tangent altitudes higher than 50 km and lower than ISS orbit altitude</td>
<td>Minimum complete, Comprehensive under evaluation</td>
</tr>
<tr>
<td><strong>Performance Evaluation</strong></td>
<td>Average 1 lunar or UV star observation every 30 days for sensor flatfield evaluation and performance tracking</td>
<td>Comprehensive – (multiple stars identified; duration of each apparition is 7-10 days)</td>
<td></td>
</tr>
</tbody>
</table>

1.2 Measurement Objective 1: Nighttime Ionosphere

LITES measures the number densities of electrons and $O^+$ ions in the nighttime F-region ionosphere by remote sensing of the naturally occurring OI 911 and 1356 Å emission features. This method has been used successfully for several decades in studies of the equatorial and mid-latitude ionosphere.[4-9] Both emissions are produced by radiative recombination of $O^+$ ions and electrons. The 1356 Å emission doublet arises from recombination to an excited state of atomic oxygen that subsequently and rapidly decays by emitting a photon, expressed by the reaction:

$$O^+ + e^- \rightarrow O (^3S) \rightarrow O (^3P) + h\nu_{1356}.$$  (1)

The 911 Å continuum emission is produced by recombination directly to the ground state as represented by:

$$O^+ + e^- \rightarrow O (^3P) + h\nu_{911}.$$  (2)

Under most nighttime conditions the bulk of the plasma is in the F-region where the predominant ion is $O^+$ and the plasma is quasi-neutral (ion density equals electron density). Since both of these emissions are optically thin, the observed nightglow brightness ($4\pi I$) is effectively the path integral of the photon volume emission rate, $J$, along the line-of-sight. With the above conditions, $J$ can then be expressed as:

$$J = \alpha n_e n_{O^+} \approx \alpha n_e^2,$$  (3)

where $\alpha$ is the partial recombination rate into the electronic state of interest. The observed brightness can then be expressed as:

$$4\pi I = 10^{-6} \int_0^\infty J(z) \, dz = 10^{-6} \alpha \int_0^\infty n_e^2(z) \, dz.$$  (4)

In practical applications, these simplified equations also include the temperature dependence of the recombination rate $\alpha$, multiple scattering, and radiation transport effects in the lower ionosphere.[10,11] However, in general this radiance integral represents a quantity that is similar in interpretation to total
electron content (TEC), but with a proportionality to the square of ionospheric density that makes this observing method more sensitive to important ionospheric gradients than a direct TEC measurement yielded by other methods. The measurements can also be analyzed in more detail using different methods, the foremost of which is tomographic algorithms that combine multiple intersecting lines of sight to infer the multi-dimensional structure of the volume emission rate and thus the corresponding ionospheric electron density field.\textsuperscript{[6-9,11,12]}

1.3 Measurement Objective 2: Daytime Ionosphere

LITES measures the number densities of electrons and O\textsuperscript{+} ions in the daytime F-region ionosphere by remote sensing of naturally occurring extreme ultraviolet OII 834 and 617 Å emission features. The daytime ionospheric radiative recombination emission at 1356 Å becomes greatly overwhelmed below about 250-300 km (depending on solar activity) by emissions generated via the excitation of atomic oxygen by photoelectron impact. The emission at 911 Å can be equally difficult to analyze due to other nearby emissions from atomic nitrogen.\textsuperscript{[13]}

The 834 Å emission connects to the ionosphere by a multi-step process. First, solar EUV (\(\lambda < 436\) Å) ionizes an inner shell electron of atomic O, followed by the 4P\(\rightarrow\)4S transition from this triplet excited state of O\textsuperscript{+} to the singlet ground state, and the emission of corresponding photons in the 834 Å emission feature. These photons then undergo multiple resonant scattering by O\textsuperscript{+} in the ionosphere, creating a measured altitude profile of the terrestrial 834 Å emission with a shape and brightness that depends on the ionospheric O\textsuperscript{+} density and the characteristics of the original photon source (determined by solar EUV and atomic O density) that effectively illuminates the ionosphere from below. Two secondary sources, electron impact ionization of O and direct solar 834 Å radiation, also contribute to the volume production rate of the 834 Å emission albeit at levels that are less than 10% to the total column emission.\textsuperscript{[13]}

Early studies showed the potential of determining the daytime O\textsuperscript{+} density by modeling the 834 Å altitude profile. Tests conducted using an algorithmic approach with data from the Special Sensor Ultraviolet Limb Imager (SSULI) program demonstrated the potential to infer O\textsuperscript{+} densities from measured altitude profiles of the O\textsuperscript{+} 834 Å triplet emission feature.\textsuperscript{[14]} The retrieval method used a Chapman parameterization of the O\textsuperscript{+} density as part of a forward model to calculate 834 Å volume and column emission rates. A fitting process iteratively adjusted these model parameters until it converged on a set of ionospheric parameters that yield the best fit the measured altitude profile of the 834 Å emission. Other non-iterative approaches have also been devised that use matrix solutions to the transport equations in an effort to improve computation time for near-real-time analysis.\textsuperscript{[15]}

Some studies have raised concerns about potential ambiguities in separating the contribution between the initial photoionization source and the ionospheric scattering terms in modeling and interpreting the measured altitude profiles.\textsuperscript{[16,17]} This can be mitigated by simultaneously measuring the OI 617 Å emission feature that is produced in a similar manner to the 834 Å feature but is optically thin to ionospheric scattering.\textsuperscript{[16,18]} This emission effectively serves as an independent measurement of the source region changes, enabling isolation of the ionospheric contribution to the measured 834 Å profile. Based on theoretical studies\textsuperscript{[16]} and measurements from the RAIDS experiment on the ISS,\textsuperscript{[17,19]} new algorithms have been developed that include the 617 Å emission to address, in part, these original concerns about the ambiguity in results due to the inability to fully resolve the contribution from the initial ionization term and the ionospheric scattering term in the 834 Å emission.

1.4 Measurement Objective 3: Daytime Thermosphere

LITES measures the daytime thermosphere by observing spectral emissions that are created by photoelectron excitation of O and N\textsubscript{2}. Meier and Picone\textsuperscript{[20]} first demonstrated the analysis concept where
altitude profiles of the OI 1356 Å and one or more segment of the N2 Lyman-Birge-Hopfield (LBH) band system are used to retrieve altitude profiles of atmospheric composition and temperature. The inversion iteratively adjusts a set of scalar parameters in an atmospheric model to find the best simultaneous fits to the measured altitude profiles of the column emission rates. Their implementation uses the empirical Naval Research Laboratory Mass Spectrometer Incoherent Scatter (NRLMSIS) model\textsuperscript{[21]} as its basis, and this approach has been successfully applied to data from several missions.\textsuperscript{[20, 22]} This method is also being applied to data from the new NASA Ionospheric Connections Explorer (ICON) that is scheduled for launch in early 2019.\textsuperscript{[23]} At least four and as many as nine parameters are used to fit the data: the core set includes one each for the concentration profiles of O, N, and O\textsubscript{2} returned by NRLMSIS and one for the solar F10.7 index that is used as an input to the model. Additionally, although it has been demonstrated that the result is generally independent of systematic offsets in measured radiances, each of the two emission intensity profiles may have a multiplicative scalar to adjust the absolute model radiances to offset relative inaccuracies in the calibration at each wavelength, as well as potential inaccuracies in the different excitation rates in the model. Finally, three Chapman parameters can be used in instances where the ionospheric recombination is expected to be visible above the thermospheric emission in the signal – past work has shown that this happens around 300 km.\textsuperscript{[22, 23]}

LITES has a long-wavelength cutoff at 1400 Å that excludes much of the LBH band, but does capture the segment around the bright 1383 Å peak that can be used as part of such an algorithm. However, the best determination of O\textsubscript{2} is usually obtained by measuring two segments of the LBH band where the O\textsubscript{2} absorption cross section differs. Despite this, we still expect to be able to determine densities for all three thermospheric species, albeit with higher uncertainties in O\textsubscript{2}. We also expect to develop and test an alternate approach to measure O\textsubscript{2} using stellar occultation. When stars occasionally appear in the LITES field of view, they appear to set below the horizon as the ISS moves along its orbital track. The path length through successively lower layers of the atmosphere allows O\textsubscript{2} to absorb the stellar UV signals. By measuring this change in radiance versus wavelength, and with the absorption cross-section of O\textsubscript{2} at each wavelength, it will be possible to onion-peel the atmosphere and determine an O\textsubscript{2} altitude profile. While this method is restricted to the times and locations of the serendipitous appearance of these stars, they do remain in the wide LITES field of view for nearly one week, which provides multiple opportunities to build up statistics on the O\textsubscript{2} density. It is also important to note that this method provides the only means for LITES (or any UV airglow sensor) to probe the neutral atmosphere at night.

2. EXPERIMENT DESCRIPTION AND APPROACH

2.1 Optical Design and Development

LITES is an imaging spectrograph that returns one-dimensional, vertical (altitude) profiles of 600-1400 Å airglow from Earth’s limb. The spectrograph uses a toroidal grating to image the airglow scene vertically while recording spectra of the entire field-of-regard horizontally on the two-dimensional imaging detector area.\textsuperscript{[24,25]} This simple optical configuration is shown in Figure 3, and photographs of LITES during build-up in Figure 4 also show the main optical components. The key feature of the LITES sensor design is the highly anamorphic grating. The 150.0 mm radius of curvature along the dispersion axis is equivalent to that of a Rowland spectrometer that images and disperses the pupil (the slit) along the horizontal axis. The 290.4 mm radius of curvature along the orthogonal axis is approximately a factor of two larger and creates a one-dimensional image of the sky (at infinity) onto the focal plane along the vertical axis. The imaging dimension is aligned with altitude, perpendicular to the surface of the Earth. The non-imaging dimension is aligned along the horizon. The LITES grating is ruled at 3200 lines/mm over an area 27 mm x 65 mm, blazed to the 900 Å wavelength. The grating also has a SiC coating, which provides high reflectivity over the LITES passband, particularly at the shorter wavelengths.
The original sensor design covered the 800–1400 Å passband.\textsuperscript{[25]} We have updated this design to include a new, rectangular 40 mm x 26 mm microchannel plate (MCP) detector that enabled us to extend the spectral coverage down to 600 Å in order to capture the 617 Å emission feature discussed in Section 1.3. This upgrade also provided modern cross-delay-line (XDL) technology for our two-plate, Chevron-stacked MCPs with an expanded 4096 x 4096 pixel capability and electronics that allows higher throughput with lower deadtime. The detector is coated with a KBr photocathode to provide higher responsivity, particularly at wavelengths between 800-1000 Å. KBr has also been found to be more stable than other photocathode options.\textsuperscript{[26]} One concern particularly for the night measurement is that the wings of the exceptionally bright hydrogen Lyman-α (H-Lyα) emission at 1216 Å could impact the extraction of the much dimmer adjacent features of interest. To mitigate this concern, the LITES detector was masked during coating to leave the microchannel plate bare in the ~1200-1250 Å region, thereby reducing the overall responsivity at these wavelengths compared to the surrounding emissions and keeping the H-Lyα signal muted. The LITES detector was kept dry with a tabletop pump that maintained vacuum in the detector cavity during all ground-test activity until final assembly onto the launch vehicle. The detector door, described in more detail in Section 2.2.2, included a MgF\textsubscript{2} window that could allow far ultraviolet wavelengths to still be measured in the event of a failure in the door mechanism.

The second optical design choice we made was to configure LITES with a 40.0 mm x 0.125 mm slit that balances the need for better than 15 Å spectral resolution during the day, where numerous spectral features exist, and the desire for adequate sensitivity (~15 counts $s^{-1} R^{-1}$) at night when only a few, well-separated but much dimmer features exist. The slit dimensions, along with the f-number of the grating, defines these properties. However, the design choices for LITES were more limited because we leveraged existing gratings for the design.

![Figure 3](image-url) – Three views of the optical path and main components of the LITES spectrograph. The baffle-slit system is the entrance aperture, the toroidal grating disperses the light horizontally and images vertically onto the cross-delay-line microchannel plate detector. Additional interior baffles block scattered light and other orders of dispersed light.
The LITES baffle system is a series of knife-edge stainless steel apertures with narrowing width appropriate to define the $10^\circ \times 10^\circ$ field of view. The slit is the innermost element in the baffle system shown in Figure 5. Additionally, the slit is held +28 V above chassis potential in an attempt to repel charged ions in orbit. These particle effects are expected to be most significant near the South Atlantic Anomaly and in the auroral zones where highly energized ions are known to exist. The slit is isolated from the rest of the chassis by plastic spacers as shown in Figure 5. Resistance checks were conducted to ensure electrical isolation between the chassis and the slit, and a 1 Mohm resistor was included to limit the current draw in the event of an unexpected short in the circuit lines. On power-up, this line has a default value of near +13 V. When the bias is powered, the value rises to the full +28V. This dual setting allows the sensor team to conduct tests of the effectiveness of the ion repulsion.
2.2 Mechanical Development

2.2.1 Wedge Mount

Because LITES is an imager fixed in viewing angle, it was important to optimize the orientation prior to launch to ensure the ability to capture the key altitude regions where the airglow is most informative, specifically 150-350 km for ionospheric emissions. At the onset of design of LITES for the STP-H5 payload, the most significant unknown factor was the expected ISS pitch angle. In our experience with the HREP payload during 2009-2011, this angle had ranged between 0° and -3.6° (pitched with the “nose” of the ISS downward with respect to the ram direction), with ±0.35° control. The best forecasts available during the LITES instrument development phase were for the ISS to be oriented -2.6° in pitch. We conducted numerous simulations to determine an optimal mounting angle to allow us to achieve our scientific goals. Based on these simulations and an expected ISS pitch of -2.6°±0.4°, LITES was mounted on a 14.5° wedge plate that optimized the sensor orientation to view F-region ionospheric altitudes. This mounting angle also provided a small margin for some change in the ISS nominal attitude leading up to the launch of STP-H5. The altitude coverage at these extremes is shown in Figure 6. The height of each bar represents the oblateness of the Earth over the ISS orbit. While the ISS frequently maneuvers for docking of vehicles and other operational and scientific needs, in general the ISS has been maintained over an orbit with a nominal pitch angle closer to -2.2° but still meeting the requirements for LITES – a sample in Figure 7 shows a typical oscillation, taken on 1 April 2017 early in the mission.

Figure 6 – Pre-flight analysis determined a mounting wedge of 14.5° was needed to orient the LITES field of view to optimize the 150-300 km altitude range. These figures show results for two potential pitch values for the ISS that bracket the pre-flight expectation of a -2.6° pitch. The height of each sample in the image is shown in red, with an extent created by the oblate Earth. In flight during early operations, the ISS maintained a pitch closer to the -2.2° value.
Stephan et al.

Figure 7 – ISS pitch for 1 April 2017 shows the typical magnitude and variation over a day early in the LITES mission. The amplitude shows the typical orbit variation of less than ±0.2° in pitch.

2.2.2 Door Mechanism

The LITES MCP detector is hygroscopic, and so best practices require storage under vacuum or backfilled with liquid nitrogen (LN2) gas prior to launch. A latched, hermetic, spring-loaded door was provided with the detector unit that allowed a tabletop pump to maintain vacuum at <10⁻⁵ Torr inside the cavity. The door was delivered with an attached locking mechanism that was activated by pulling the release mechanism in a direction away from the face of the detector, as shown in Figure 8. Implementing a direct-linkage connection from outside the LITES optics box to this mechanism was found to be unreliable due to torques placed on the locking mechanism that introduced friction and binding in the system. To solve this, we removed this mechanism entirely and designed a custom die-spring and plunger mechanism, shown in Figure 9, to hold the door-retaining pin in place. The spring-plunger assembly was mounted with a block into LITES. Two guide rods were retained in the block with the use of snap-rings. The two extension springs were positioned, with the door pin stop hardware, onto the guide rods and retained with snap-rings.

The die-spring was subsequently held in place by the pin of a P10 Pin-puller purchased from TiNi Aerospace, Inc. that served as the activation mechanism to open the door. To arm the deployment mechanism and create the vacuum sealed detector environment, the detector door was first positioned so the o-ring seal bears against the detector housing, creating the static face seal. An external pump then evacuated the detector volume through the external pumping manifold, which allowed external atmospheric pressure to compress the o-ring seal and position the detector door and door retaining pin for latching. The spring plunger mechanism was then positioned and compressed to the stowed configuration, which compressed the deployment springs and positioned the retractable door stop to capture the door retaining pin and hold the door closed. With the detector door retained, the pin-puller actuator pin was then extended to capture the spring plunger mechanism.
For deployment of the door, the pin-puller was activated by ground command, retracting the actuator pin. When this happened, the spring-plunger mechanism was released and pulled the door stop “up”, subsequently releasing the retaining pin and detector door. Pre-loaded torsion springs in the detector door forced the door open until it hit the hard stop (the square metal frame visible in Figure 8), outside of the view of the detector. A micro-pirani pressure sensor attached to the plumbing near the detector cavity, (primarily to monitor pre-launch vacuum levels) provided a secondary confirmation that either the door opened (via a pressure drop) or the detector cavity has been fully evacuated via passive venting of the chamber area during launch and initialization of STP-H5. The final confirmation of the door opening was to be obtained through the collection of the full spectrum of airglow emissions – the MgF₂ window in the door would otherwise block the shortest wavelengths from being measured, but still allow partial science in the event of a failure of the door-opening mechanism. In flight, the pressure sensor indicated low pressure at first power up. More importantly, the telemetry from the pin-puller returned the as-tested signature of a successful door opening on the first attempt, as well as the signature of an already-open door during the subsequent firing of the redundant activation circuit. This was confirmed with the receipt of a full spectral signature on first-light.

Figure 8 – Left, a photograph of the LITES detector and the original latching mechanism. The MgF₂ window is covered for protection. Right, the original latching mechanism and door release concept, a sequence initiated by pulling the protruding screw in the photograph away from the face of the detector. This mechanism proved difficult to operate successfully due to twisting and binding of a lever arm that translated motion of the pin-puller to this mechanism. This mechanism was eventually replaced by a custom mechanism as shown in Figure 9 and Figure 10.

Figure 9 – The die-spring and plunger mechanism used in the stowed configuration (shown on the left) to hold the LITES door pin in place until deployed via the retraction of a pin-puller actuator, which released the mechanism to the deployed configuration (shown on the right).
2.2.3 Spectral alignment

Due to the expanded wavelength coverage, the emissions of interest were tightly fit onto the active area of the detector. Exact spectral alignment was necessary to ensure not only that all emissions were visible but also to ensure positioning of the bright H Ly-α emission onto the bare area of the MCP. Our first test showed a slight offset in spectral position that required a real-time approach to realigning the grating. We designed and created a set of 3D printed tools to hold the grating in position so that we could use a visible-wavelength laser to illuminate the grating. The zero-order spot from the grating allowed us to adjust the angle of the grating and re-secure it in its mount with the precision needed to achieve the proper alignment. In particular, the 3D printing allowed multiple thicknesses of the same grating support tool to be tested rapidly to efficiently complete the realignment in less than a week. Any alternative solution would have required a complete disassembly of the optics box and re-alignment from scratch, a process that would have potentially been prohibitive for both the schedule and cost to the mission.

2.3 Concept of Operations

LITES was designed to operate as an always-on sensor with a simple and limited need for daily commanding. However, for orbits where the Sun may transit near the field of regard, the detector high voltage must be powered off to avoid damage from the bright UV illumination. LITES is mounted on the STP-H5 payload such that the 10° x 10° field of view is oriented to view in the wake-direction from the ISS and in the orbit plane. During early mission operations, our command activities enforced a conservative 30° safety zone about the center of the field to provide a factor of three margin, thereby allowing for pre-launch alignment uncertainties and ISS attitude changes. This meant that when the solar beta angle was within 30° of zero (see Figure 11) we required the capability to shut off the high voltage to the sensor detector when the Sun was transiting near the LITES field of view. In the wake-viewing configuration, this generally corresponds to no more than about 15 minutes of total off time each orbit as the ISS transitions from daylight to night (sunset from the ISS perspective). To maximize scientific return
without requiring a riskier approach to operations, it was necessary to have the capability for on-orbit scheduled command capabilities to implement timed HV off/on commands. As an added precaution, a sunsensor was installed near the LITES aperture, coaxial with the LITES bore-sight with a conic full-angle field of view of 30° defined by a 3D-printed housing base and cover made of black Ultem. This sensor provided shutdown protection in the event of an unplanned exposure to sunlight or other bright sources. The only other inherent command and operations requirements for LITES are the routine checks and adjustments of the high voltage level setting as normal aging of the MCP detector occurs.

![Solar beta angle of the ISS orbit over one year starting from launch in February 2017. The pattern closely repeats in following years, shifted only a slight amount shown near day 50. Angles between the red dashed lines require LITES commanding to avoid solar exposure. See text for more detail.](image)

**2.4 Power and Data Interface**

The STP-H5 payload avionics included a power distribution box (Jenkins Memorial Unit 2, or JMU2) built by NRL Code 8000, and a NASA Goddard Space Flight Center (GSFC) SpaceCube Communications Interface Box (CIB). The need to provide onboard scheduled commanding for both LITES and the nighttime ionospheric photometer in GROUP-C was provided by linking the NRL experiments through another experiment on STP-H5, the ISS SpaceCube Experiment – Mini (ISEM) that was also developed at GSFC. ISEM is functionally similar to the CIB but provides the capability to interface multiple experiments into the main STP-H5 CIB.

The interfaces for both LITES and GROUP-C with the JMU2 and ISEM was handled by another custom-built unit, the GROUP-C and LITES Interface Box (GLIB). GLIB was developed at NRL based in part on the interface to the CIB designed for NRL experiments on the STP-H4 mission. Each of the two NRL experiments is handled separately within GLIB by custom power and data interface modules, but physically contained in a single unit. A schematic of the interfaces between these units for LITES and GROUP-C is shown in Figure 12. A photograph of the full sensor build-up of LITES with GLIB for STP-H5 with the detector electronics and high voltage boxes was shown in Figure 2.
For LITES, GLIB took the 28 V bus line from the JMU2 and provided ±6V and ±12 V lines to run the detector electronics. It also provided programming voltages (0-5V) to the redundant Emco C40N high-voltage power supplies units used to power the LITES MCP detector. While GLIB monitored and reported the HV level as part of the sensor overall health, simplicity in design necessitated that this was only recorded at gross (~150 V) resolution, wider than the 15 V resolution of the HV settings. The true settings were confirmed in real time via the observed change in instrument performance and the reported good/bad command count, and were documented in the detailed procedures and record keeping. As part of that circuit, GLIB also received the sunsensor signal and compared it to the stored (set by command) threshold value to immediately power off the HV and safe the LITES sensor if the value was exceeded. The sun sensor threshold must be reset to an appropriate level by ground command to allow HV operation to resume. GLIB also provided +13V/+28V switchable options to charge the entrance aperture that is used to repel ions from the sensor cavity. On the communications side, GLIB collected and processed to the raw detector image signals from the LITES MCP detector electronics which were functionally similar to recent detector upgrades made to the SSULI operational sensors. As such, LITES provided an in-flight test and demonstration of this module that could be used to modernize future SSULI-like sensors.

![Diagram](image_url)

Figure 12 – LITES and GROUP-C electrical (red) and command and data handling (green) interfaces for STP-H5. The ISEM unit is an experiment developed by the Goddard Space Flight Center, and serves as the payload interface for multiple payload experiments including the NRL LITES and GROUP-C experiments.

<table>
<thead>
<tr>
<th>Table 2 – LITES As-Flown Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size</strong></td>
</tr>
<tr>
<td>LITES</td>
</tr>
<tr>
<td>GLIB (for LITES + GROUP-C)</td>
</tr>
<tr>
<td><strong>Mass (total)</strong></td>
</tr>
<tr>
<td>LITES</td>
</tr>
<tr>
<td>Mounting Wedge</td>
</tr>
<tr>
<td>GLIB (for LITES + GROUP-C)</td>
</tr>
<tr>
<td><strong>Power</strong></td>
</tr>
<tr>
<td>19.4 W, 2.4 A</td>
</tr>
<tr>
<td><strong>Data Rate (maximum)</strong></td>
</tr>
<tr>
<td>300 kbps</td>
</tr>
</tbody>
</table>
2.5 Command and Data Handling

GLIB (including LITES and half of the GROUP-C experiment complement) and ISEM are on separate power bus lines from the JMU2. On initial power-up, the payload procedure dictates that the ISEM bus receive power first to allow that experiment to initialize itself, followed by the power bus containing GLIB. Any time ISEM is rebooted (including payload power-up sequences), it sends a power off command to the LITES HV in order to put the LITES in a known, safe state. ISEM waits until it receives a health and status (H&S) packet from the CIB to synchronize the ISEM clock. ISEM then compares the current system time to any uploaded schedule table files and resumes automatic commanding in the appropriate place. If no schedule table is found for the current time, this condition will be reported to the ground and the LITES HV will remain off until a ground (pass-through) command is sent to turn it on or a new schedule table is uploaded. When power is then applied to GLIB, the clock in the LITES module is synchronized to the ISEM time (GROUP-C does not synchronize time, but instead contains GPS information as part of its data stream). We note here that this synchronization is only conducted during power-up, and drifts in the GLIB clock of 2-3 seconds (fast) per day have been observed.

Data from the LITES detector is collected in the form of photon events and telemetered by GLIB with a 3 second cadence. The raw data consist of the X and Y position of the event on the 4096 x 4096 pixel detector, plus the ‘pulse height’ that relates to the energy of the event. The pulse height information is a useful diagnostic of detector performance and can be used to discriminate real photon events from high energy particles and other background events. LITES does not conduct any such discrimination of events. Each photon event is individually recorded with 12-bit X and Y values, and a 8-bit pulse height value (range 0-256), but the overall volume of data can be highly variable due to changing airglow conditions. GLIB maintains two storage buffers that allow LITES the capability to capture a large dynamic range of airglow expected but maintain as much of the raw data as possible within the imposed cap the telemetry stream at 300 kbps for STP-H5. One buffer contains all the raw events while the second builds an integrated two-dimensional image that records just the number of counts collected in each of the image bins. Because the detector significantly oversamples the spectral and spatial resolution of the image, the image buffer collects data in larger ‘super-pixels’ that create a 320 (spectral dimension) x 128 (vertical/imaged dimension) image. Additional details on the binning and packaging of these data are described later in this document. LITES can thus be configured into two different operating modes. (1) Raw mode forces raw XY events to be collected and transmitted regardless of the count rate. This mode is only intended to facilitate diagnostics of sensor performance. In this mode, any events beyond what can be handled by the data transfer rate will be lost, but the events that are transmitted will provide better insight into the overall health of the sensor and detector. (2) Normal mode compares the total accumulated counts in the 3-second integration interval and sends either the raw event buffer if the count rate is below a set (programmable by ground command) count threshold, or the accumulated image buffer if above. Note that in this mode the raw events are still sent down for processing if the count rate is below the set threshold. Since it is preferable to receive as much raw data as possible and conduct all data processing on the ground, adjusting this threshold can optimize the data that is returned. LITES boots in raw mode but was normally configured for routine operations to use the normal operating mode.

LITES is controlled with five basic commands (aside from the door-open command); (1) operating mode, (2) sunsensor threshold, (3) count threshold, (4) charged slit voltage potential (or bias level), and (5) HV supply 1 or 2, with a level setting. All of these ground commands are processed on the payload by ISEM and forwarded on as ‘pass-through’ commands to LITES for immediate execution. As noted earlier, LITES is designed to remain powered on in a data-collecting state but does require shutting off the detector HV to safe the instrument during parts of the orbit where the Sun nears the LITES field of view. In these cases, tables of on/off times are uploaded to ISEM to allow LITES to continue science operations over the remainder of the orbit. ISEM stores an ‘on command’ and ‘off command’ buffers that can be updated by command at any time (the specifics of these commands are transparent to ISEM, and thus any
two commands, including non-HV commands, could be used). The schedule upload to ISEM identifies a sequence of times for commands to be issued, and which command buffer to be applied. These schedule tables can be deleted at any time, and pass-through commands can still be issued to update the sensor configuration at any time without impact to the operational table.

When powered for normal operations, LITES comes up in Raw mode with a default Count Threshold of 10,000 and sun threshold of zero (exceeded state). During initialization, the operating mode is set to “Normal” and sunsensor threshold must be set. Additionally, the count threshold should be set at a desired value. Once the sunsensor threshold is set to a level that is not exceeded by the current reading, the HV can be powered on. High voltage is set with an 8-bit digital-to-analog converter (DAC) (see HV command description). The full range for the programming voltage is 0 to 5 Volts, corresponding to a HV output range from 0 to -4000V.

LITES science data are transmitted from STP-H5 to the ground in 1264-byte data frames (not including CCSDS headers, TREK headers, and checksum values) collected in 3-second intervals. All data frames are zero-padded to complete a frame, if necessary. The data for each interval nominally include between 1-49 detector event data frames, and one pulse height frame, for a total of 2-50 frames for each 3-sec interval. With this scheme, LITES generates a maximum of 505.6 kbits in a 3 second integration, or 168.6 kbits/sec average telemetry rate. The frame type is identified in byte 7, per Table 3 below. The detector event data are sent down in either Raw or Image mode depending on (1) the Count Threshold setting in comparison to the realized event total, and/or (2) the OpMode. In addition to the frame type (byte 7), each frame includes a 4-byte time stamp (bytes 1-4) marking the end of the data collection, and the total number of counts (bytes 5-7). It is expected that the time and total count values should match for all data frames within a given 3-second collection. The pulse height frame also includes a 2-byte word marking any additional increment to the integration time that occurred due to software initialization, although it is unlikely that any counts will accrue in this initialization frame since the HV cannot be powered to an operating level within the 3-second window that the first frame is accumulated. The exception to this general format is the pin-puller data that is inserted as it occurs in response to the door-open command, with the format described below.

Table 3. LITES Science Data Format

<table>
<thead>
<tr>
<th>Byte</th>
<th>Content</th>
<th>Raw</th>
<th>Raw PH</th>
<th>Image</th>
<th>Image PH</th>
<th>Pinpuller</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Packet time</td>
<td>(LSB)</td>
<td>(LSB)</td>
<td>(LSB)</td>
<td>(LSB)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0xfe</td>
</tr>
<tr>
<td>4</td>
<td>(MSB)</td>
<td>(MSB)</td>
<td>(MSB)</td>
<td>(MSB)</td>
<td>(MSB)</td>
<td>0xfe</td>
</tr>
<tr>
<td>5</td>
<td>Total Packet Counts</td>
<td>(LSB)</td>
<td>(LSB)</td>
<td>(LSB)</td>
<td>(LSB)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>(MSB)</td>
<td>(MSB)</td>
<td>(MSB)</td>
<td>(MSB)</td>
<td>(MSB)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Frame ID</td>
<td>0x00</td>
<td>0x40</td>
<td>0x80</td>
<td>0xC0</td>
<td>0x00</td>
</tr>
<tr>
<td>9-1264</td>
<td>Data</td>
<td>Raw XY position data, per event on 4096 x 4096 detector image; (3 bytes/event)</td>
<td>Byte 9-520: 256 2-byte words (LSB-MSB order);</td>
<td>Image bins 320 x 128 rebinned image</td>
<td>Byte 9-520: 256 2-byte words (LSB-MSB order);</td>
<td>2-byte values, sampled at 400 Hz.</td>
</tr>
<tr>
<td></td>
<td>See Table 4</td>
<td>See text and Table 5</td>
<td>See text and Table 5</td>
<td>See text and Table 5</td>
<td>See text and Table 5</td>
<td></td>
</tr>
</tbody>
</table>
2.5.1 Raw Mode data format

Each raw event is generated as a 12-bit X and 12-bit Y position of the event. These are merged into a 3-byte value as described in the table below. Raw event data reports the XY position of each detector pulse on its 4096 x 4096 pixel space (12-bits). Each frame uses bytes 8-1263 (1256 bytes total). Note that each frame does not exactly fit an exact number of events, but all bytes are used and wrapped to the next frame – e.g. 1254 bytes = 836 events, with two extra bytes in the first frame used and the third byte in a 3-byte event pair is continued in the second frame. Also note 49 frames = 41029 total events in 3 seconds, should be used as a metric for setting the maximum threshold event because LITES does not store events beyond the 3-second increment. Any events collected in this mode that exceed the LITES data transfer rate to ISEM may be lost (although more than 49 data packets might be transmitted), although the total counts reported and the pulse height array may still accumulate events and will reflect the total number of events. Finally, GLIB does not zero out the Raw event buffer, such that events may appear in the frame beyond the expected range (e.g. if a prior integration interval contained a higher event count value – the reported total counts should be used to identify the position of the last valid event.

Table 4. LITES Raw Mode bit order

<table>
<thead>
<tr>
<th>Byte 1</th>
<th>Byte 2</th>
<th>Byte 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 7 6 5 4 3 2 1</td>
<td>8 7 6 5</td>
<td>8 7 6 5</td>
</tr>
<tr>
<td>Y MSb</td>
<td>Y LSb</td>
<td>X MSb</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>X LSb</td>
</tr>
</tbody>
</table>

2.5.2 Image Mode data format

The 4096 x 4096 pixel raw detector data is rebinned in the Image Mode format as follows: In X (spectral dimension) there are 320 bins, each 10 pixels in width starting at pixel 400 (e.g. raw X detector pixel 400-409 = bin 1, 410-419=bin 2, ..., 3590-3599 = bin 320). In Y (imaging dimension) there are 128 bins, each 27 pixels in size starting at pixel 245 (e.g. raw Y detector pixel 245-271 = bin 1, 272-298 = bin 2, ..., 3674-3700 = bin 128). Any other events outside these ranges are placed in the [1, 1] bin (lowest corner) of the imaged array to be sure these events are still identified and counted in the overall diagnostics.

The total number of reported bins is 320 x 128 = 40,960. At 12-bit depth for each bin, this means each image requires 491,520 bits, or 61,440 bytes. Packaging the data using three bytes to transmit two values and not wrapping values between frames means 1254 bytes are used in each frame to transmit these values (bytes 9-1262 of the 1264 byte frame – 1263-1264 are not used). Therefore, we required 49 frames to return all the image mode data (the final frame includes 14 additional unused bytes, 1249-1262), plus one frame for a pulse-height array that accompanies every image. The image is transmitted down within the LITES HRT frames in the order (X1, Y1), (X1,Y2), ... (X1,Y128), (X2, Y1)...(X320,Y128). Images are oriented such that position (X1,Y1) is at the longest-wavelength, highest-altitude position of the image. Mapping the 12-bit data into the byte sequence is similar to the raw image mode scheme, as exemplified in Table 5.

Table 5. LITES Image Mode bit order

<table>
<thead>
<tr>
<th>Byte 1</th>
<th>Byte 2</th>
<th>Byte 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 7 6 5 4 3 2 1</td>
<td>8 7 6 5</td>
<td>8 7 6 5</td>
</tr>
<tr>
<td>Bin 1 MSb</td>
<td>Bin 1 LSb</td>
<td>Bin 2 MSb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bin 2 LSb</td>
</tr>
</tbody>
</table>
2.5.3 **Pulse Height data format**

Although separate identifiers are used for Pulse height (PH) data from Raw or Image mode (to ensure proper matching to the detector data information), the data format is otherwise the same for both modes, and is reported as a 0-255 array with 2-byte (16-bit depth per bin) = 512 bytes.

In the PH array, bin 256 records additional time beyond the 3-second integration that might occur due to GLIB software delays in setting the start-stop times. This is only observed on system start and non-zero values can be used to identify a reboot or power cycle of GLIB. Values in this field are reported in ms, with 2-byte depth, value range 0-999 and a typical value near 80 ms.

2.5.4 **Pinpuller data format**

The pinpuller packet uses bytes 8:1263 to report pinpuller current, 16-bit (2 byte) format, reported in (MSB, LSB) order. No packet is transmitted if the pinpuller does not draw current (e.g. the circuit is open due to successful firing). These are raw values reported at 400 Hz (2.5 ms intervals). During test operation, an activated circuit showed a raw value of near 150 and duration of less than 100 ms. This packet does not have a timestamp and is inserted as soon as it is received. Time can be inferred by the surrounding packet information, since it is expected this command will only be used during experiment initialization.

2.6 **Safety and Mission Assurance Considerations**

One of the most significant mission assurance concerns was the need to minimize contamination and exposure of the detector to humidity prior to launch. Detector quantum efficiency (QE) decreases from 0.36 to 0.24 at 1200 Å wavelength after 65 months were expected, or about 0.002 per month (conservatively) at 5% humidity were expected.\(^{[20]}\) We set an acceptable degradation limit of 10% of the original, as-manufactured detector QE over the ground phase testing and launch of the experiment. Vacuum was maintained inside the LITES detector cavity by a tabletop pump. From this, we developed a process to calculate and monitor the total accumulated exposure after each test — primarily times after testing in a vacuum chamber where the detector was exposed to conditioned (clean room) air for a brief period until the door could be manually closed and vacuum reestablished. During transfers and prior to launch (at L-8d), the cavity was backfilled with gaseous LN2 until vacuum could also be reestablished.

Due to an extended launch delay, the system had to be maintained at vacuum for more than a year. Fortunately, only one pump failure occurred during this time, after more than 15 months of nearly continuous pump operation. The DoD STP team reacted quickly to replace the pump within about 24 hours of discovering the failure and less than 48 hours of pump down-time. The detector cavity exhibited only minor loss in pressure with pressure peaking around 100 Torr before the backup pump was installed. The payload was also purged with N\(_2\) prior to storage, with humidity holding near 7%, so the overall exposure of LITES consumed less than 0.25% of the overall budget for water vapor exposure.

We were able to use this unexpected failure to test and confirm calculations of leak rates and water vapor diffusion through the o-ring surfaces that sealed the detector cavity. These calculations were completed to help define the pre-launch requirements for how long the LITES experiment could sit on the launch pad, with a back-filled detector cavity, before it would be necessary to return the vehicle, restore vacuum, and back-fill the detector cavity for another launch. The results of those calculations related to the total budgeted exposure is shown in Figure 13 for an external environment with 80% relative humidity, and include an evaluation of the gain from a refresh at 30 days — the timeline at which a refresh would
reasonably provide a second attempt with a 30-day launch window while still ensuring LITES total water vapor exposure was kept within limits.

Another mission risk was the door mechanism. Although LITES contains no other moving parts, it was necessary for the door to successfully open not only to ensure full mission success (partial success could be achieved since the door contained a window to allow long-wavelength emissions to still be measured), but also to ensure that the cavity was properly vented prior to operating the detector HV. We developed a multi-point verification system to ensure the successful opening. First, the pinpuller circuit was tested on the ground and the opening sequence and telemetry in the pinpuller data packets was carefully documented. Second, a micro-pirani pressure sensor was installed in the plumbing to obtain a verification of the pressure in the system. In practice, the cavity evacuated during the two-week transit, docking and installation and the pressure sensor was pegged at its lowest possible reading, $1.0 \times 10^{-5}$ Torr, at power-up of the LITES payload. However, the pinpuller circuit also triggered exactly as expected, providing confidence the door mechanism had opened. Final confirmation was achieved with verification of airglow emissions across the full spectrum, including short wavelength emissions that would have been blocked by the window in the door.

Another concern was thermal survival, particularly during unpowered transfer. The LITES operating and storage survival limits are shown in Table 6. The detector electronics presented the primary concern only because they had not been formally verified beyond the limits presented here, although it was expected they could survive a wider range particularly on the hot side. On the cold side, the high voltage power supplies presented the greater challenge, particularly during the unpowered transfer. These considerations were included in setting requirements for transferring the payload after docking with the ISS.

A significant operational concern was that LITES and GROUP-C were interfaced via ISEM, itself an experimental payload. Even with tested protocols for ISEM that were consistent with heritage protocols used by the CIB on STP-H4, handling all C&DH through ISEM presented one of the top three risks to

Figure 13 – Plot showing the timeline for determining the risk to the LITES sensor due to launch-pad exposure to humidity. Calculations include diffusion of water vapor through the o-ring seals of the detector cavity and connected plumbing.
mission success. At the initiative of the STP personnel overseeing the program, this risk was greatly mitigated through two merged interface tests completed at NRL with flight or flight-like hardware early in development. In addition to providing both teams with face-to-face, real-time troubleshooting and opportunities to understand (in both directions) the operations processes, protocols, concerns, and caveats, the teams were able to enter integration with a reasonably well-tested system. Some of the testing procedures developed during those meetings became integrated into the in-flight procedures that were eventually developed to run the LITES and GROUP-C payloads. Related to this concern, in the event that ISEM became non-responsive to data being sent from LITES and GLIB, a watchdog timer in GLIB would force a reboot that returns LITES to its pre-launch state, unable to power HV even if commanded from ISEM since the sun threshold needs to be reset manually before any HV unit can be powered. This, combined with the HV power-off command sent from ISEM and sunsensor protections, ensure minimal risk to the LITES sensor in the event of ISEM SEUs, reboots, ISS command outages, and other issues that might affect ability to send real-time commands.

Table 6 – LITES Thermal Limits (driving limits in red).

<table>
<thead>
<tr>
<th>Component</th>
<th>Storage Low (°C)</th>
<th>Operational Low (°C)</th>
<th>Operational High (°C)</th>
<th>Storage High (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLIB</td>
<td>-55</td>
<td>-40</td>
<td>70</td>
<td>85</td>
</tr>
<tr>
<td>Detector electronics</td>
<td>-25</td>
<td>0</td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td>LITES HV Power Supply</td>
<td>-20</td>
<td>-10</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Sun sensor photodiode</td>
<td>-30</td>
<td>-25</td>
<td>85</td>
<td>100</td>
</tr>
<tr>
<td>Door Opener Mechanism</td>
<td>-150</td>
<td>-65</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>LITES Optics Box</td>
<td>-60</td>
<td>-60</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

2.7 Validation

Perhaps the most important aspect of the combined LITES and GROUP-C experiment pairing is the opportunity for complementary measurement to validate and enhance the results of each measurement. LITES samples within the orbit plane. TIP provides high-sensitivity measurements of ionospheric gradients. Crossing lines-of-sight permit tomographic inversion of data to produce altitude latitude maps of electron density. Radio occultation is possible both night and day but is sporadic and frequently out of the orbit plane due to the geometry of the particular occultation event, with samples distributed randomly and more widely

Terminator crossings provide a particularly unique opportunity to use the GPS radio occultation data to evaluate the transition between the day and night ionosphere airglow approaches. Although historically these approaches have been separated by the specific emission mechanisms, there is potential to find new approaches to address the transition where the application of all of the current airglow approaches is questionable. Finally, the combination of GPS and ultraviolet airglow provides a method to further evaluate overall calibration, flat-fielding, and pointing variations of the airglow sensors.

The space-based LITES and GROUP-C measurements will be further complemented by data from the GIRO network, an international ground network consisting of over 60 digisondes whose data are available in near-real time. These data, along with incoherent scatter radar data, will serve as ground-truth for the LITES and GROUP-C measurements that will span the globe and fill in the 70% of the Earth (oceans) and other geographic locations where no ground-based measurements are possible.
3. TECHNICAL RESULTS

3.1 Optical Performance

The overall performance of the LITES optics is excellent. The grating maintained its original pre-flight alignment as shown in Figure 14, including both the spectral positioning with the 617 Å on the right side of the image and the bright 1216 Å emission centered on the photocathode mask. The natural electrical distortion of the detector image is minor and the emission features show brightening at the lowest altitudes (top of the raw image) that demonstrate signatures consistent with pointing required for LITES to achieve its optical science return. Evaluation of the spectral resolution of several of the key emissions showed a value of 13.1 Å, in close agreement with laboratory measurements (see Figure 15) and on par with similar sensors such as SSULI.[29] At this spectral resolution the our 320-bin image mode sampling, which has a dispersion of 2.51 A/bin, is more than adequately sampled for analyzing all LITES data.

![First light image collected by LITES on 6 March 2017. Wavelength decreases from left to right, altitude decreases from bottom to top. The 1216 Å emission is centered around pixel 75, centered on the 30-pixel wide mask in the photocathode.](image)

3.2 In-Flight Calibration Concept

In order to verify the instrument responsivity, we have compared LITES measurements of key lower-atmospheric airglow features with the same calibrated products measured by SSULI collected on the same day and similar local times. These comparisons give an estimate for the responsivity of 0.004 counts/second/Rayleigh/pixel at 1356 Å. This translates to a responsivity over the full 128-pixel image field of LITES on the order of 0.5 counts/sec/Rayleigh. This performance is on par with the responsivity of SSULI. However, it is noteworthy that LITES images the full field continuously, whereas SSULI builds up the profile by scanning through the region in 90 seconds. Thus, LITES provides an inherent improvement in overall response that provides flexibility in applying trade-offs in sensitivity versus sampling resolution.
Periodic recalibration is an important requirement during the course of a mission. For an imaging spectrograph such as LITES, where the same emission region continually hits the same portion of the two-dimensional detector, gain sag can be significant. As such, not only is a radiometric calibration important but also a flat-field measurement. One approach is to reorient the field of view onto the terrestrial disk such that the different imaging segments view the same emission field as the sensor orbits. The planning and operational requirements make this option costly and impractical for the ISS. In rare cases, a vehicle docking provides such a serendipitous orientation to make these measurements.

Instead, LITES can use UV-bright stars passing through the field of view to provide both the radiometric calibration and the flat-field measurement. Given the precession rate of the ISS and the wide 10 degree horizontal field of view of LITES, each star will be visible for ~5 days. However, this has proved to be even more complex in flight than originally anticipated – particularly in the convolution of atmospheric absorption of stellar signatures (that enables the O\textsubscript{2} density determination) with the instrument flat-field. Additionally, calibration stars have a spectral cutoff at 911 Å created from absorption by interstellar hydrogen. Additional work is ongoing to address these well-known issues and advance our characterization of the LITES sensor with these stellar signatures.

One supplementary goal of the joint LITES and GROUP-C mission is to develop and test an approach to validate the retrieved FUV limb brightness by direct comparison with GROUP-C GPS occultation profiles that are obtained toward the same limb that LITES views. Although the GPS receiver can see signals from satellites in the full sky, it is estimated that 24 of these occultations will fall within the 10° horizontal field defined by the LITES optics within a 24 hour period. The high-precision in-track electron density profiles from GPS occultation would be used to calculate the equivalent UV signals that would be expected from the same line-of-sight.

A more comprehensive approach also under consideration is to fold in the high-sensitivity nadir-viewing 1356 Å radiances to cross-calibrate measurements from all of three sensors simultaneously, and complete additional validation against ionospheric density profiles obtained from ionosondes during overflights. This is an extension of the approach that has been successfully adopted for in-flight calibration of the
Tiny Ionospheric Photometer (TIP) sensors on COSMIC.\textsuperscript{30,31} In this case, the profiles would be vertically integrated and compared to the photometer measurements acquired over the ionosonde or GPS tangent point locations. The photometer data themselves can be simultaneously used to ensure that no in-track horizontal gradients are present to compromise the GPS electron density profiles used in validation.

### 3.3 In-Flight Alignment Determination

Stellar apparitions are also vital to mapping and geolocating the measurements by enabling a definition of the range and orientation of the LITES field of view. In order to determine alignment on the ground, it would be necessary to determine the alignment between a reference cube and the actual optical positioning (optical axis) of the full-field ray paths off the grating and onto the detector. This can only be determined by a comprehensive at-vacuum mapping – not a practical possibility. Instead, we have started with our estimation of the alignment based on mechanical tolerances for installation of LITES on the STP-H5 payload, and the STP-H5 payload on the ISS, and used the ISS attitude quaternions in concert with stellar apparitions to resolve these factors. It is noted here that a star-tracker is included on the STP-H5 data, but the attitude solutions we have determined using the ISS quaternions and our stellar mapping have been demonstrated to be more than adequate for the modest spatial resolution of the LITES images.

The vertical and horizontal field of view (FOV) is determined by adjusting the mechanical estimates for the field of view size and orientation to match the appearance and disappearance of stars. First, it was determined when stars appear and disappear in the imaging dimension – appearing first in bin 5 (as shown in Figure 16) and last visible in bin 124 (note that although LITES has 128 super-bins in this dimension, the active area of the detector was mapped to fit inside the full reported range). We used the TD1 Stellar Ultraviolet Flux Survey collected by the Ultraviolet Sky Survey Telescope on the European Space Research Organization TD1 satellite, as compiled by Dr. Scott Budzien at NRL. The range of the full LITES FOV is mapped along with the brightest stars from this UV star catalog as shown in Figure 17. It is serendipitous, and advantageous, that there are two stars in this particular field, and that they are aligned closely with the edge of the LITES FOV. Regardless, by adjusting the active FOV and mapping the scene in this way until the appearances and disappearances match the observations, it was possible to determine the angular width of the FOV across these pixels in the imaging dimension is 9.74°.

As part of this analysis, the pitch angle was simultaneously adjusted to match the position (Right Ascension/Declination, or RA/Dec) of these known stars when they first appear at one edge and disappear on other edge. The offset in pitch was determined to be 14.15°. Since the mechanical wedge was designed to 14.5°, this suggest there exists 0.35° offset in optical alignment and/or mechanical tolerances from installation on the ELC-1 location.

Based on apparitions of stars, each bin is then known to correspond to 9.74°/119 pixels = 0.081849°/pixel. With this scale factor, we then conducted a spectral fit to the stellar image in the vertical dimension to determine the imaging resolution. Using a Gaussian-fit to an image summed across the spectral dimension returns a 2.39 pixel FWHM, equivalent to 0.22° imaging resolution. Note that we did not make any attempt in this early estimate to complete any image straightening, so that this result represents an upper limit. In reality, any tilt in the grating with respect to the detector pixels will result in a slant in the apparent stellar position across the wavelength dimension – a very mild tilt is visible in Figure 16. Even ignoring this factor, the result also shows that our 128-bin imaging data format is properly oversampling the spatial domain by more than a factor of two.
Using this same sequence of stellar apparitions, the LITES FOV in the horizontal (non-imaging) dimension was determined by the apparition over each orbit, through several days. This is the only method that this dimension of the FOV can be determined. A star will appear over several consecutive days, so this requires data to be collected continuously as the star passes on and off each edge of the horizontal field of view (although nice to have, it is not necessary to have continuous measurements as the star passes through the middle of the FOV). The size of the FOV is adjusted in this dimension until it matches the first and last appearance of the star. With this approach, the LITES field was determined to be 10.0°. Akin to the determination of pitch offsets in the imaging dimension, the orientation in the yaw direction was determined to be 180.5° with respect to the ISS body, 0.5 degrees off from a true aft view but certainly a reasonable value given the reliance purely on mechanical tolerances.
3.4 Thermal Effects

During the payload and experiment checkout that occurred in the first 30 days of the mission, we determined that the responsivity of the detector showed early changes due to warming of the microchannel plate. Powering the detector on initiated a short warm-up period as the thermal properties of the detector stabilized. We investigated the possibility that payload temperatures were also contributing to changes in the detector performance observed early in the mission, but concluded that these effects were minor on short timescales. However, the thermal properties of the payload did change such that the observed temperature in the vicinity of the LITES experiment varied by about 12°C over the full 57 day orbit precession (see Figure 19). At low beta angles, the lengthy time spent in shadow were sufficient to cool the payload while high beta angles resulted in higher temperatures, as might be expected. However, we were not able to correlate any changes in the LITES detector to this more gradual trend. In all likelihood, the localized heating of the detector is mostly constrained to the effects of resistive heating on the microchannel plates and not transferred in any detectable amount either to or from the rest of the LITES experiment or STP-H5 payload.

3.5 Ion Mitigation

It was determined early in the mission that the +28 V potential was insufficient to fully reject ions from the detector image. Not only were ions observed over the SAA and auroral regions (primarily in the southern hemisphere near Australia, where the auroral oval reaches to more equatorward geographic locations encompassed by the ISS orbit), we have observed a recurring signature of charged particles that appear to be correlated to a transition of the ISS solar arrays, as exemplified in Figure 20. Although the ISS arrays pass occasionally pass within range of the LITES field of view and potentially could create glints, we have not observed any such signatures in the data. Since we have observed the ion signature repeatedly under both sunlit and fully shadowed conditions, we infer that some interaction (perhaps with the full payload) is generating these signatures in the LITES image. Additionally, lowering the LITES potential on the slit back to +13 V resulted in a discernable increase in ion signal, confirming the source. However, it is also clear that 28 V is insufficient to overcome the energized particles, and may be influenced by a changing potential of the payload chassis introduced by surface charging on the ISS.
Figure 19 – Temperature readings on the STP-H5 payload during the first two months of operation. This includes a two-week period starting in mid-March when the payload was powered off while the ISS program office assesses temperature concerns on the ELC-1. The temperature near LITES routinely oscillates between about 19 and 31 °C over the course of a full orbit precession.

Figure 20 – Ion noise present in the middle of a processed image, which is reoriented here to show the typical location with respect to the approximate tangent altitude and wavelength regions of the detector image.
4. PRELIMINARY SCIENTIFIC RESULTS

4.1 Nighttime Ionosphere

As a demonstration of the potential application of LITES data, we present some of the data collected early in the mission. The brightness of the 911 Å emission reflects the total column electron density, as described in Section 1.2. We have extracted and co-added the segment of the image around the 911 Å emission for each pass through the lower latitudes that include the ionospheric equatorial arcs. These arcs are regions of higher density that form on either side of the equator due to the plasma fountain effect – the uplifting of plasma at the magnetic equator due to $E \times B$ drift followed by gravitational forcing that moves the charged particles back down along the magnetic field lines to either side of the magnetic equator. Longitudinal patterns have been observed in these arcs that may be tied to gravity waves in the lower atmosphere, although the true cause and the variability of these patterns is still a primary topic of investigation and study.

To demonstrate the ability of LITES to measure this variability, we have taken a segment of each orbit as it crosses these equatorial arcs and summed the raw LITES images during that time. We have then taken the segment of the image around the 911 Å emission as outlined in the yellow box in Figure 21 and displayed a full day of these against the location of the orbit track as shown in Figure 22. Each strip is the segment of the detector containing the raw LITES data – brighter emissions mean more ionosphere. The surrounding segment of the detector (in horizontal space) is included to provide an assessment of the background conditions, to ascertain the true background of the emission. In particular, the SAA that spans a region over the eastern part of South America and into the Atlantic shows up prominently in these images as a bright background at all altitudes.

![Figure 21](image.png)

**Figure 21** – A sample of a binned LITES image, color-scaled to emphasize the 911 Å emission that reflects the total column electron density. The companion 1356 Å emission is visible on the left side of the image, near horizontal bin 20. The yellow box marks the region of the detector extracted over each orbit and shown in Figure 22.

The results in Figure 22 are presented according to the approximate local times of the orbit, which means the first image in panel (a) was collected on 18 April 2017 when the ISS orbit plane was crossing the magnetic equator just after sunset near 2000 LT. The next panel (b) is from the previous day, 17 April, but at a later local time. In this manner, Figure 22 shows the progression of the ionosphere in local time.
from just after sunset to early morning when most of the ionosphere disappears. There is also a 6-day gap between 14 April (e) and 7 April (f) when the ISS orbit plane transitioned across the local noon-midnight plane. Due to care taken with implementing and testing the scheduled operations needed during this time (to avoid exposure to the Sun on the daytime segment of the orbit), LITES did not collect data during this period.

The map shows the orbit track where LITES is looking during the data collection, along with the magnetic equator location. The first orbit of the day is shown in blue on the map, and as time progresses the orbit location moves to the west on the map (as the Earth turns under the ISS orbit plane). The image data shows the raw altitude profile of the 911 Å brightness. Each strip represents the brightness for the track for the approximate global location of the orbit shown in the map above it – the track on the far right in each image is the first pass corresponding to the blue orbit track. The part if the image closest to the map (toward the top of each figure) is the lowest altitude, projecting to higher tangent point altitudes away from the map (toward the bottom, and visually projecting out of the page).

There are a few early conclusions that can be made from these images. The LITES data does show similar longitudinal variability to what has been seen in other space-based images. The circled regions in each image mark locations where the ionosphere shows denser structure that may be part of the longitudinal variability seen in previous studies, with higher densities near the west coast of the United States and eastern Pacific Ocean, over the Asia-Australian longitudes, and over the African continent. However, this pattern changes over local time. Importantly, these measurements represent the first measurement of this longitudinal variability of the equatorial anomaly at the 911 Å wavelength whereas all previous measurements in the UV had all used the brighter 1356 Å emission. Additionally, by viewing the altitude structure from the low, 410 km orbit of the ISS, it can be ascertained that the pattern does not suggest any cause due to unique patterns in vertical motion or position of the ionosphere. In fact, our data show on April 3 (Figure 22j) and April 6 (Figure 22g) that ISS maneuvers are apparent in the raw data as the ISS orients the LITES field of view to slightly different tangent point altitudes. No strong changes in ionospheric height are otherwise visible in the data.
Figure 22 – Daily maps of the 911 Å emission from LITES (see text for discussion).
(d)  
15 April 2017  
2100-2240 LT  

(e)  
14 April 2017  
2130-2300 LT  

13-8 April 2017  
No data due to low solar beta angle  

(f)  
7 April 2017  
0020-0140 LT  

Fig. 20 (continued).
Fig. 20 (continued).
(j) 3 April 2017 0155-0315 LT

(k) 2 April 2017 0225-0335 LT

(l) 1 April 2017 0245-0400 LT

Fig. 20 (continued).
4.2 Daytime Ionosphere

The daytime ionosphere is evaluated using two airglow emissions, the 834 Å and the 617 Å as outlined in Section 1.3. The primary measure is the altitude profile of the 834 Å emission. Figure 23 shows the accumulated profiles for four segments of an orbit on 1 April 2017. The first part of the orbit is in early morning local times when the sun is just beginning to recreate the ionosphere. Densities are low, and the low solar zenith angle also means the brightness is low. As the ISS moves to higher solar zenith angles, the emission increases in brightness by a factor of 4. When the ISS moves through the equatorial regions in the mid to late afternoon where the ion density is high, the effects of scattering of the 834 Å emission by these ions results in a decrease in signal along with a slight flattening out of the altitude profile at the highest altitudes. Algorithms have been developed at NRL for the SSULI mission and the upcoming NASA Ionospheric Connection Explorer (ICON) that can be adapted in the future to use these altitude profiles in an inversion algorithm to retrieve ionospheric density profiles.

Figure 23 – Map of the orbit, divided into four segments: (1) is early morning, (2) and (3) represent increasing solar zenith angles, and (4) represents late afternoon when looking through the equatorial arcs.
LITES does measure the 617 Å emission feature but the emission is very close to the far-most edge of the active area on the detector and so is partially clipped (see the example image in Figure 14). However, it does measure enough of it to ascertain the details of the solar ionization term that is used to improve ionospheric retrieval algorithms. To demonstrate this capability, the total brightness of both the 617 Å and 834 Å emissions for one daytime pass on 2 April 2017 are shown in Figure 24. The underlying airglow generation is represented by the 617 Å profile and shows the changes due to solar illumination. The 834 Å emission shows a similar trend, but has two large bite-outs in brightness on either side of the magnetic equator caused by absorption of these photons by O⁺ ions. It is also interesting that at the low altitude of the ISS orbit that the emission is directly connected to the location of the ISS rather than the tangent point. This may be expected since the ISS is very near the source of these photons. Digisonde data taken at Guam (13.62 N latitude, 144.86 E longitude) between 0330-0400 UT show NmF2 of near 7.2 x 10⁵ cm⁻³ and hmF2 of 299-312 km (data available from the University of Massachusetts Lowell Global Ionosphere Radio Observatory (GIRO)²¹ at http://ulcar.uml.edu/DIDBase/). It is important to emphasize that these are the closest ground-based measurements available for comparison (nearly 40 degrees in longitude away) since the orbit path is over the middle of the Pacific Ocean, which highlights the necessity for space-based remote sensing for global ionospheric and thermospheric specification.

4.3 Daytime Thermosphere

The daytime thermosphere traditionally requires measurement of the atomic oxygen emission at 1356 Å along with some part of the N₂ Lyman-Birge-Hopfield (LBH) band. While LITES does measure the 1356 Å emission, most of the LBH system is longward of the LITES passband cutoff around 1400 Å. The best opportunity to fit within this construct is to analyze the part of the LBH system around 1383 Å. Figure 25 shows a mapping of the altitude profile of these two emissions across one segment of a daytime orbit. This segment is the same used to demonstrate the daytime ionospheric emissions in Figure 24. The top
Figure 25 – Top: image of the 1356 Å emission measured by LITES during one daytime pass on 2 April 2017. Contours of equal tangent point altitudes are shown. The vertical line shows the point where the line of sight at 300 km tangent altitude intersects with the magnetic equator. High-altitude airglow above 250 km is a product of radiative recombination in the daytime ionosphere. The remainder at low altitudes derives from atomic oxygen in the thermosphere. Middle: The 1383 Å N₂ Lyman-Birge-Hopfield band. Bottom: ISS orbit for the data shown. The magnetic equator is shown in blue.
panel shows the 1356 Å emission that is produced primarily by photoelectron impact in the lower thermosphere, below 200 km. On top of this, the contribution from the radiative recombination of oxygen ions is also visible, both in the general increased glow between hours 3.5 and 4.0 that correspond to the lower latitude crossing. Additionally, the bright equatorial arcs are visible at higher altitudes extending up to 350 km. The dashed line represents the time when the line of sight at 300 km tangent altitude is crossing the magnetic equator. Even though the 1356 Å emission is a line-of-sight quantity, these data confirm that LITES is still able to cleanly separate the arc locations under normal conditions. These directly correspond to the dip in emission seen in the 834 Å emission in Figure 24, providing qualitative confirmation that LITES is able to observe the key ionospheric emission both day and night at least during solar minimum. The N\textsubscript{2} LBH emission is shown in the middle panel and primarily reflects the lone photoelectron source for this emission. Some residual emission is seen at the highest altitudes – it is not clear if these are edge-effects of the signal processing or if they represent real emissions.

Analysis of the above emissions allows us to directly determine O and N\textsubscript{2} densities, but only infer O\textsubscript{2} based on how these emissions are absorbed. When done in the context of a complete inversion, this has been found to have some ambiguity because the airglow itself is changing. Stellar observations present an alternate opportunity to obtain O\textsubscript{2} densities in the lower thermosphere due to the attenuation of stellar signals. Since there are several stable UV-bright stars, it is possible to observe the change in brightness as the star sets below the horizon as the ISS orbits. This option has been briefly examined and, although we do not present a detailed analysis here, it has been shown to be feasible to determine thermospheric O\textsubscript{2} densities at lower altitudes using stellar occultation.

**SUMMARY**

The LITES experiment has flown on the ISS as part of the STP-H5 payload, to demonstrate the capabilities of a novel sensor that can provide ionospheric and thermospheric imaging information from a low size, weight, and power sensor. The optical imaging capabilities allows full altitude profile emissions to be collected without the need for scanning mechanisms or other moving parts.

We have successfully collected more than one year of data that demonstrates several of the key measurement goals for daytime and nighttime ionosphere, and daytime thermosphere. Although the detailed scientific analysis of the data is ongoing, the LITES experiment has already met its intended mission objectives and passed all criteria for minimum mission success.

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Digisonde data are openly available from the University of Massachusetts Lowell Global Ionosphere Radio Observatory (GIRO) Data Center at http://spase.info/SMWG/Observatory/GIRO. This paper uses ionospheric data from the USAF NEXION Digisonde network; the NEXION Program Manager is Mark Leahy.
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