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Tiny Remote-sensing Instrument for Thermospheric Oxygen and Nitrogen: A Concept Study

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EXECUTIVE SUMMARY

The primary objective of this project is to develop the Tiny Remote-sensing Instrument for Thermospheric Oxygen and Nitrogen (TRITON), an innovative sensor concept to measure exospheric temperature and O & N_2 concentrations in the thermosphere on a global scale. Thermospheric specification is critical for the next generation, assimilative Coupled Ionosphere/Thermosphere Models (CITMs) currently under development at the NRL and elsewhere. CITMs are expected to facilitate unprecedented nowcasting and forecasting capabilities with significant impacts on Naval applications, including ship-to-ship and ship-to-shore high frequency (HF) communications, HF over-the-horizon radar (OTHR), and HF emitter geolocation. TRITON is envisioned as a next-generation instrument to make high accuracy measurements of the Earth's thermosphere from a low-cost, CubeSat platform. The TRITON instrument concept, once built, could be space-flight-tested through the DoD Space Test Program. The measurement objective also fits within Objective 2.4 of the National Space Weather Strategy and Action Plan to "Identify, develop, and test innovative approaches to enable enhanced, more informative, robust, and cost-effective measurements."

The measurement concept and techniques were tested and refined using far ultraviolet (FUV) measurements from the Special Sensor Ultraviolet Limb Imager (SSULI) and inverted using Volume Emission Rate Tomography (VERT) algorithms to infer the 2D distribution of species along the orbit plane. Thus, the TRITON approach can be validated using existing thermospheric measurements. Additionally, the results of the SSULI inversions will be compared to thermospheric models for additional validation.

Primary accomplishments made during the year of effort include:
1. TRITON instrument concept development and refinement based on lessons learned from test and evaluation of heritage sensors
2. Demonstration of thermospheric measurement capability expected from TRITON observations based on legacy SSULI observations

Details of the TRITON concept are detailed in the following report. Specific engineering considerations are laid out for the needs of the experiment in a generalized sense, and the engineering development needed to advance the state of technology is described. The instrument development is not funded as of the submission of this report, so the expected performance of the instrument is still purely conceptual.

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TINY REMOTE-SENSING INSTRUMENT FOR THERMOSPHERIC OXYGEN AND NITROGEN: A CONCEPT STUDY

1. INTRODUCTION

The Tiny Remote-sensing Instrument for Thermospheric Oxygen and Nitrogen (TRITON) is an experiment concept under development at the U.S. Naval Research Laboratory (NRL) for specification of primary components in the Earth's lower thermosphere, O and N_2, via inversion of Far Ultraviolet (FUV) dayglow observations. Space-based images of FUV dayglow have been used for several decades to determine quantitative information about the thermosphere, from George Carruthers' moon-based FUV telescope [1] and the Dynamics Explorer 2 imager [2] to some of the most recent NASA missions like the Ionospheric Connections (ICON) Explorer [3] and the Global-Scale Observations of the Limb and Disk (GOLD) Mission. [4]

Disk observations of Earth's FUV dayglow emissions produced by O and N_2 are often used to determine column density ratio, $\Sigma O/N_2$, between the two species. [5] Along with a few additional parameters - solar zenith angle and viewing angle from nadir - the geophysical importance of the column density ratio has been repeatedly demonstrated. However, assumptions made when deriving the column density from dayglow measurements prevent empirical determination of the height distribution of gases in the thermosphere. [6] One way to determine the vertical distribution of thermospheric density is through inversion of dayglow measurements along Earth's limb, as is intended for the TRITON experiment.

Limb measurements are made by a variety of space missions with FUV spectrometers. For example, the ICON/FUV spectrometer and the Thermosphere Ionosphere Mesosphere Energetics and Dynamics/Global Ultraviolet Imager (TIMED/GUVI) spectrometer both measure the Earth limb perpendicular to the spacecraft orbital trajectory, providing profiles adjacent to the spacecraft orbit. [7, 8] The Defense Meteorological Satellite Program (DMSP) Special Sensor Ultraviolet Limb Imager (SSULI) spectrometer provides tomographic specification along the orbit track, but this is a large, complex, operational instrument that requires significant size, weight, and power (SWaP) considerations. [9]

TRITON is the next step in a spiral development of ultraviolet remote sensing technology under the NRL Space Science Division (NRL/SSD) and will measure under-sampled thermospheric regions with new, innovative technology applications. Specifically, TRITON will use measurements of FUV dayglow emissions to determine the density of atomic oxygen (O) and molecular nitrogen (N_2) in the thermosphere. A third ultraviolet emission "color" will be measured to determine the density of oxygen ions (O^+) in the ionosphere to account for their contribution to the oxygen dayglow. The three dayglow emissions will be combined through a tomographic inversion process to determine the altitude distribution of O and N_2. The measurements are especially targeted to measure altitudes below 200 km, which has recently been called the "ignorosphere" due to the lack of observations in the range from 100-200 km. [10]

The vertical distribution of thermospheric density has a significant impact on satellite drag as well as distribution of ionosphere density. Thermospheric specification is applicable to ionospheric prediction because

improved specification of the thermosphere increases the accuracy ionospheric forecasts. In other words, today's thermosphere is tomorrow's ionosphere because the neutral atmosphere is the seed population for the ionosphere, which is created each day by solar extreme ultraviolet (EUV) radiation. Some ionospheric forecasts rely on empirical models of the thermosphere, which are data starved for thermospheric measurements. A state of the art operational model for predicting total electron content and other ionospheric behavior is the Coupled-Thermosphere-Ionosphere-Plasmasphere-electrodynamics (CTIPe). [11] CTIPe is a first-principles model operated by the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC). The model takes solar wind input from the Advanced Composition Explorer and previous day's F10.7 value to drive the model and provide a prediction approximately 30 minutes ahead of real-time. The thermosphere component of the model simulates the time-dependent global structure of the wind vector, temperature, and density of the neutral atmosphere by numerically solving the non-linear primitive equations of momentum, energy, and continuity on a three-dimensional spherical polar grid rotating with the Earth. The neutral model output provided is the wind vector, temperature, and number density of O, O_2, and N_2, as well as mean molecular mass. Even with a first principles model, the outcome of a model in such a highly complex and coupled system can depend heavily on the initial or forcing conditions. [12] Thermospheric measurements returned and processed on the order of only a few hours would provide the near real-time information necessary to improve ionospheric forecasts in a significant way.

A limb-scan implementation of TRITON in the orbital plane of a high inclination orbit would provide significant improvements over current observational capabilities. Limb inversions provided by an instrument like TRITON can provide composition information at a range of altitudes with consistently high accuracy, especially in the 150-350 km altitude range. Altogether, the TRITON instrument suite provides a small, simple alternative to larger, operational spectrometers while still providing meaningful capability. Small, CubeSat-class instruments would enable distributed arrays of instruments that would increase measurement coverage for either real-time knowledge of the region or improved empirical specification. The following document lays out the mission concept and requirements needed to successfully carry out the experiment.

2.   EXPERIMENT OVERVIEW

The Tiny Remote-sensing Instrument for Thermospheric Oxygen and Nitrogen (TRITON) is a space-based remote sensor suite for thermospheric density specification through dayglow emission measurements. TRITON will measure three FUV emissions to determine the density of primary components in the ionosphere-thermosphere: (1) atomic oxygen (O), (2) molecular nitrogen (N_2), and (3) oxygen ions (O^+). Evaluation of the TRITON measurements relies on this "three color" approach to invert the measured FUV and MUV dayglow emissions to specify oxygen density, [O], and molecular nitrogen density, [N_2]. The third "color" helps correct for contaminating ionospheric emissions produced by O^+ in highly ionized regions, particularly around the equator. The TRITON experiment has a simple, primary objective.

> **Experiment objective:** TRITON will determine O and N_2 density in the daytime thermosphere with ultraviolet remote sensing from a CubeSat-sized platform.

TRITON is a 6U CubeSat-compatible instrument (1U = 10 cm × 10 cm × 10 cm) that relies broadly on commercial, off-the-shelf (COTS) components. TRITON also relies on a simple optical layout with minimal moving parts to provide a robust design with low SWaP needs. The full experiment consists of

Fig. 1—Model concept of the TRITON modular instrument sensor head based on two individual Tri-TIP-like photometers and a single Tri-MIP-like photometer, along with the SUVM scan mirrors

three 1U-sized sensor heads, one for each target emission, and three identical 1U scanning mirrors, one for each sensor head. Figure 1 shows the mechanical concept of the full instrument suite.

TRITON is a modular instrument concept based on a combination of legacy sensor designs, the Triple Tiny Ionospheric Photometer (Tri-TIP) [13] and the Triple-MUV Ionospheric Photometer (Tri-MIP) [14]. In addition to the primary sensors, TRITON also relies on a Scanning UV Mirror (SUVM) that was first developed for use with Tri-MIP. TRITON is designed as a Low Earth Orbit (LEO) experiment and orbital requirements are flexible across the LEO domain in terms of operating altitude and inclination. A key requirement to achieve the desired program objective would include reaching sufficient orbital altitude to observe from above the peak density of the ionosphere ($\geq$400 km). Maintaining nominal mission operations for a year would enable coverage over a full range of geophysical conditions at a particular point in the solar cycle.

2.1   Experiment Concept of Operations

The primary concept for TRITON operations as a limb scanner will provide altitude profile measurements for inversions of thermospheric density. The primary operating region is on the Earth's dayside, but the detectors are capable of running continuously through the nightside and would represent the simplest operational concept at the cost of additional power requirements. TRITON requires a host spacecraft and ground support for managing the downlink of payload telemetry. Each subassembly in TRITON is individually operated, and in its most basic configuration would communicate directly with the host spacecraft. Additional command and control is possible to provide through additional control electronics, but would come with an increase in SWaP and would be handled on a case-specific basis.

The optimal implementation of TRITON is to measure the limb in the orbit plane such that the measurements may be used to perform tomographic inversions of the thermosphere. The in-track style of limb scan

measurement has been used previosuly with space-based remote sensing instruments (e.g. SSULI). Alternatively, the instrument may be oriented to scan the limb perpendicular to the spacecraft trajectory, which has also been used with success in missions like TIMED/GUVI and ICON, though the TRITON mirror scan would reduce potential spatial resolution. The major caveat to any operational scenario is the risk of pointing at the sun. Each detector has an auto-protect feature built in to guard against accidental exposure to direct solar illumination, but regular exposure under routine operations would significantly degrade the photocathode at the core of the sensors and quickly reduce mission lifetime. Risks associated with this sort of routine exposure can be mitigated with regular communication with the spacecraft operators, but is best avoided entirely if possible.

2.2   Alternate Concepts

The simplest data product possible with the fewest complications for spaceflight application is the $\Sigma O/N_2$ ratio measured by a disk-viewing platform from well above the F peak region of the ionosphere. This ratio is a neutral density data product provided by missions like GOLD, ICON and TIMED/GUVI disk measurements. [7, 15, 16] The $\Sigma O/N_2$ ratios based on these data provide a simple quantity that enables a direct comparison with thermospheric models. While full altitude profiles of absolute density are the desired data product, there is some utility in additional coverage of $\Sigma O/N_2$, which a disk implementation of TRITON would provide. Depending on the flight opportunity, the 6U volume can be rotated such that the SUVM scans the disk rather than the limb.
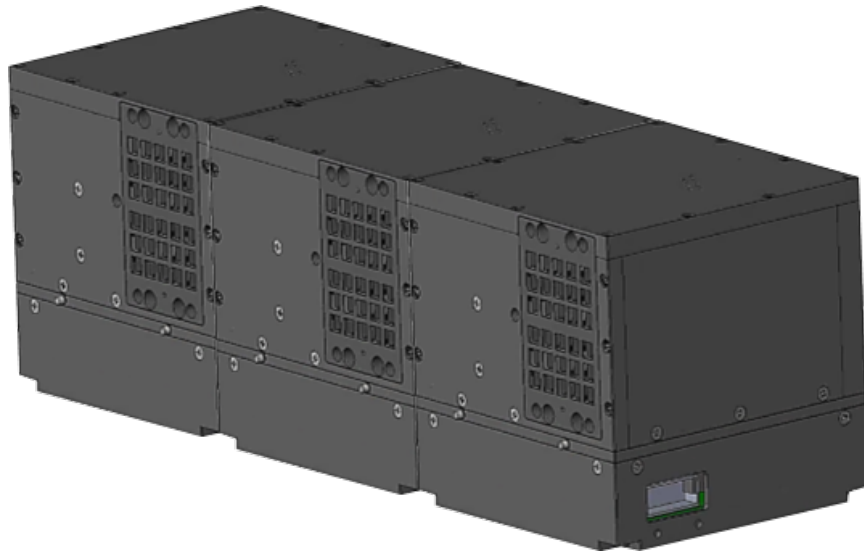

Fig. 2—Model concept of the TRITON modular instrument sensor head based on two
individual Tri-TIP-like photometers and a single Tri-MIP-like photometer

In an even further simplified concept, the TRITON sensor head could operate without being paired with a SUVM. This provides limited capability but has lower size, weight, and power requirements. Figure 2 shows a model concept of the instrument sensor heads with each of the three photometers co-aligned, as evident by the gridded collimators visible in each of three cubes. There are two primary ways the TRITON ways could operate with just the sensor head.

- Mirrorless Scan Mode – This would effectively accomplish the same objective as the primary concept of operations but requires the host spacecraft to perform the pitch angle scan procedure, which could be a prohibitive mode for any other payloads on the mission

- Nadir Stare Mode – The sensor could stare along spacecraft nadir to observe the column O/N_2 ratio. In this scenario, an in situ neutral density sensor paired with TRITON could help to better infer the density profile, but not as accurately as a direct measurement.

3. PAYLOAD ENGINEERING

The TRITON suite of instruments derives heritage from two specific instruments developed at NRL/SSD. The first, Tri-TIP, was developed for the Coordinated Ionospheric Reconstruction CubeSat Experiment (CIRCE), a joint US/UK mission. The CIRCE objective is to accurately characterize the dynamic ionosphere by providing tomographic specification of electron density versus altitude derived from simultaneous UV observations of the ionosphere from multiple CubeSats and different view angles. [13] Tri-TIP measures the FUV emission of atomic oxygen (O) at 135.6 nm to determine ionospheric density on the nightside. TRITON will adapt Tri-TIP to measure the same emission line in the brighter dayside environment where the photochemistry of the emission line can be used to infer neutral density.

The second instrument TRITON derives heritage from, Tri-MIP, was developed to detect magnesium ion signatures in the ionosphere as an indicator of sporadic E. [14] The Tri-MIP design will be adapted to measure an emission of oxygen ions (O^+) at 247 nm. The mechanical design will remain nearly identical, and a change of filters will allow for a shift in primary wavelength of detection. An adjacent optical path will measure a nearby bandpass to determine a background signal for correcting the primary signal.

Each Tri-TIP / Tri-MIP sensor (hereafter called Tri-XIP when referred to collectively) will be paired with its own dedicated SUVM. Each of the 6 payload modules are independently controlled through their own internal electronic system. Figure 3 shows the architecture of the payload relative to the command and data handling (CDH) system. Although the components are controlled individually, the experiment as a whole will be treated as a solid unit.

The optics relevant for TRITON are purely conceptual at this point and require development to reach a flight-ready maturity. The current Technology Readiness Level (TRL) is 2 based on the maturity of the optics. Test and analysis as performed for prior missions like CIRCE would easily raise the TRL to level 4. Optical characterizaton will also allow for an assessment of the optimal emission target for measurement of N_2. There are options in both the FUV and MUV, each with their own advantages and disadvantages. The FUV spectral region contains the LBH band, which is most commonly used to measure N_2, but narrow-band filters suitable for use in the terrestrial dayglow are not commercially available. The MUV region contains a wide array of emission targets that may be used to infer the N_2 density. For example an emission of ionized nitrogen (N^+) at 214.3 nm has been used for this type of analysis previously [17] and there are narrow band filters that are potentially available in this spectral range, but the MUV spectrum is rich with emission lines (NO, N_2 VK bands, etc) which would complicate the analysis process.

The specific requirements for the total payload will vary, depending on adaptions for the O and O^+ sensors as well as future optical evaluations for the most suitable N_2 sensor solution. Component-specific attributes are discussed in subsequent sections. The full 6U payload mass will total $\approx$ 9 kg in the 6,000 cm^3
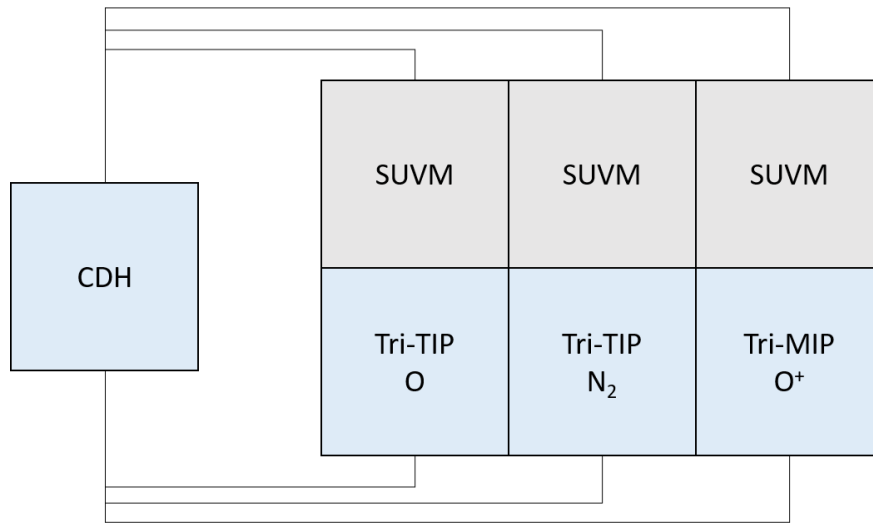
Fig. 3—Simple block diagram illustrating the overall architecture of the TRITON
experiment.

volume. All six subpaylods operating together draw $\approx$ 15 W orbit averaged and peak at $\approx$ 32 W. TRITON is an optical payload that requires a pointing accuracy requirement of 1°and a pointing knowledge requirement of 0.1°. The full TRITON payload can be operated at a range of orientations with the proper knowledge of conditions. Additional needs specific to each sensor are addressed in the following sections.

3.1   Tri-TIP Sub-Assembly

Tri-TIP is a low-mass ($\approx$ 1.6 kg), low-power ($\approx$ 1 W orbit averaged, $\approx$ 3.6 W peak), 1U (1,000 cm^3) CubeSat class instrument. The core of the Tri-TIP consists of two sub-assemblies, an Instrument Data Controller (IDC) and a Photometer Sensor Module (PSM). The IDC is contained in an aluminum tray at the base of the instrument assembly and generates telemetry packets at 1 Hz (115.2 kbps). The PSM sits on top of the IDC tray and contains the three photomultiplier tubes (PMTs), a Strontium Fluoride (SrF$_2$) cut-off filter with heater and temperature sensors, a sapphire (Al$_2$O$_3$) or magnesium fluoride (MgF$_2$) beam splitter, and a primary parabolic mirror (see Figure 4). Tri-TIP also includes a shutter in the optical path between the parabolic mirror and the heated SrF$_2$, but is not shown here for clarity of the optical components.

Light enters Tri-TIP through a series of baffles. After the baffle, an off-axis parabola (OAP) mirror focuses the parallel input light. The SrF$_2$ filter is heated to 100° C to shift the filter cutoff longward of 130 nm, which cuts out the bright airglow emission at 130.4 nm. The polka dot beam splitter then reflects half of the signal to one PMT and passes half to another PMT. Tri-TIP uses commercially available, Hamamatsu R13194 PMTs with a peak response at 130 nm. The sapphire beam splitter has a natural cutoff of $\approx$ 140 nm that measures all emissions that may potentially contaminate the UV signal of interest at 135.6 nm. The signal reflected off the surface of the beam splitter is the primary signal, and the signal that passes through the beam splitter is the "red" signal that captures long wavelength contamination. Slits are installed in front of the both the UV and red PMT apertures to limit the field of view to 0.2° $\times$ 7.25°. The third PMT is sealed from incoming light and measures the effects of high energy particles and other sources of background dark noise in the system.
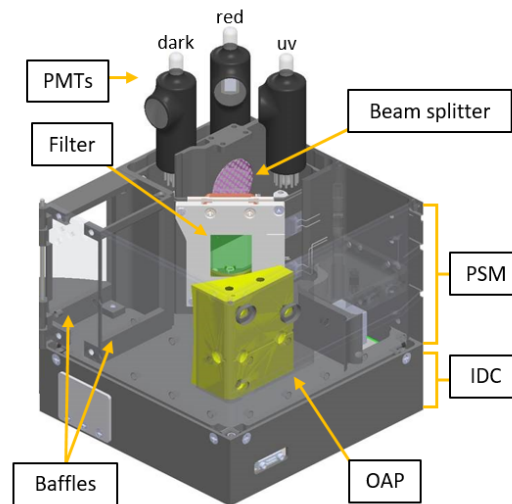
Fig. 4—Partially exploded view of the Tri-TIP instrument with primary components
labeled

Tri-TIP was designed specifically to measure emissions of neutral atomic oxygen at 135.6 nm. Post-processing uses data from all three Tri-TIP PMTs to provide a true measure of the atomic oxygen signature. Figure 5 illustrates the data flow through the instrument, including post processing, to produce the isolated measurement of 135.6 nm. The PMTs are extensively tested and characterized during the build process to match up dark count characteristics and photocathode response at long wavelengths. [18]

Several updates will be required to adapt the optics for use on the dayside in TRITON, primarily to account for the much brighter conditions in the dayglow. A TRITON version of Tri-TIP will require a more robust baffle system, or potentially even a pinhole aperture, but further analysis is required to determine the optimal solution for conditions on the dayside. Solar filters may be placed at the entrance aperture to block as much as possible of the bright, visible portion of the solar spectrum. FUV bandpass filters may also be placed closer to the PMT slit to narrow the effective bandpass and help to suppress other bright, nearby FUV emissions. Future trade studies will be conducted to assess the suitability of each component in question.

3.2 Tri-MIP Sub-Assembly

The Triple-MUV Ionospheric Photometer (Tri-MIP) is a low-mass ($\approx$ 1 kg), low-power ($\approx$ 1 W orbit averaged, 7.4 W peak), 1U (1,000 cm^3) CubeSat compatible instrument, based in large part on the Tri-TIP instrument. [14] Each Tri-MIP contains, in general, the same two sub-assemblies as Tri-TIP, an Instrument Data Controller (IDC) and a Photometer Sensor Module (PSM), and both serve the same function as for Tri-TIP. The general structure of the Tri-MIP is shown in Figure 6. The PSM sits on top of the IDC tray and consists of a collimator, narrow band filters for on-band/off-band measurements, two lenses, shutters in each optical path, UV calibration LEDs, slits, and three photomultiplier tubes (PMTs). A sun sensor, oriented perpendicular to the baffle entrance is co-aligned with the field of view (FOV) of the scan mirror. The sun sensor is included on the IDC to shut down the HVPS and close the two shutters in the event of close incursions of the sun (or other overly bright source) on the FOV of the sensor.

Light enters through the stacked-grid collimator before passing through the bandpass filter. Tri-MIP was designed with a Fresnel lens to focus incoming light onto the detector. The shutters are positioned in front of
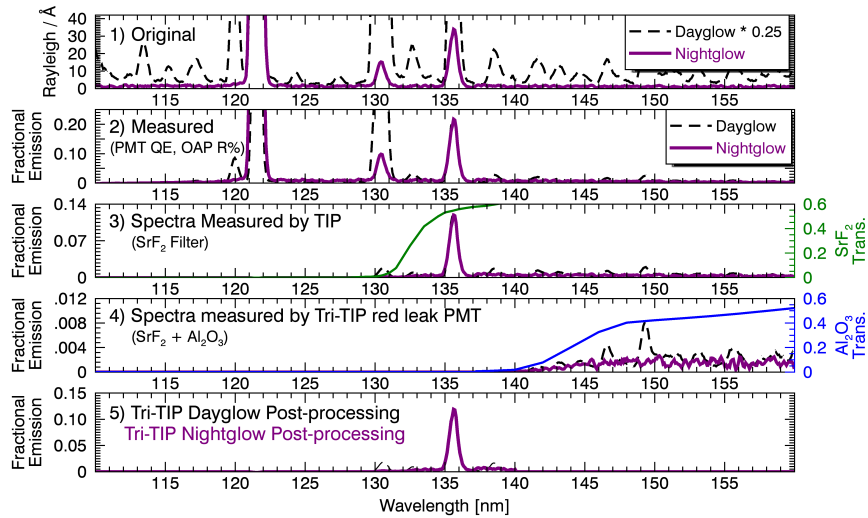
Fig. 5—Sample airglow spectra illustrate the effect of the optics and post-processing in producing an isolated measurement of the desired emission line. A full, raw spectrum in the top plot is filtered multiple times, and the difference between panels 3 and 4 are used to determine the final emission in panel 5. Plots highlight the effects on nightglow, but the same principle applies to dayglow emissions.

the PMTs to control access to the slits, which a sized to provide a $5° \times 0.1°$ field of view. To accommodate a different PMT form factor for Tri-MIP, the PMTs were split off to a separate detector card that mounts to the back of the optical path shown in Figure 6. One PMT measures the primary signal airglow emission, another is used to account for the background contributions in the primary signal. A third PMT detects background high energy particle contamination due to electrons, protons, and cosmic ray particles. Included in the Tri-MIP PSM are two UV LEDs used for functional/performance testing and on-orbit calibration.

Tri-MIP will be adapted to measure O^+ emission in the ionosphere at 247 nm. Figure 7 shows the filter bandpasses that were used in the original Tri-MIP design to illustrate the spectral behavior expected for the TRITON adaptation. Narrow bandpass filters were developed specifically for target emissions of Mg^+ at 280.0 nm and a nearby emission line (N_2 Vegard-Kaplan) for a background. The TRITON implementation Tri-MIP will require updates to the optical path in a similar manner to Tri-TIP. The baffle throughput will be reduced, likely down to a pinhole. The reduced baffle throughput means a smaller lens may be used, which would allow for a more conventional spherical lens rather than the Fresnel lens currently in use. Bandpass filters with appropriate spectral characteristics will need to be acquired and characterized. Finally, the Tri-MIP PMT (Hamamatsu R9875P) will be evaluated for suitability in light of the new emission target.

3.3 SUVM Sub-Assembly

A Scanning UV Mirror (SUVM) has been developed by for use with the Tri-XIP instruments. SUVM is an independently functioning, 1U (1,000 cm^3) compatible unit that has a mass of ≤ 1 kg. The mirror can scan over a full $46°$ range, to provide a $90° \times 6°$ field of view. The mirror scans at rates ranging from $0.05° \text{ s}^{-1}$ to $35° \text{ s}^{-1}$ and requires less than 7.5 W power at its peak. A SUVM will be paired with each PMT instrument on a common assmbly plate for optical alignment with the sensor head.

A model of the mirror with transparent walls is shown in Figure 8. The mirror will be stowed during launch with a launch lock in place, shown on the left, external face of the model. The launch lock will retract
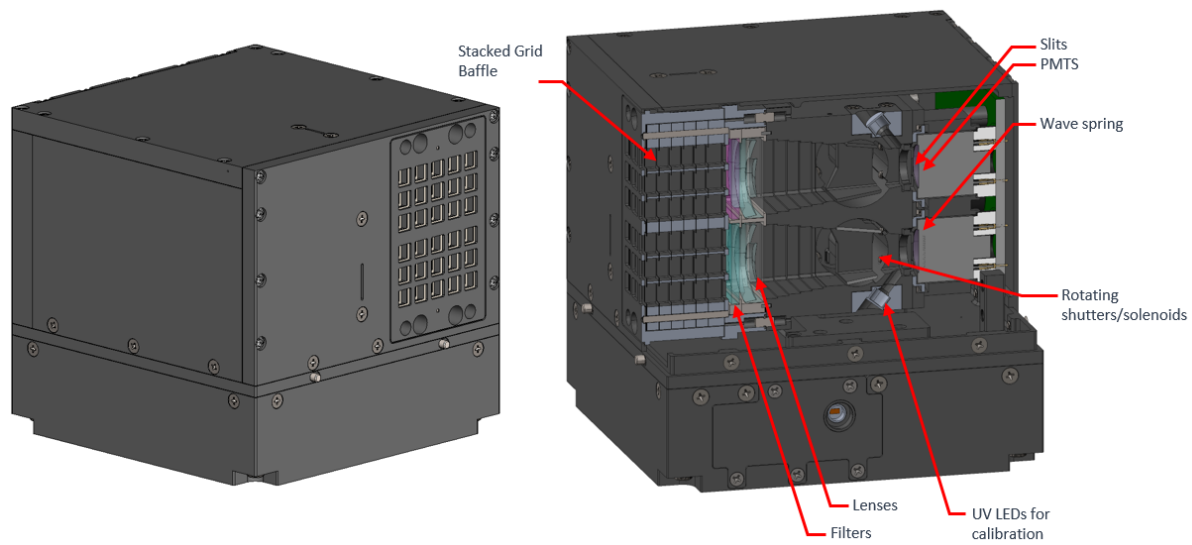
Fig. 6—CAD Model of the full Tri-MIP Instrument (left) and a cutaway to highlight the essential internal components of the instrument (right). The full instrument fits within a 1U (10 cm × 10 cm × 10 cm) envelope
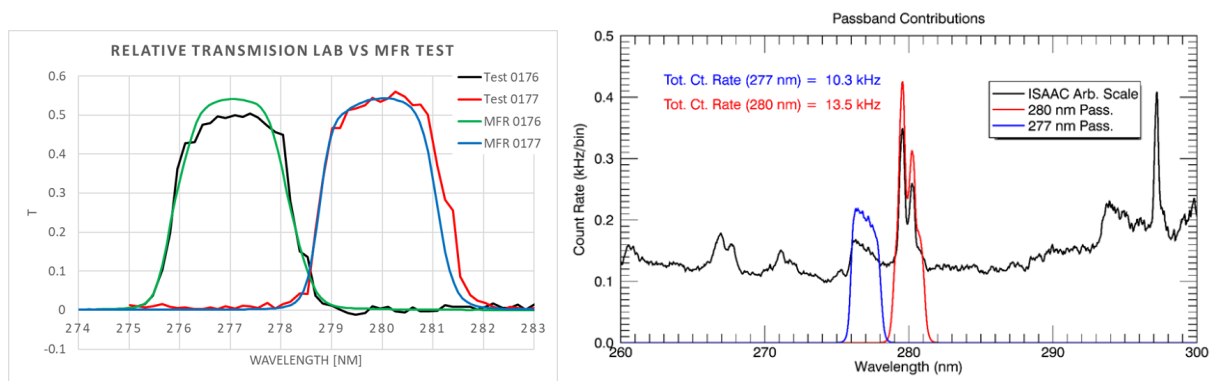

Fig. 7—Left: Transmission plot shows the manufacturer specification (MFR) and the in-house test results (Test) for the two bandpass required for Tri-MIP. Right: Sample airglow spectrum illustrate how the bandpass filters will be applied to the target airglow emission features. [14]

after payload deployment. The scan mirror is contained within the upper portion of the instrument volume. The mirror is completely recessed within the housing and is exposed through a 5.5 cm × 10 cm aperture. The lower portion of the instrument contains the motor and associated electronics.

4. DATA REDUCTION AND APPLICATION

TRITON telemetry will be received and processed at NRL/SSD for ingestion into assimilative models of the thermosphere. Data processing and analysis algorithms have been developed to invert MUV and FUV airglow emissions into ionospheric and thermospheric quantities. The data reduction methodology needed to convert raw Tri-TIP signal into the isolated emission has been covered extensively. [19] The
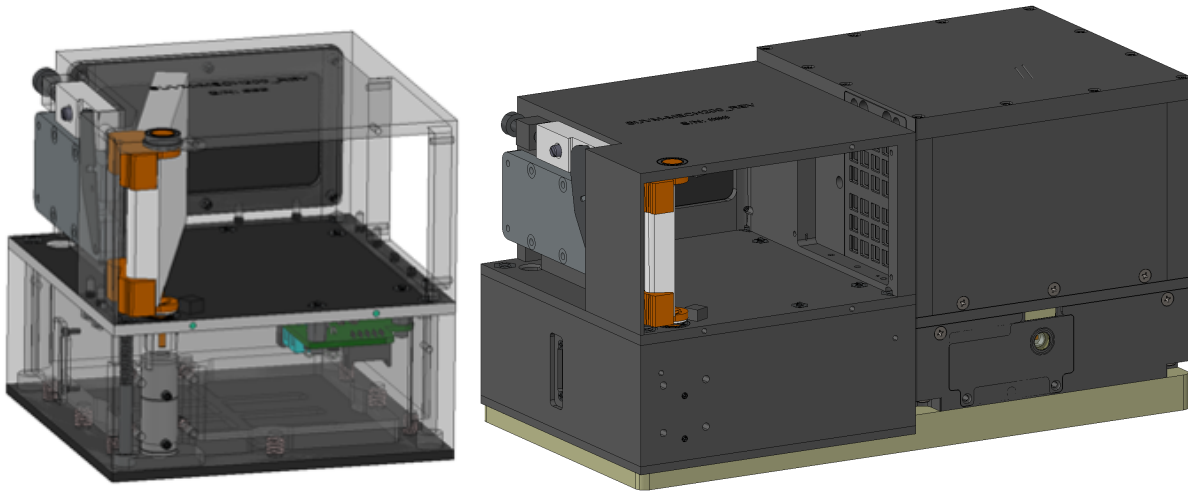
Fig. 8—Semi-transparent CAD model of the SUVM showing the internal components (left) and scan mirror added to the front aperture of the Tri-MIP instrument (right)

preferred limb-viewing geometry for TRITON makes the data reduction cleaner because there is less red-leak contamination to account for, but other long wavelength emissions are still a concern on the dayside and need to be removed.

Similar methodology will be applied to the Tri-MIP emissions, with sensitivity and dark count corrections being most important. However, the bandpass filter approach used in Tri-MIP doesn't require the differential subtraction to create the target bandpass. Instead, the N_2 V-K emission is used to correct for other background effects. For TRITON, a similar concept will be applied, with the primary signal at 247 nm being paired with a nearby emission, possibly the NO γ (1,0)) emission.

The third "color" in the TRITON data reduction approach that hasn't been directly addressed in detail, so far, is for determination of the N_2 density. The final selection for the target nitrogen emission has not yet been made, as several approaches are in consideration. The FUV instrument could be adapted to measure the N_2 Lyman-Birge-Hopfield (LBH) emission bands between 150 nm - 200 nm. The LBH emission band is used often to determine the N_2 contribution when measuring the dayglow with spectrometers, but the FUV has limited options for materials, which can make engineering a challenge. Another option under consideration is to adapt the Tri-MIP design to measure one of the N_2 generated emissions in the MUV dayglow, of which there are several to choose from. The bandpass filters that would be manufactured to support this choice would make some of the engineering simpler, but the rich spectrum of emission lines in the MUV would make analysis of the output signal a very challenging problem.

The atomic oxygen emission, OI 135.6 nm, is perhaps the most frequently used FUV airglow feature to study Earth's ionosphere and thermosphere. On the nightside, this emission line is used to determine the electron density in the ionosphere. Extensive work in NRL/SSD has been done to infer electron density from SSULI observations. [20] Contemporary missions like ICON and GOLD also rely on OI 135.6 nm to specify the nighttime ionosphere, where the photochemistry of the ionosphere makes the emission feature a useful proxy for electron density. On the dayside, however, photoelectron excitation means that the same emission line is an indicator of the neutral density rather than the plasma density. SSULI, ICON and GOLD can all also measure the N_2 Lyman-Birge-Hopfield (LBH) emission bands in order to quantify the O/N_2 ratio in Earth's dayside thermosphere, or in the case of SSULI, vertical profiles of the neutral density.

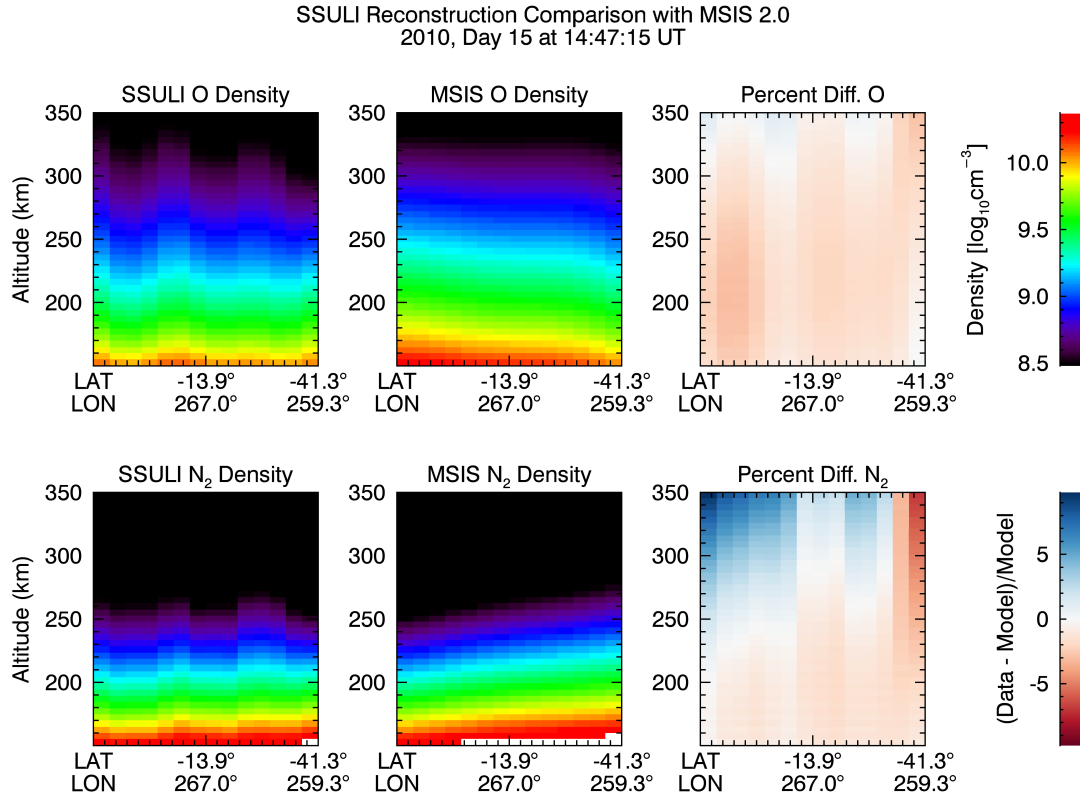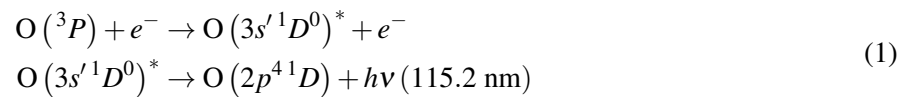SSULI Reconstruction Comparison with MSIS 2.0
2010, Day 15 at 14:47:15 UT

Fig. 9—Atomic oxygen and molecular nitrogen two dimensional profiles from Special Sensor Ultraviolet Limb Imager (SSULI) data (left panel) compared to the same parameters derived from the MSIS climatological model (center) for Jan 15, 2010. Percent difference between two (right) shows large differences and unexpected structure.

Figure 9 shows a recent analysis of dayside SSULI observations on 25 January 2010. The analysis used spectral emissions of oxygen and ionized nitrogen to tomographically invert limb scans of airglow into vertical profiles of neutral density along the orbit track (left column). The center column shows the neutral density derived from the NRLMSISE-00 climatological model for the same locations and under the same conditions. The right column shows the percentage difference between the reconstruction and the model output, which highlights the major differences that can be found in the data when compared to climatology. These inversions were done using two optically thin emissions of O (OI 115.2 nm) and N^+ (NII 108.5 nm) that allow for direct interpretation of their measurement. The oxygen emission is produced through direct photoelectron impact excitation of oxygen,

$$O\left(^3P\right) + e^- \rightarrow O\left(3s'\,^1D^0\right)^* + e^-$$
$$O\left(3s'\,^1D^0\right)^* \rightarrow O\left(2p^4\,^1D\right) + h\nu\,(115.2\text{ nm})$$

(1)

The nitrogen ion emission is produced by photodissociation of N_2,

$$N_2\left(X^1\Sigma_g^+\right) + h\nu \rightarrow N\left({}^4S\right) + N^+\left({}^3D\right) + e^- \quad (108.5 \text{ nm}) \tag{2}$$
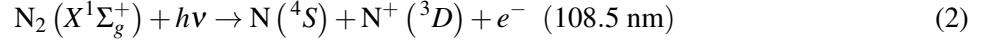
These emission lines are difficult to measure, however, and so most often the brighter emission features, OI 135.6 nm and N_2 LBH, are used. One complication that arises on the dayside is that there are both thermospheric and ionospheric sources that contribute to the OI 135.6 nm emission. The ionosphere can be measured by the O^+ emission at 247.0 nm and used to correct the 135.6 nm emission by subtracting off the ionospheric component. [17] Further complications include the radiation transport that is needed to interpret the OI 135.6 nm emission.

5. SUMMARY

Data assimilation of in situ neutral density measurements have shown model prediction improves with a single data point, by as much as 50% RMS reduction in error. [21] Full vertical profiles of O and N_2 determined by TRITON would provide a data set to improve the model prediction over many scale heights, not just at a single altitude. It is imperative to enhance the observations of neutral density and winds with remote and in situ observations. Current space observations observed the thermosphere from above and provide proxies of the mass density ratio for two primary components, oxygen and molecular nitrogen. The [O]/[N_2] ratio has been a useful metric for validation of physical models for several years now, and has been demonstrated by NASA missions like TIMED/GUVI and the ICON/FUV instrument. In situ measurements are lacking. Otherwise the only other in situ information comes in total mass density measured by missions like CHAMP and GRACE, which are useful, but spatially limited. The vertical profiles provided by a TRITON payload would be a significant contribution to the advancement of space weather research. The measurements provided by TRITON will be a valuable addition to the space weather and heliophysics research community. [22]

The TRITON design is still in the concept development phase, due in large part to the new optical components that would be required to implement the approach. The Tri-TIP and Tri-MIP designs are both mature (TRL6) and are both expected to have flight heritage by the end of 2022. Tri-TIP will achieve TRL 8 upon launch and successful operation of the CIRCE mission in 2022. A successful demonstration will provide proof-of-concept for using photometer data in the real-time prediction of space weather phenomena. Tri-MIP and SUVM will achieve TRL 8 upon launch of the Slingshot-1 spacecraft, also expected to launch in 2022. This will demonstrate both the measurement capability and the inversion technique for future use. Thus, successful tests of the TRITON optics will have the instrument poised for rapid advancement to flight readiness.

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