SSUSI and SSUSI-Lite: Providing Space Situational Awareness and Support for Over 25 Years

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ABSTRACT

The Defense Meteorological Satellite Program (DMSP) Special Sensor Ultraviolet Spectrographic Imager (SSUSI) program provides operational space weather information to support U.S. government needs. SSUSI delivers operationally useful information about the state of the upper atmosphere, the ionosphere, and the aurora to operators, forecasters, and scientists. The SSUSI sensor program has also been instrumental in the development of other sensors for NASA programs; these include the Global Ultraviolet Imager (GUVI) on NASA's Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) mission and the Near Infrared Spectrograph (NIS) on the Near Earth Asteroid Rendezvous (NEAR) mission. With the Advanced Spectrographic Retrieval Ionospheric Electrons on the Limb (ASRIEL) design study and the SSUSI-Lite program, the Johns Hopkins University Applied Physics Laboratory (APL) has designed and prototyped the next-generation sensor—one that is half the size, mass, and power of SSUSI but with all the capability and greater operational flexibility.

INTRODUCTION

The Special Sensor Ultraviolet Spectrographic Imager (SSUSI) family of sensors contributes to deepening our understanding of the space environment and its impact on satellite and other systems as well as our ability to predict anomalous behavior in these systems. With an increasing number of near-peers and peers in space, and the ready access to space provided by a burgeoning commercial space industry, the need to maintain our unique capabilities is even more urgent than it has been in the past.

One of the most difficult problems we face today is characterizing the space environment. APL has a significant presence in space programs and, in particular, a defining presence in geospace programs for research and applications. (Geospace is the space environment that is of direct concern to humans. It is the region of space near Earth and extends from the mesosphere to the outer boundary of the magnetosphere.)

One of APL's contributions is the SSUSI family of sensors, which provide space weather information to deepen our understanding of the near-Earth space environment as well as to support the basic research community (Fig. 1 shows SSUSI and its variants). The SSUSI and Global Ultraviolet Imager (GUVI) websites at https://ssusi.jhuapl.edu/ and http://guvitimed.jhuapl.edu/, respectively, offer a wealth of such information.

APL has a long tradition of providing valuable, innovative solutions to challenging problems. GUVI, developed by APL and flown on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) mission, has been in operation since 2001. Four Defense Meteorological Satellite Program (DMSP) satellites currently carry the SSUSI instruments (DMSP F16, F17, F18, and F19) in Earth orbit. They were launched in October 2003, November 2006, October 2009, and April 2014, respectively. APL continues in this tradition with SSUSI-Lite, which builds on the foundation of its predecessors to offer improved capabilities and more flexibility.

All instruments in the SSUSI family are hyperspectral imagers. Scanning hyperspectral imagers produce a two-dimensional spatial image with a third, spectral, dimension. SSUSI produces this image cube by using the cross-track motion of a mirror that directs the field of view of the spectrograph across the plane of the orbit as the spacecraft moves along. This is represented somewhat schematically in Fig. 2. Figure 3 shows the GUVI flight unit in the process of being installed on the TIMED spacecraft, the SSUSI instrument and its nadir-viewing photometer package, and the layout of the internal components. The SSUSI and GUVI sensors operate in the far ultraviolet (FUV)—from 115 to 180 nm. Operating in

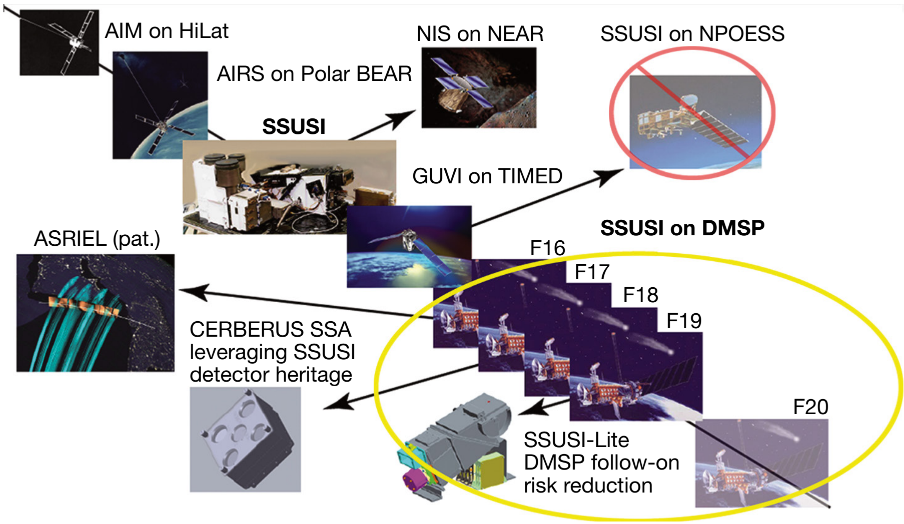

Figure 1. The SSUSI family of sensors. The SSUSI program began in 1990 at APL. The much simpler AIM and AIRS sensors laid the groundwork for an operational auroral imager. SSUSI extended the concept of an auroral imager to a space weather hyperspectral imager. The GUVI sensor was the first of the family of instruments to fly, in 2001, on the TIMED satellite, followed by the launch of the DMSP F16 satellite with a SSUSI in 2003. A version of SSUSI was slated for flight on the ill-fated National Polar-orbiting Operational Environmental Satellite System (NPOESS). The latest SSUSI was launched in 2014. The SSUSI program spawned other instruments, concepts, and capabilities, including novel detector technology and successful designs for the next generation of sensors. AIM, Auroral Ionospheric Mapper; AIRS, Auroral Ionospheric Remote Sensor; ASRIEL, Advanced Spectrographic Retrieval Ionospheric Electrons on the Limb HiLat, High Latitude Ionospheric Research; NEAR, Near Earth Asteroid Rendezvous; NIS, Near Infrared Spectrograph; Polar BEAR, Polar Beacon Experiment and Auroral Research; SSA, space situational awareness.

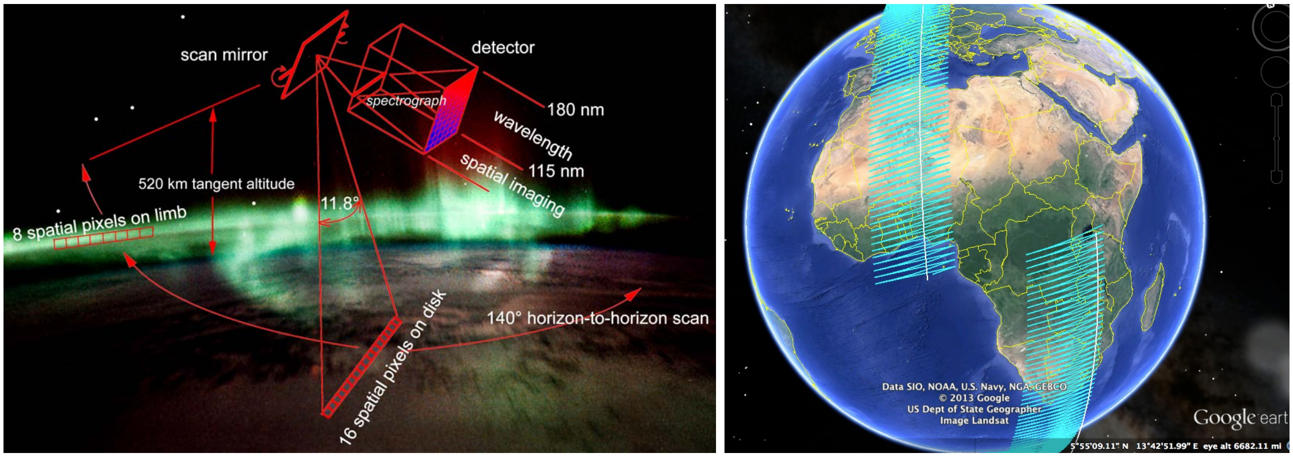

Figure 2. The operational concept for the SSUSI family. The system provides a 3-D view of the structure of the upper atmosphere as it scans across the disk and up onto the Earth's limb. This is enabled by the (up to) 140° scan angle range of the scan mirror (a "whisk broom" observing strategy). Light is directed by the scan mirror into the spectrograph imager. This consists of an off-axis paraboloid telescope that sends light to the entrance of a Rowland circle spectrograph. The spectrograph's grating disperses the light spectrally (this is only shown in a conceptual sense in the illustration). The light falls on the detector, which provides the spatial, temporal, and spectral location of the observation. The right panel shows the pattern traced by the center of the field of view as the spacecraft moves in its orbit higher above the Earth (white line). This zigzag pattern is designed to produce an overlapping sequence of images that produce a continuous stripe.

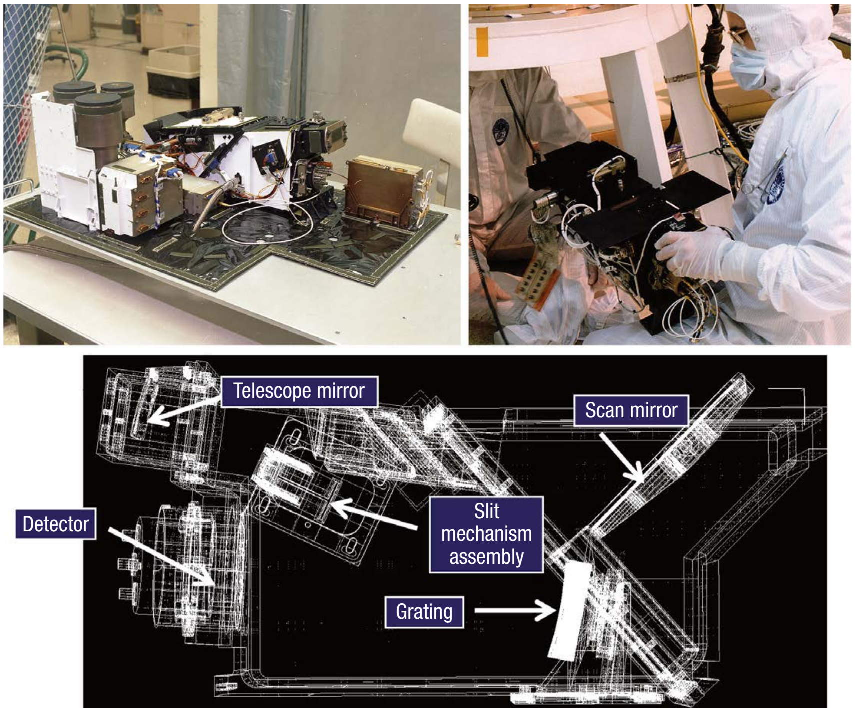

Figure 3. Sensor appearance and layout. The top left panel shows the first SSUSI installed on its storage/transport interface. The SSUSI photometer package is visible in the lower left-hand portion of the image. In the top right panel, an engineer prepares to install the GUVI sensor on the TIMED spacecraft; he is grasping the GUVI instrument at the end with the telescope mirror. The lower panel provides a transparent view of the instruments, with major elements indicated. For instance, in the top element of the figure, the scan mirror is located, under the deployable instrument cover, in the upper left-hand part of the instrument.

this wavelength range, as discussed below, makes these sensors both unique and powerful.

Hyperspectral data can provide the information needed to produce an environmental observation. For SSUSI and GUVI, we have carefully chosen particular groupings of wavelengths in the hyperspectral imager, which we call colors, to produce environmental data records (EDRs) to support our users. EDRs are required to answer many pressing operational and scientific questions. Table 1 summarizes the various records or products these instruments provide.[1]

THE GEOSPACE ENVIRONMENT AND SPACE WEATHER

The SSUSI and GUVI projects have contributed to advancing our understanding of the space environment—in particular from about 100 to 600 km altitude.[2] See Table 1 for a summary of SSUSI and GUVI products. Despite nearly 60 years of operations in space and many more decades of observations from the ground using sounding rockets and optical and radar instruments, only the average characteristics of the space environment are well known, and the SSUSI and GUVI instruments address major gaps in our knowledge. Variability in the space environment have proven to be difficult to characterize and even more difficult to predict.

Anomaly resolution, the process of discerning the cause of a failure in a spaceborne system or the failure of an element in a system-of-systems that relies on a spaceborne capability, requires that we distinguish between a natural event and an event that arises because of human action. Human action can be either deliberate or the result of a flaw or accident. Anomaly resolution further drives our needs because for the information to be decisionable, the knowledge must be unequivocal and rapidly available so that it can be used to successfully disambiguate a situation. Our inability to adequately characterize the space environment hinders anomaly resolution—whether it is predicting spacecraft orbit, radio frequency propagation, or events in spacecraft electronics.

We have been working toward a better understanding of the variability of the space environment, or space weather, because space is not empty—it embodies a wide range of phenomena that are poorly understood, exceedingly difficult to predict, and impact the operation of key systems.

Terrestrial weather, the weather that we directly experience, is largely defined by what happens between pressure levels at the surface (1 atmosphere or 100 kPa) to about 1/10th of that (at the tropopause, typically 7 km in altitude). The space environment covers pressures from 1/1,000th to 1/1,000,000,000th of that at the surface. This change in pressures means that at the lower altitudes of the space environment, the upper atmosphere behaves like a well-mixed fluid (due to collisions and turbulence). As altitude increases, the atmosphere transits to one in which the constituents separate by mass. This diffusion process leads to a situation in which lighter constituents come to dominate. The upper atmosphere extends from the mesosphere (at about 50 km) into the exosphere (about 600 km) where the gas is essentially so tenuous that atoms have little chance to collide with one another before escaping the planet or falling back to the atmosphere. This change from a fluid-like to a particle-like behavior means that the electric fields and perturbations to Earth's magnetic field begin to define the behavior of the system.

Earth's ionosphere is a weakly ionized plasma in our upper atmosphere (see Fig. 4 for examples of SSUSI observations of the equatorial ionosphere and its structure as summarized in Table 1). A plasma is a gas consisting of ions and electrons; a plasma is quasi-neutral, meaning that the total charge density of electrons and ions are nearly equal. Ion-neutral collisions give rise to complex behavior in this system. The ionosphere can be relatively stable because, as the atmospheric density drops, the time between collisions increases until the point is reached where significant numbers of ions can exist. They exist because recombination, which destroys the ions, occurs slowly enough that a significant number of ions persist for many hours. These ions are created by solar UV radiation (typically light with wavelengths shorter than 0.12 µm or 121 nm). In the E-region and F-region ionosphere, the electron densities reach the point where they affect the propagation characteristics of radio waves at high frequency (~3 MHz) and beyond.

As one might imagine, after sunset, the ionization source (the Sun) is no longer present and the ions begin to disappear (through recombination), leading to a decrease in the density of ions and electrons and thus changing the radio frequency propagation characteristics of the ionosphere. In fact, there are times when this decrease in the ionosphere charge density leads to the formation of a plasma bubble. (Technically speaking, the plasma bubble is a manifestation of a Rayleigh–Taylor density instability in which a lighter "fluid" is under a heavier one—in this case an ionospheric depletion at the bottom of the ionosphere.) It was one of these ionospheric bubbles that is believed to have contributed to the tragic events at Takur Ghar in 2002.[3]

The term *thermosphere* describes the region of the upper atmosphere above the upper atmosphere's temperature minimum, termed the *mesopause*. The mesopause is usually at about 100 km but may be as low as 85 km at the poles. The mesosphere, stratosphere, and finally, tro-

Table 1. SSUSI and SSUSI-Lite products

Product Required	Description	Notes
Ionospheric density	Latitude, longitude, and altitude data cube of electron density providing total electron content (TEC) and peak density and height	Every SSUSI provides over 50,000 profiles per orbit. The cross-track capability cannot be matched by a topside ionospheric sounder or GPS radio occultation.
Equatorial ionospheric scintillation	Latitude, longitude, and altitude data cube showing the exact location of the scintillating region	This unique capability cannot be provided by GPS radio occultation (which only indicates that scintillation occurs somewhere along the line of sight).
Auroral characterization	Auroral boundary, field line mapping, and actual radar clutter maps as well as auroral E-region ionospheric density profiles	This unique capability maps auroral emissions in latitude and longitude as well as energetic particles' (electrons and protons) energy and flux. Maps of auroral emissions show regions of potential auroral clutter.
Low-Earth orbit (LEO) energetic particles	Maps of regions of >50 keV particle precipitation in sub-auroral and South Atlantic Anomaly regions for operational users	This proven no-cost capability provides notification of energetic particle precipitation events.
Neutral density	Neutral density profiles and warnings of upper atmospheric "storm fronts" that will impact satellite drag/orbit/collision warning predictions	These are true altitude profiles covering 130–600 km altitude. "Storm fronts" produced by geomagnetic disturbances are visualized as maps that cover swaths 4000 km wide.
Geomagnetic fields	Maps of auroral field lines into space based on the auroral boundary location for spacecraft charging predictions and anomaly resolution support (SSUSI); global geomagnetic field configuration information for disturbed and quiet times (SSUSI-Lite)	While this capability does not measure the field, it does provide information about the path of higher-altitude particle streams that feed the aurora.
Auroral ionospheric information	Operational images of the auroral E-region density and E-region height	These products have been extensively validated and provide the latitude and longitude structure needed for propagation forecasts—something not achievable with other techniques.
Height of F-layer	Operational ionospheric information including F-region height	The F-region height is a latitude and longitude map of the heights at 25-km resolution.
Neutral temperature	Operational neutral temperatures of the upper atmosphere (the exospheric temperature)	SSUSI provides a latitude, longitude, and altitude cube of temperature profiles along the orbital track.

posphere, lie further below the mesopause. We use the term *thermosphere* when we are focused on the behavior of the neutral gas and *ionosphere* when we are focused on the plasma behavior. Of course, the thermosphere coincides with a significant part of the ionosphere (referred to as the E-region and the F-region). Years of observations of the neutral composition have given us the ability to describe the density profile of the thermosphere and its composition at mid and low latitudes to a fairly good degree. The problem is that, for practical applications such as satellite collision avoidance in LEO, our average knowledge is not sufficient to serve as the basis for accurate decisions about collision avoidance.

Above 300 km, we can reliably nowcast the density and composition in the upper atmosphere under quiet conditions to better than 30%. However, our ability to nowcast during disturbed conditions (i.e., when the Sun is causing geomagnetic disturbances in Earth's atmosphere) is much worse than that. A nowcast is a projection, usually based on some limited set of measurements, of the global state of the system. Most operations require the ability to project that state forward in time—a forecast. This is a current limitation, driven in part by the physics of the upper atmosphere and in part due to the paucity of measurements used in operational space weather models. As a consequence, our inability to accurately determine the satellite drag environment makes it difficult to unambiguously attribute the difference between predicted and observed orbital position changes in LEO satellites to natural or human causes. Figure 5 illustrates the dramatic changes seen in the upper atmosphere (in this case observed by the GUVI instrument) during a geomagnetic storm.

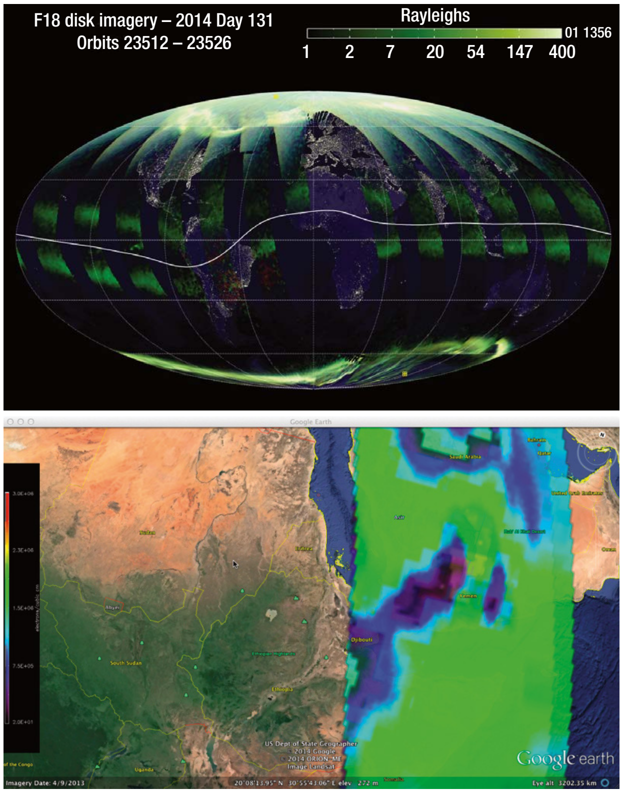

Figure 4. SSUSI images the ionosphere—in latitude, longitude, and altitude (3-D). SSUSI creates horizon-to-horizon maps of the nightside ionosphere. The top panel indicates the result of a day of images of the nightside FUV emissions. The image shows the equatorial ionospheric structure as a series of vertical swaths, one for each orbit. Within the individual swaths are ionospheric bubbles (see the bottom panel) as holes in the ionosphere. These holes lead to interruptions in high-frequency (HF) skywave communications as signals can propagate through the holes into space instead of reaching their intended endpoint.

The aurora is a visible manifestation of space weather. Ions and electrons in the plasma surrounding Earth (and to a limited extent, coming directly from the Sun in the solar wind) precipitate down along magnetic field lines into the polar regions (in effect, an electric current flowing along the field lines that completes an electric path through the polar upper atmosphere). These particles have energies great enough to create visible and UV emissions. At times, eruptions from the Sun (e.g., coronal mass ejections) can cause the aurora to extend to mid or low latitudes. Arguably, the most important role of these auroral particles and currents is in producing heating in the tenuous upper atmosphere. This localized heating creates large-scale upwelling (which can lead to changes in spacecraft orbits) and changes in the global circulation of the upper atmosphere. These heating events can also create waves (TADs) in the upper atmosphere. TADs alter the orbits of LEO spacecraft; atmospheric drag is a frictional force, meaning that when a spacecraft encounters a TAD enhancement it decelerates, but when it enters the lower density region it does not accelerate. This means that, since climatological models of the space environment do not yet include TADs, the presence of TADs leads to unaccounted-for changes in the predicted location of spacecraft.

TADs can interact with the ionosphere to create TIDs. TIDs significantly affect our ability to determine radio frequency (RF) propagation effects. They have peak-to-peak distances, or wavelengths, of hundreds of kilometers. In practice, this means that a radio wave propagating through the ionosphere will see what amounts to a random tilt in the ionospheric layer—the amount depending on where the RF wave intersects the ionosphere and the local properties of the ionosphere. This is somewhat akin to the distortion observed when one looks through the rippling water at a fish below the surface—objects (the fish and the background) appear to move about when in reality they are stationary. Just as waves in water can distort where we think an immersed object is, the ionosphere distorts information about where RF signals come from. This can create significant errors in the location of items of interest, whether on the ground or in space.

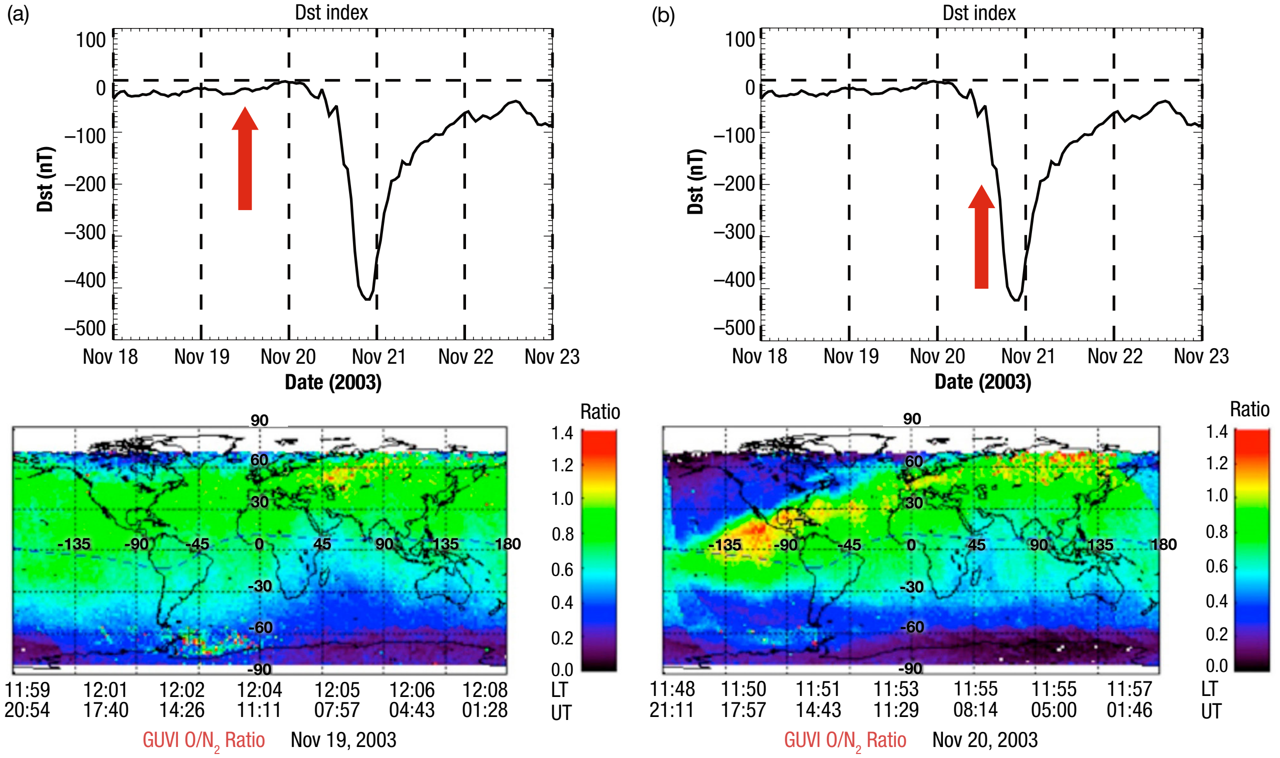

Figure 5. Upper atmosphere composition changes. The upper panels indicate the change in the Dst index (a measure of geomagnetic activity) as the storm progressed. Large negative Dst values indicate significant geomagnetic storm activity. The lower panels illustrate the change in thermospheric composition. Each GUVI O/N$_2$ panel shows the change in composition from day to day. The decrease in the O/N$_2$ column density ratio shows that the composition (and satellite drag environment) changed dramatically over the course of the storm.[4] O is the principal component in the thermosphere from about 300 to 800 km. Variations in O map to variations in the orbital drag experienced by a satellite.

FUV REMOTE SENSING

FUV remote sensing (from about 110 nm or 0.11 μm to 180 nm or 0.18 μm), pioneered for operational use by APL, provides a unique depth of insight into the space environment as well as space situational awareness. See Table 2 for a high-level summary of the relationships between the phenomena observed by SSUSI and the operational impacts. We can take advantage of the natural properties of the upper atmosphere to design a relatively simple system. Molecular oxygen, or O_2, is an important constituent of the upper atmosphere; O_2 happens to be an excellent absorber of FUV emissions.[5,6] For our application, this means that the lower atmosphere and surface are invisible when observed from space. The upper atmosphere is seen to glow above a black background. In point of fact, the traditional name for the emissions from the upper atmosphere is airglow. Dayglow refers to the dayside emissions, and nightglow refers to the nightside emissions—collectively airglow. The airglow is created by scattering of sunlight; the excitation of the upper atmosphere constituents by photoelectrons, or electrons created by the solar photons ionizing the upper atmosphere; radiative recombination of ions and neutrals; chemiluminescent reactions; and energetic auroral particles precipitating from the magnetosphere—or, to a limited extent, from the solar wind.

The principal advantages of FUV observations are as follows:

- They provide quantitative and qualitative images under any conditions (day or night, moon up or down, clear or cloudy sky), and the lower atmosphere is essentially black at these wavelengths.
- The algorithms and techniques for understanding the observations are mature.
- The technology is mature, and instruments can be small and provide useful information with a relatively low data rate.
- They provide global contextual information (i.e., inputs and response).
- They can be applied to a wide range of investigations.

A variety of sensor configurations are applicable to providing observations of the airglow. These range

Table 2. Impacts of the space environment on our systems' capabilities

Environmental Parameter	Environmental Effect	Potential Operational Impacts (Selected Examples)
Ionosphere • Electron density profile • Total electron content • Height of the ionosphere • Density at the peak	• Ionospheric scintillation • Ionospheric refraction • Presence of traveling ionospheric disturbances (TIDs)	• GPS location errors • Unexpected HF radio/radar signal propagation paths • Loss of radio communications
Aurora • Auroral imagery • Maps of energetic particles • Auroral boundary (poleward and equatorward) • Auroral clutter • Energy inputs into upper atmosphere (hemispheric power) • E-region height and density • Auroral ionospheric conductivity • Polar rain electrons from solar wind • Hot ion and energetic neutral atom precipitation from the magnetospheric ring current • Polar cap patches	• Auroral ionization of neutral atmosphere • Localized heating of the upper atmosphere • Changes in extent of the aurora (location)	• Decreased utility of GPS • High-latitude radar clutter • Polar HF radio signal degradation
Thermosphere • Neutral density profile • Composition	• Changes in upper atmospheric density • Presence of traveling atmospheric density (TAD) waves and tides • Changes in the upper atmosphere circulation pattern • Signatures of enhanced high-latitude cooling	• Unexpected changes in satellite drag nowcasts can lead to loss of spacecraft tracking • Degradation of transionospheric HF skywave signals due to TAD-induced ionospheric waves • Inability to forecast satellite drag due to incomplete knowledge of thermosphere cooling rates

from simple zero-dimensional or point measurements by photometers to imaging cameras to spectrographs.[2] APL flew the first hyperspectral imagers in space on the Midcourse Space Experiment (MSX).[7] The APL FUV instruments are very sophisticated spectrographic imagers and are part of that MSX lineage—that is, they are spectrographs that use a grating to disperse the light into its spectral constituents and spatial information into a second dimension.

SSUSI

The SSUSI project began in 1990 as an experiment for the DMSP.[8,9] The SSUSI family includes the SSUSI, GUVI, SSUSI-Lite, and Advanced Spectrographic Retrieval Ionospheric Electrons on the Limb (ASRIEL; U.S. Patent No. 8,594,972) sensors. In this section, we discuss the SSUSI sensor in particular, but most of the SSUSI design elements are common to all members of the SSUSI family of instruments.

The instrument records the data as hyperspectral images, but because of data telemetry constraints, only a portion of the data cube (two dimensions in space and one in wavelength) is telemetered to the ground—typically just five segments of the spectrum, which we refer to as colors. APL prides itself on producing a sensor that balances technology and capabilities to provide the most effective return, and SSUSI was carefully optimized to provide the maximum return for the minimum overall cost. The SSUSI sensor was designed to interface to the Operational Line Scanner (OLS), a primary sensor on the DMSP spacecraft. The data rate was just 3814 bits per second. SSUSI also includes three photometers to measure nightside 630-nm (the atomic oxygen "red line"), 629-nm (a measure of the ground albedo and background signal), and 42-nm (N_2 first negative band) signatures.[10]

SSUSI is carefully optimized for the spectral regime and the observational scenarios for which it is used. The SSUSI instruments use photon-counting detectors. These systems record individual photons as they arrive at the detector.[11] The instruments do require technologies (e.g., gratings, coatings, filters, optical designs) that, while well understood, are supported by a relatively small market. Maintaining our FUV capability requires a small but continued investment to maintain a practical manufacturing readiness level. Sensors are characterized and their radiometric efficiency determined in a laboratory setting, specifically in a custom vacuum facility that enables a complete characterization of the instrument.[12]

An accurate radiometric calibration is extremely important to the instrument's ability to produce useful information. We thoroughly calibrate the instrument on the ground, and then, in space, we use well-characterized stars as our calibration sources. Stellar calibration is usually considered the only practical means of maintaining calibration traceability on orbit (good to within about 10%).[13] On-orbit calibration is achieved by using spectrograph mode (a mode in which the scan mirror is held in a fixed orientation to stare at a star during part of the orbit). Several bright hot stars are sufficiently stable and well characterized and produce enough FUV radiation that their output can be used to calibrate the SSUSI family of instruments without requiring us to resort to an onboard calibration lamp.

The optical design is very simple. Few optical materials transmit in the FUV, so we use an all-reflection design. The spectrograph is a Rowland circle design. The name, interestingly enough, comes about because Henry Rowland, a professor at Johns Hopkins University in the late 19th century and the inventor of the diffraction grating, created this novel design that provides good spatial imaging characteristics along the slit.

To provide a spatial image, the sensor's field of view is scanned by moving the scan mirror. The scanning imaging spectrograph subassembly consists of a cross-track scanning mirror at the input to the telescope and spectrograph optics. At the focal plane of the spectrograph are redundant 2-D photon-counting detectors. Higher gain makes slightly higher spatial resolution possible but shortens detector lifetime. The detectors were "prescrubbed" before assembly to reduce the amount of on-orbit aging. The aging, which is driven by the amount of charge pulled through a particular location on the microchannel plate, results in a change in the pulse height distribution, which may, if the detector electronics are not designed with a broad enough window, manifest itself as a reduced sensitivity at that location. This is of particular concern for the relatively narrow locations of the bright atomic hydrogen Lyman alpha line and the atomic oxygen line at 130.4 nm. These sensors have been remarkably stable over the lifetime of the mission. The SSUSI on the DMSP F16 satellite has shown little change (<20%) in the detector response after over 12 years of on-orbit operations.

The imaging spectrograph builds multispectral images by scanning in the across-track direction (for an example see Fig. 2). The detectors employ a microchannel plate intensifier and a position-sensitive anode (wedge and strip layout) to determine the photon event location. These processes are summarized schematically in Fig. 6. We refer to the quantization of the position

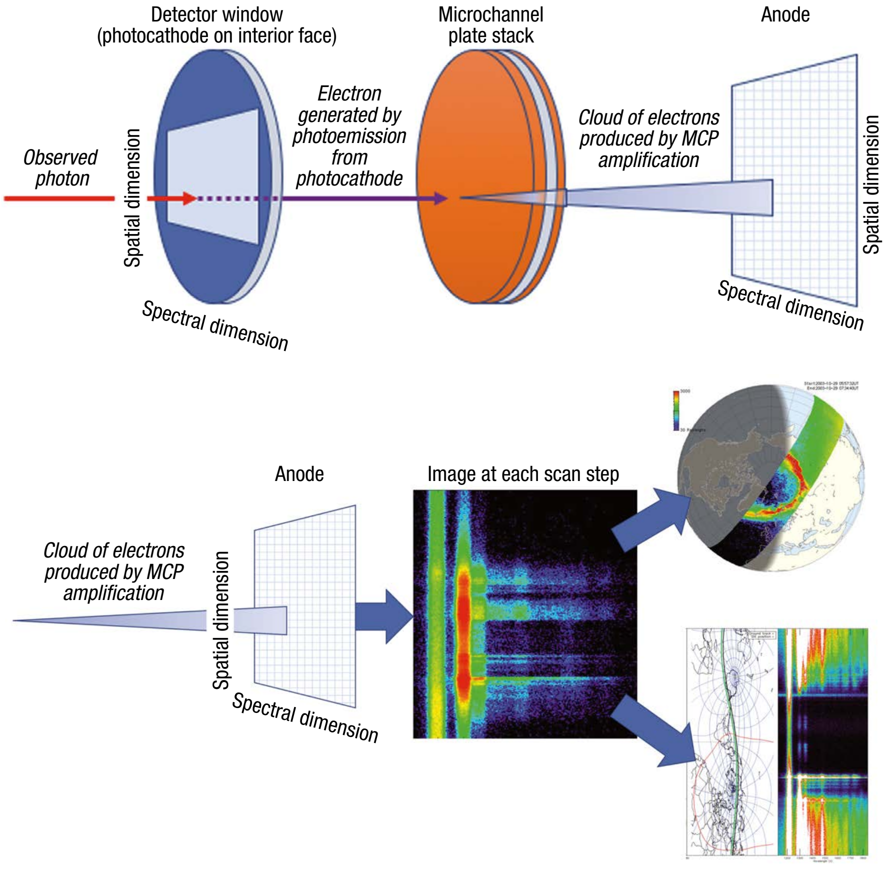

Figure 6. Event flow from photon arrival at the detector window to image mode or spectrograph mode data collection. Shown in the upper panel, a photon event at the image plane produces a photoelectron from the photocathode. This photoelectron is accelerated and amplified into a charge cloud by the microchannel plate (MCP) intensifier. The charge cloud leaves the back of the microchannel plate stack and is allowed to spread before falling on the position-sensitive anode. The charge is collected on three elements of the anode; the location is determined by the relative amount of charge collected on the wedge and strip components of the anode. This analog calculation is converted to a digital location that is binned in a spatial and spectral location in memory. The data are then either sent down as spectra at 3-s intervals or in five selected wavelength bins to form five images (one of which is shown in the upper right-hand corner of the lower panel).

determination on the detector as defining a pixel. In imaging mode, the scan mirror sweeps the spatial pixel footprint from horizon-to-horizon perpendicular to the spacecraft motion, producing complete swath every scan period (22 s for SSUSI and 15 s for GUVI).

Because we use a 2-D detector, we accumulate an image with a spatial domain and a spectral domain at each step of the scan mirror. The resultant products can be visualized[14] in a single wavelength as a geographically referenced map using bespoke software or the KML files that Google Earth uses to enable users to customize their view of the horizon-to-horizon images (e.g., Fig. 7). We downlink only five user-selectable spectral segments, which we call colors, to minimize the telemetry impact and maximize the mission return. The SSUSI family of instruments also preserve the option of telemetering the entire spectrum to the ground. In this mode, called spectrograph mode, the scan mirror is held fixed and the integration period is set at 3 s. This allows all the wavelength bins to be sent down for analysis within the data rate allocation provided to us.

The SSUSI data are available at https://ssusi.jhuapl.edu. The SSUSI website was designed, and still functions, to support the DMSP calibration and validation team efforts and to enable the SSUSI team to maintain the calibration and characterization of the SSUSI sensor. A unique feature of the SSUSI program is not only the depth of its algorithms but also that the algorithms run operationally at the 557th Weather Wing to support the warfighter. By running an identical system at APL, we ensure the continuity of product quality and support without having to stand up a large and expensive support team.

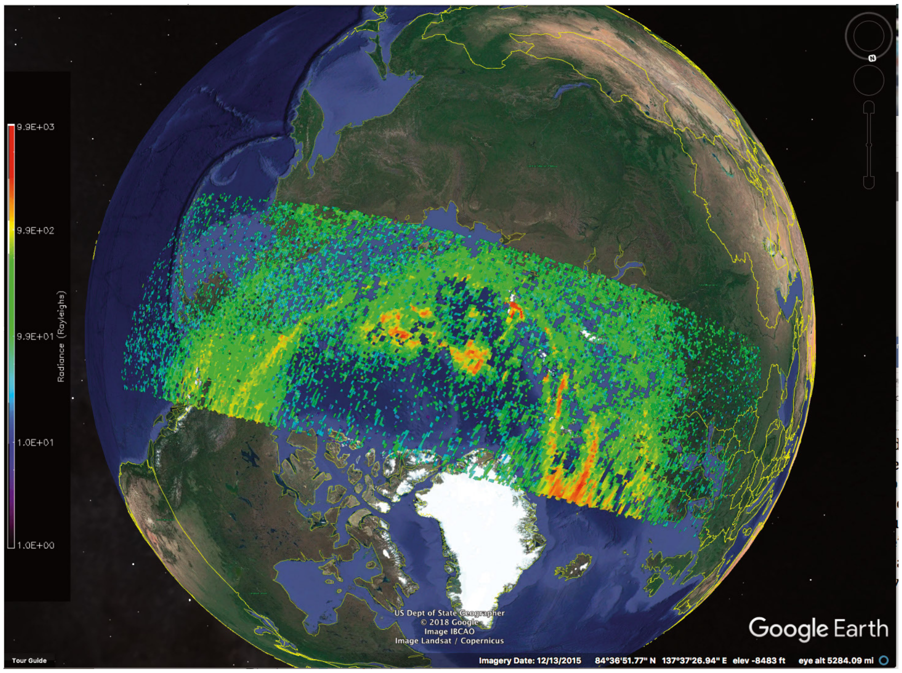

Figure 7. DMSP F17 SSUSI image of the aurora on 8 September 2017. SSUSI captures spatial structure at an unprecedented resolution (8 km) from space in the FUV. Maps of intensity, such as this one, yield information on the amount of energy entering the atmosphere from above and characterize the auroral ionosphere. The auroral morphology and structure has been described in recent reviews.[15,16]

GUVI

The SSUSI instrument and software formed the basis for the NASA TIMED mission's GUVI instrument. The mission (see http://timed.jhuapl.edu for details) has its roots in scientific studies of the upper atmosphere that began in the mid-1980s following the Dynamics Explorer and Atmosphere Explorer missions. TIMED was a response to the "faster, better, cheaper" initiative started by then NASA administrator Daniel Golden. NASA authorized APL to execute the mission in a cost-constrained environment, and the original TIMED concept was reformulated within these constraints. GUVI had been proposed and selected in 1994 and was based on the SSUSI sensor.[17–20] With its strong design heritage from SSUSI, the GUVI instrument was the low-cost, high-capability sensor needed for the TIMED mission.

TIMED, launched 7 December 2001, is the first mission in the NASA Heliophysics Division's Solar Terrestrial Probes (STP) line. TIMED is exploring the Earth's mesosphere and lower thermosphere and ionosphere, or MLTI (60–180 km). The MLTI is a difficult region to nowcast and forecast without the ability to model its physics, chemistry, and dynamics; we lack a fundamental ability to predict how the atmosphere will respond to geomagnetic disturbances or even to characterize its quiet state because we do not have enough observations to constrain the system.

GUVI, the second-generation SSUSI sensor, has provided comprehensive measurements of the state of the upper atmosphere and ionosphere. Over 600 published scientific papers describe GUVI's data or its design and capabilities, and the scientific community has cited these papers thousands of times. GUVI observations have been referenced in well over 1000 talks and posters delivered at various scientific conferences. The main goal of GUVI was to provide basic research products, whereas the main goal of SSUSI was to contribute to our operational understanding of space weather.

SSUSI-LITE

SSUSI-Lite refreshes the design of its predecessors, the SSUSI and GUVI sensors that have demonstrated their value as space weather monitors.[21,22] The refresh updates the 25-year-old design and ensures that the next generation of SSUSI/GUVI sensors can be accommodated on any number of potential platforms. SSUSI-Lite maintains the same optical layout as SSUSI; updates key functional elements; and reduces the sensor volume, mass, and power requirements. SSUSI-Lite's improved scanner design enables precise mirror pointing and variable scan profiles. The detector electronics have been redesigned to employ all-digital pulse processing. SSUSI-Lite achieved significant reductions in total size, weight, and power by the use of modern space-qualified components that enabled us to consolidate the control and power electronics into one data processing unit.

The key advantage of a refresh, rather than a complete redesign, is that existing software and visualization tools can be reused because the refreshed sensor is identical to previous versions in both form and function—especially in the data stream. APL has produced over 75,000 lines of operational SSUSI software code, with additional libraries totaling close to 1,000,000 lines of code.

The refreshed design takes advantage of enhancements in the electronics design for the detectors and associated electronics to improve performance and reduce size, weight, and power requirements.[11] SSUSI-Lite's size, weight, and power parameters are summarized in Table 3. Its design is much more flexible because it includes a limited-range torque motor with a position detection system that detects the mirror's position at any point in the scan. With SSUSI-Lite, we have demonstrated a cost-effective solution that can continue to provide heritage space weather data products to the community while reducing the size, weight, and power required by the payload. In addition to enabling data continuity, SSUSI-Lite can fly on many platforms; its software can be readily ported to other systems and translated into other programming languages.

THE FUTURE: CRITICAL CHALLENGES

The APL SSUSI-like sensors provide a tremendous amount of valuable information, and the cost per measurement is minimal. A typical orbit yields over 50,000 ionospheric soundings. Only a SSUSI-like limb or an *in situ* mass spectrometer can make the measurements needed to produce neutral density profiles. Of course, mass spectrometers make excellent measurements at just one altitude, but that is not what we require to develop an adequate understanding of the thermosphere. The challenge in the past has been twofold, and the SSUSI sensors have contributed to meeting the challenge:

1. How do we convert observations into useful environmental observations? The SSUSI software and visualization environment address this challenge.

Table 3. SSUSI-Lite and SSUSI Comparison

Parameter	SSUSI-Lite	SSUSI
Field of view (scanned)	140° × 11.7°	134° × 11.7°[a]
Pixel resolution (per scan)	160 × 16	160 × 16
Spectral range	117.5–180 nm	117.5–180 nm
Spectral resolution (narrow slit)	1.8 nm	2 nm
Spatial resolution at nadir	10 km	10 km
Responsivity at 1356 Å	0.30 count/s/Rayleigh	0.15 count/s/Rayleigh
Mass	10 kg	25.4 kg
Footprint—scanning imaging spectrograph	51 × 23 cm	73 × 33 cm
Footprint—data processing unit	22 × 10 cm	38 × 21 cm
Number of boxes	2	6
Average power	9.4 W	28 W
Data rate—minimum	3.8 Kbit/s	3.8 Kbit/s
Data rate—maximum[b]	30 Kbit/s	3.8 Kbit/s
Event rate—maximum[c]	500 K counts/s	200 K counts/s
Detector digitization	14 bits	10 bits
Detector pulse processing	Field-programmable gate array	Analog
Motor jitter	0.1°	0.4°
Operating temperature	–25 to +65 °C	–24 to +61 °C

[a] Not used because of spacecraft limitations.

[b] Data downlink requirements are flexible. All SSUSI heritage products can be produced at the minimum data rate. Enhanced products can be produced within the "maximum" rate allocation.

[c] See note in text.

2. How do we use measurements to specify the global state? Global data assimilation computational codes can now address this challenge effectively.

We can attempt to capture the state of the space environment in a numerical representation, or model, in three ways:

1. **Climatology**—computer codes that fit existing databases of observations to a specific set of basis functions (e.g., spherical harmonics) in terms of an observable parameter (local time, sunspot number) and location

2. **First-principles models**—computer codes that solve some form of the basic physics equations that describe the system. These computer models rely on the accurate specification of the boundary conditions (the initial conditions and the values at the upper and lower bounds of the model, as well as the drivers or forcing functions).

3. **Assimilative**—computer codes that capture the covariances, or relations between various parameters and a background model, thus enabling us to stitch disparate observations into a contiguous picture of the environment at a time consistent with the observations

The APL SSUSI family enables us to provide the state of the space environment by making fundamental and unique measurements of the state of the upper atmosphere. These contributions range from models of the aurora[23] to observations of the constituents in the upper atmosphere[24] to comparisons with first-principles models of the composition and structure,[25] especially during geomagnetic storms,[26] and maps of the South Atlantic Anomaly (a region where the radiation environment experienced satellites is enhanced).[10]

APL has developed a new predictive software program that enables us to specify the state of the geospace environment by assimilating a wide range of observations. Known as IDA4D,[27] it includes modules that ingest and assimilate data to produce a best-fit specification of the ionosphere. IDA4D is an open-source ionospheric assimilation model that provides ionospheric assimilation and nowcasts to U.S. government users.

Assimilation models such as IDA4D are driven by data, but they are often data starved. The SSUSI family of sensors is capable of providing 50,000 ionospheric profiles per instrument per orbit; these profiles characterize the electron density structure ingested by ionospheric assimilation models in detail greater than many individual point-like observations can achieve. In addition, SSUSI sensors provide information on the thermospheric neutral density. The thermospheric neutral density responds to changes in the energy deposited at high latitudes during space weather events. The ionosphere is created by ionization of the neutral components of the thermosphere (O, O_2, and N_2).

This new open-source approach takes full advantage of the decades of scientific research APL has led. By building on past achievements and offering an architecture that can accommodate contributions from the research community, the IDA4D open-source approach will provide the best possible nowcast and forecast of the physical conditions in the space environment. Tailored applications then can be used to produce the decision aids required by the user community.

We need to understand the space environment to improve our ability to secure and maintain assured access to space and the "high ground" that space provides us for operations in a contested environment. Understanding how gaps can be exploited and managed, as well as the impact of the steady transition of space-based assets from fully engineered, high-cost, high-reliability systems to COTS solutions, will enable new applications such as supporting electromagnetic maneuver warfare. While COTS solutions may be robust against an occasional random failure, by their very nature they are vulnerable to systemic effects. As the DoD and intelligence community increasingly turn to lower-cost COTS products and data, they become increasingly reliant on systems that are not resilient against space weather impacts. FUV remote sensing plays an important role in developing our understanding of the space environment so that we are better able to respond to these challenges. The SSUSI-Lite program illustrates a clear path toward a deeper understanding of the space environment and a fuller appreciation of our vulnerabilities.

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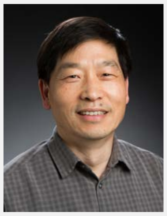

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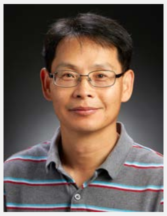

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