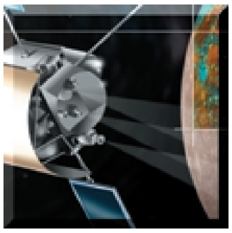

Auroral Imaging and Space-Based Optical Remote Sensing

Larry J. Paxton and Ching-I. Meng

The Space Department has played a significant role in the development of space-based remote sensing instruments for scientific and military users. In this article we review the progress made here in the last 30 years as new instruments, designed to image the aurora, have been developed and flown. This effort is an integral part of the Space Department's emphasis on understanding the connection between the Sun and Earth and exploring the ways in which energy and mass are transferred from the Sun to the Earth. Auroral imaging is a key element of that effort since the aurora is a visible manifestation of the interaction between the Earth's magnetic field and the solar wind (the hot, ionized gas blown off from the Sun). (Keywords: Aurora, Instrumentation, Remote sensing, Space physics.)

INTRODUCTION

The Space Department has made significant contributions in the development of space-based remote sensing for the scientific and military communities for over 30 years. Activity began when an APL instrument, on the DODGE 3 (DoD Gravity Gradient Experiment) spacecraft, produced the first full-color image of the Earth from space on 25 July 1968. The Department has built upon that early foundation and produced a line of unique and powerful sensors for DoD and NASA. These sensors first flew in the early 1980s and are expected to continue to fly until about the year 2010 (see Table 1 and Fig. 1). These imagers provide information about the Earth's atmosphere and its response to solar inputs. Understanding the aurora has been a fundamental thread in the Space Department's optical instrumentation as well as modeling and data analysis activities. We have taken advantage of these opportunities to significantly expand our research and instrumentation capabilities. For example, the Midcourse Space Experiment (MSX) demonstrated that viewing a star as it sets through the atmosphere (referred to as a "stellar occultation") is a powerful means of determining the altitude distribution of ozone and monitoring that profile for changes, not an area in which APL has been widely known to be actively engaged. The MSX "proof of concept" has been successfully proposed for NASA's Instrument Incubator Program, and a new instrument is now under development.

APL's Space Department has led the way in imaging the Earth's aurora from low-Earth orbit (LEO).

Table 1. Major APL space-based optical remote sensing missions.

Mission/instrument	Operational dates	Instrument type
HILAT/AIM[a]	1983	Single-color imaging
Delta 180	1985	Imagers and spectrometers
Polar BEAR/AIRS[b]	1986–1987	Four-color imaging (two in far UV)
Delta 181	1987	Spectrographs and imagers
MSX/UVISI[c]	1996–present	Spectrographic imagers and imagers
TIMED/GUVI[d]	2000–2002	Scanning imaging spectrograph
DMSP/SSUSI[e]	2000–2010	Scanning imaging spectrograph

[a] High Latitude/Auroral Imaging Mapper.

[b] Polar Beacon and Receiver/Atmospheric and Ionospheric Remote Sensing.

[c] Midcourse Space Experiment/Ultraviolet and Visible Imagers and Spectrographic Imagers.

[d] Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics/Global Ultraviolet Imager.

[e] Defense Meteorological Satellite Program/Special Sensor Ultraviolet Spectrographic Imager.

The aurora is a spectacular manifestation of the link between our magnetized planet and the magnetized plasma that constantly streams out from the Sun. Understanding this link is key to understanding "space weather" for military and civilian users, an issue that becomes more important as we begin to make the transition to a permanent presence in space. By imaging the aurora we gain insights into the physical processes that couple the Earth to the local plasma environment. The Laboratory's sensors provide spectral information as well as images, information that can be used to locate ionospheric irregularities, local heating events, and regions of intense particle precipitation.

THE AURORA

What Is the Aurora?

No one knows when the aurora was first observed, but it must have been met with amazement. This is not conjecture, for we have historical accounts of people's reactions to the appearance of the "northern lights" at low latitudes where they are rarely seen. Often the fantastic moving shapes were regarded as a supernatural portent. Even now the occurrence of an aurora visible from low latitudes prompts calls to the soothsayers of today: local television stations, observatories, and occasionally universities.

The aurora was known for many centuries as the northern lights precisely because it is a polar phenomenon and lies to the north when viewed from Europe. An understanding of the global nature of the aurora was slow to evolve, due in no small degree to the difficulty of piecing together a global snapshot of the phenomenon before modern communications, timekeeping, and imaging technologies (Fig. 2) were available.

We know now that auroral emissions are distributed in an oval centered on the geomagnetic poles and that this oval maintains an orientation fixed relative to the Sun. The geomagnetic poles are offset from the geographic poles that, together with the fixed orientation relative to the Sun, cause the auroral oval to move relative to a location on the ground. Since an observer on the ground rotates about the geographic pole, an auroral observing station could be equatorward of the oval, then inside the oval, and then poleward of the oval, which complicates the interpretation of ground-based data. The auroral oval is not static; it expands and contracts as solar conditions and the electric potential across the polar cap, the dawn–dusk potential, change. When the potential increases, the oval expands toward the equator and the width of the oval grows.

The aurora is visible because of the interaction of electrons and protons that are accelerated along the Earth's magnetic field lines, from the magnetosphere (the cavity

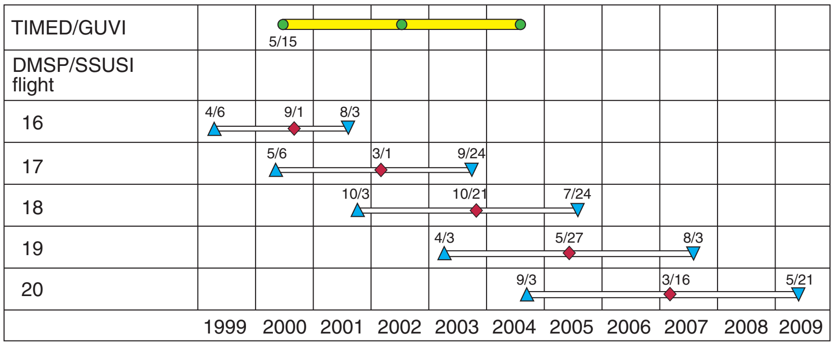

Figure 1. Launch schedule for TIMED/GUVI and DMSP/SSUSI. APL has supplied instruments which will image the aurora during the next complete cycle of solar activity. Since DMSP is an operational program, launches are determined by need. There is a statistical database which provides some indication of the expected time frame for the launch. The 10% likely values (triangles), 50% likely values (diamonds), and 90% likely values (inverted triangles) for the time by which launch will have occurred are indicated; circles represent schedule dates. The SSUSI and GUVI instruments have been built and delivered and await flight.

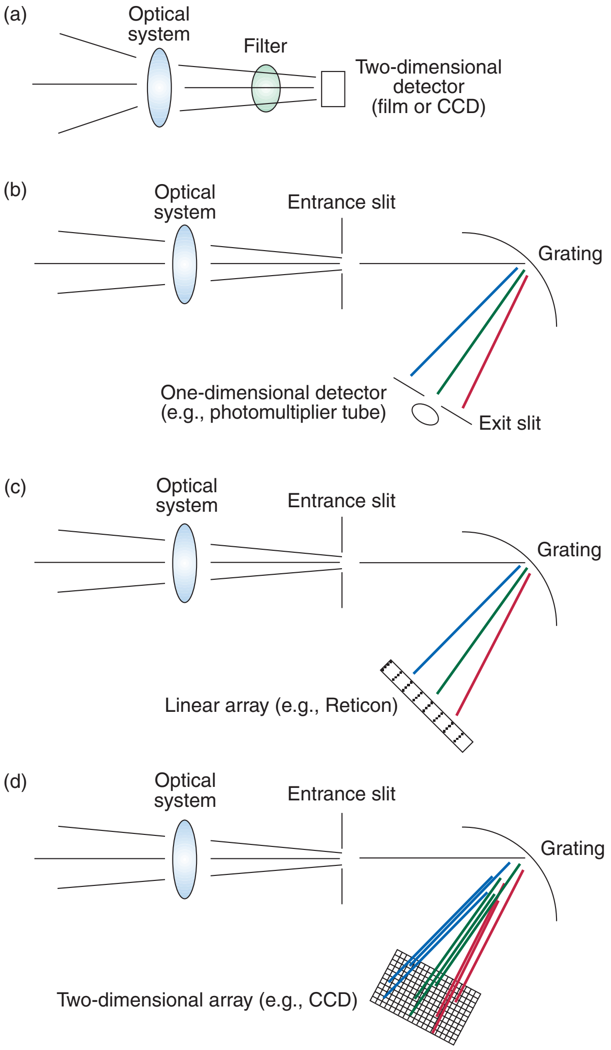

Figure 2. Detector-driven approaches to obtaining spectral images. The evolution and availability of detector systems have driven the implementation of imaging and spectroscopy of the aurora from ground- or space-based systems. (a) A typical all-sky imager or space-based imager in high Earth orbit. (b) A spectrograph (a Rowland circle mount is shown). The three colored rays indicate that only one wavelength is passed by the exit slit to fall on the one-dimensional detector. (c) A linear array to capture the spectral information at all wavelengths simultaneously. In the system shown in 2b, a mechanism would have been required in order to change the sampled wavelength. (d) A two-dimensional array. Note that an entrance slit has length as well as width. In Figs. 2b and 2c, the length dimension is of limited use and is set to fill the detector. By using a spectrograph with good imaging properties, the along-slit spatial information can be preserved. A two-dimensional detector, placed at the image plane of the spectrograph, will yield spatial information in one dimension and spectral information in the other.

in the solar wind created by the Earth's magnetic field) into the Earth's atmosphere, where they undergo collisions with the background gas. Light is produced by these collisions, thus mapping the distribution of the charged particles and the auroral current systems. Currents flow in regions where auroral precipitation has occurred. The energetic particles, accelerated in the magnetosphere, create electrons and ions when they collide with the neutral gas in the upper atmosphere. This highly localized process enhances the E-region ionosphere (around a 100-km altitude) and is, in fact, the major mechanism for increasing the conductivity of the polar atmosphere. Currents in the magnetosphere, which are aligned with the Earth's magnetic field, can then close through the E-region ionosphere. The aurora also induces changes in the local magnetic field due to the creation of large current systems in the ionosphere. These changes can be detected on the ground, an effect first observed over 250 years ago.

The aurora is a visible manifestation of space weather, which is the name given to the highly variable interaction between the Sun and the Earth's magnetosphere, upper atmosphere, and ionosphere. Auroral emissions indicate where auroral ionization will cause local changes in high-frequency (3–30-MHz) radio propagation. The ionospheric currents enabled by auroral precipitation can cause degradation of long pipelines or create high-voltage surges in high-voltage transmission lines. Electrons and ions that precipitate into the polar atmosphere have been energized through interactions with the magnetosphere; since they originate in the magnetosphere, auroral imaging can tell us about the distribution of energetic particles in the magnetosphere.

Why Study the Aurora?

During the beginning of modern science (the 18th and 19th centuries), the desire to understand the nature, distribution, and origin of the aurora drove a number of theoretical and experimental investigations. Early investigators were interested in the relationship between the aurora and the emerging theory of electromagnetism. Even after 200 years of study, an astonishing amount of basic research is still being done on the aurora and its electromagnetic and electrodynamic properties. Today's researchers are concerned with questions ranging from the origin of very small scale features (down to a few meters) to how the magnetosphere interacts with solar conditions. The aurora is used as a "television screen" to map the incoming or "precipitating" particles back to their points of origin within the magnetosphere.

Today, we also know that it is energetic electrons and protons that produce the emission we observe. These particles have energies of thousands of electronvolts, whereas a molecule of gas at room temperature will have about 1/40th of an electronvolt of energy. The interaction of these particles with the atmosphere causes the atmosphere to emit light at certain specific wavelengths, just as a "neon" light will glow different colors depending on the gas in the discharge tube.

Needless to say, since the aurora is highly variable, the spectrum of the aurora is variable too. Although observations of the spectrum of light emitted by the aurora do provide valuable insight into the precipitation process, light is only one facet of the interaction of these particles with our atmosphere. They also create additional ionization, about 300 ion–electron pairs per incident particle. They are, in fact, responsible for creating the auroral E-region ionosphere. It is for this reason that the Department of Defense has been interested in the aurora.

High-frequency communications and radars operating in the polar regions are affected by changing radio-propagation paths. Intense, high-energy particle precipitation can also create regions where radio waves are absorbed, thus preventing communications in the polar regions. This auroral activity can affect satellite tracking and communications. Ground stations are located at high latitudes to take advantage of the greater number of contact opportunities available for polar-orbiting satellites and so are susceptible to auroral "interference." The aurora also contributes a significant optical background to the problem of target identification and tracking.

Auroral activity shows increases due to changes in the orientation of the interplanetary magnetic field (IMF) near Earth. The total power in the solar wind–magnetosphere dynamo varies as the sine of the angle between the IMF and the north geomagnetic pole to the 4th power. Fluctuations in this angle occur with periods of hours, leading to changes in the dynamo power of between 10^5 and 10^7 MW. These fluctuations cause an auroral disturbance known as an "auroral substorm." Since the aurora also maps a region of increased ionization or conductivity, large currents flow through these regions. These currents cause intense magnetic disturbances or "magnetic substorms." The currents that flow under the auroral oval are called the auroral electrojet, which produces a potential drop of up to 1 V/km on the Earth's surface, thus producing a significant current in long conductors such as power lines and pipelines.

How Do We Study the Aurora?

The aurora covers more than 10 million km^2: space provides the "high ground" from which to observe this global-scale phenomenon. Optical remote sensing, the subject of this article, is a powerful technique that is varied in its application. Placing an optical instrument in space allows one to observe the aurora at wavelengths that would, for an observer on the ground, be absorbed by the intervening atmosphere.

The atmosphere absorbs very short wavelength light (ultraviolet and X rays) and long wavelength or infrared emissions. At the Laboratory we have concentrated on exploiting the potential inherent in the far ultraviolet or FUV (110 to 180 nm). By choosing the FUV as our operating region, we can image the aurora under sunlit conditions in which the Earth's atmosphere is anywhere from a thousand to a million times brighter at visible wavelengths (about 400 to 700 nm) than the aurora. FUV auroral emissions allow us to map the regions where particle precipitation is occurring and characterize their average energy and flux, two key parameters that have a major effect on the E-region ionosphere.

The aurora can be characterized by other measurement techniques as well: radars, *in situ* instruments on orbiting spacecraft or sounding rockets, and ground-based optical instruments are among those most commonly used. *In situ* measurements and radar observations provide important information not directly available from orbiting FUV imagers. They are, however, limited in their temporal and/or geographic coverage. *In situ* instruments, for example, provide a detailed picture of what is happening only at the exact time and place of the measurement. Since the aurora can change rapidly with time, removing this fundamental ambiguity in space and time is difficult without remote sensing observations.

Ground-based optical measurements are limited to the area visible from their site (a few hundred kilometers in radius), but they do provide continuous nighttime imaging. Radars are also fixed. Incoherent scatter radars sample a volume that is essentially local. Coherent scatter radars, such as the SuperDARN System described in this issue in the article by Greenwald et al., provide greater geographic coverage and continuous time coverage. SuperDARN detects plasma irregularities, and from them determines the convection electric field, which is an important complementary data set that helps us build a picture of the dynamics of the polar region.

OBSERVATIONS FROM SPACE

The APL Space Department has been actively involved in using and producing auroral imagery for more than 16 years (Table 1). Our main focus has been on developing a means of routinely providing spectrally pure or "monochromatic" images of auroral emissions from LEO to map the energy and flux of precipitating electrons in the auroral region.

Multispectral Imagery

Multispectral imagery, i.e., imagery at a number of discrete wavelengths or "colors," yields a significant added value by enabling automated software that can produce image-interpretation products tailored to the user. With the advent of a modern computing infrastructure and the maturation of our scientific understanding of the aurora, we can now take FUV auroral images and convert them into ionospheric information, which can then be sent to the warfighter or scientist to facilitate the development of the next generation of products. As we shall see, this presents significant design challenges.

An optical instrument can obtain images in more than one wavelength interval by two basic techniques (Fig. 2). The first and most common is to use a two-dimensional detector (e.g., a charge-coupled device [CCD] or film) with a filter in front. This simple camera can take pictures but requires a mechanism to change the filter and, generally speaking, has a limited field of view (FOV): 30° would be considered a large, undistorted FOV. Filter technology generally precludes spectrally pure measurements. Narrow wavelength bandpass filters are not generally available, and passing uncollimated light (i.e., light from a range of angles) through a filter broadens its effective bandpass.

A spectrograph can be used to create an instantaneous image of the spectrum of the FOV. A spectrograph takes light incident at the entrance slit, breaks it up into its constituent wavelengths, and disperses it over a range of angles. Prism and grating spectrographs are available. Gratings are used in the FUV since most common optical materials absorb all FUV light. A simple point detector, such as a photomultiplier tube, is placed at the exit slit of the spectrograph. The spectrograph must then be "scanned" in wavelength, either by moving the grating or the detector, in order to produce a spectrum.

The method of implementing the scan depends on the spectrograph mount chosen (see Ref. 1 for a discussion of the various options). Given enough room, two detectors could sometimes be accommodated in the small space available at the exit plane of the spectrograph. This provided information at two wavelengths simultaneously. Once linear array detectors such as the Reticon and Digicon devices became affordable and available,[2] an entire spectrum could be obtained simultaneously. Generally, grating-based spectrographs are restricted to, at most, a factor of 2 in the difference between the longest and shortest wavelength images. Other limitations, such as the response of the detectors, also play a role in further restricting the available wavelength range.

As two-dimensional detectors (e.g., CCDs used in visible light applications) became available, they were applied for spectrographic purposes. With a two-dimensional detector at the focal plane of a spectrograph, an image with spatial and spectral information could then, in principle, be obtained. Here, the limitations of spectrograph design became important. A spectrograph produces a focused image, but not at all wavelengths or all spatial points. New technology has remedied this to some degree: instead of using simple plane gratings as in the early Ebert spectrometers or the spherical gratings of the Rowland spectrograph (e.g., Ref. 1), a grating with a toroidal shape could be used to improve the imaging properties of the system.

Figure 2 shows the evolution of these systems schematically. An "optical system" is indicated as the first element of the imaging system. Although represented in Fig. 2a as a simple lens, in practice it is never that straightforward. Optical systems for ground-based all-sky imaging are optimized for sky coverage and can image nearly an entire hemisphere, for example.

A space-based spectrometer would typically implement a telescope consisting of a parabolic mirror operated so that its focus is off the optical axis of the system (hence, the appellation "off-axis" system). The telescope determines the spectrograph's FOV and prevents stray or off-axis light from entering the system. If the telescope stares at a mirror that scans a range of angles, then two spatial dimensions can be sampled as well as the spectral one. This is called a scanning imaging spectrograph (SIS).

To produce an image from horizon to horizon from LEO, which would require about 140°, a scan mirror is introduced into the optical path. This mirror directs the relatively small, undistorted FOV over a larger field of regard. As we shall see in the following section, an early innovation was to introduce a scan mirror to a simple spectrograph to produce horizon-to-horizon images.

The modern scanning imaging spectrographs such as the Global Ultraviolet Imager[3–7] (GUVI; Figs. 3 and 4) and the Special Sensor Ultraviolet Spectrographic Imager[8,9] (SSUSI; Fig. 4) required technical innovation, namely, the ability to machine nonspherical mirrors and gratings and two-dimensional detectors. With nonspherical mirrors, we could design systems with good imaging properties over the length of the spectrograph's slit. With two-dimensional detectors, the grating could be held in a fixed position and the entire spectrum recorded for each spatial point within the slit (Fig. 4). The large range of motion of the imaging adds a fundamental property that allows the instrument to obtain spectrally pure images of the limb. These limb "profiles" can be inverted to yield the altitude distribution of major constituents, thus adding another dimension to the auroral imaging.

The FUV spectrum of an aurora contains information about the fundamental processes at work in the aurora and the physical manifestation of those processes. In Fig. 5 we show calculated FUV spectra for two cases: (1) an intense "hard" aurora with an energy input rate of 10 $\mathrm{erg/cm^2/s^1}$ and a characteristic energy of 10 keV and (2) a case of "soft" precipitation with an energy flux of 1 $\mathrm{erg/cm^2/s^1}$ and a characteristic energy of 1 keV. Five spectral regions are highlighted, each yielding unique geophysical information.

Auroral precipitation causes heating and ionization. Heating can lead to changes in the altitude distribution

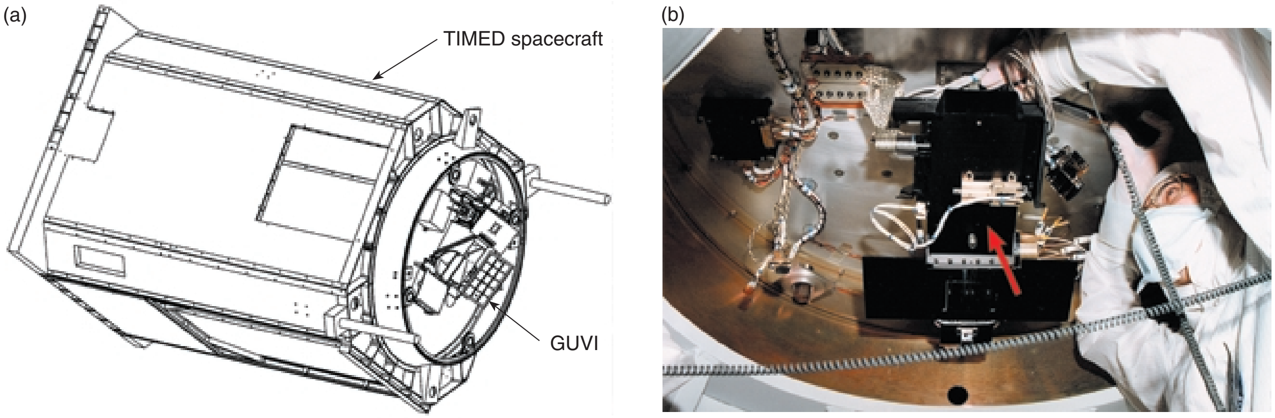

Figure 3. GUVI (a) flight configuration with the one-time cover open and (b) as it appears on the NASA TIMED spacecraft before the installation of the thermal blankets. A test fixture is shown installed on the instrument, indicated by the arrow. GUVI is mounted on the Earth-facing panel of the TIMED spacecraft.

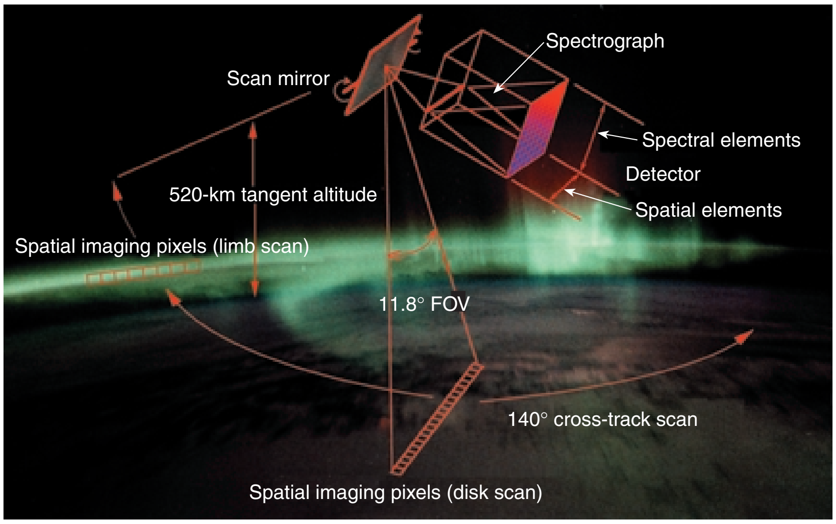

Figure 4. Concept for the horizon-to-horizon scanning imaging spectrograph. These instruments use a scan mirror to move their fields of view (FOVs) over an arc 140° long. The entrance slit, which defines the apparent FOV, is nearly 12° long. This allows the scanner to cover the entire field of regard relatively slowly while still providing complete, contiguous coverage of the area below the instrument. Spacecraft motion provides the along-orbit spatial component of the image. Light is mapped spatially and spectrally onto a two-dimensional detector. Before the advent of reasonably priced nonspherical optics and two-dimensional detectors, only a single wavelength and spatial element could be recorded at each instant.

of the three major upper-atmosphere constituents: O, O_2, and N_2. These changes are reflected in the relative intensities of the atomic oxygen spectral features at 130 and 136 nm and the N_2 Lyman-Birge-Hopfield (LBH) bands in the 165- to 180-nm region. The intensity of the incoming flux is proportional to the overall magnitude of the spectrum, particularly as observed in the 165- to 180-nm range. The incoming auroral particles have, at any one time and place, a range of energies. This energy spectrum is often approximated by a Gaussian or Maxwellian distribution, which then has a characteristic or average energy. Energetic particles can penetrate further into the atmosphere than less energetic ones. Since molecular oxygen (O_2) is a strong FUV absorber between 140 and 150 nm, a diminished signal in that range is indicative of an energetic input. Electrons and protons are the major components of auroral precipitation. Proton precipitation is indicated by emission in the hydrogen line at 121.6 nm.

Optical Instruments

APL's involvement with developing auroral imagers began with the Auroral Ionospheric Mapper (AIM) instrument on the Defense Nuclear Agency's HILAT satellite (P83-1). The Defense Meteorological Satellite Program (DMSP) Operational Line Scanner had been obtaining auroral imagery at visible wavelengths since the mid-1970s,[10–13] but the bright sunlit disk of the Earth prevented the sensor from imaging the aurora during daylight. AIM was designed to demonstrate the value of imaging the sunlit aurora to DoD.

HILAT was launched on 27 June 1983 into an 830-km-altitude circular orbit that had an 82° inclination. AIM was the first horizon-to-horizon imager. Its instantaneous FOV was quite small (0.4° × 1.7°, across track and along track, respectively). To provide contiguous coverage on the ground so that the FOV from one scan matched the following one, the instrument had to scan over its entire 134.8° field of regard in 3 s, which reduced its effective sensitivity. The scan mirror fed a

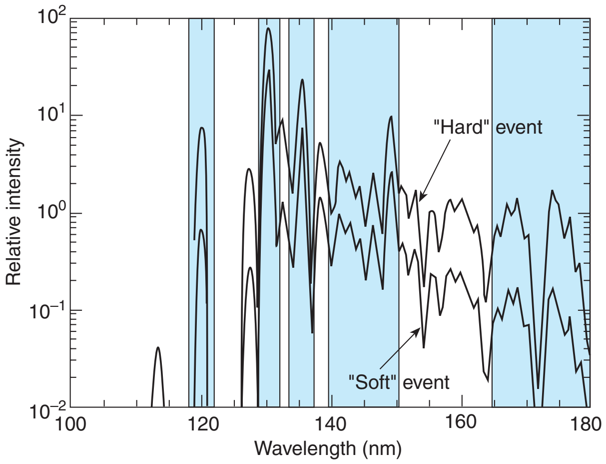

Figure 5. The FUV spectrum responds to the amount and energy (or "hardness") of the incoming particles. Here we show two cases: a low-intensity "soft" auroral event (1 erg/cm^2/s^1 at 1 keV) and a "hard" event (10 erg/cm^2/s^1 at 10 keV). The overall magnitude of the observed intensity responds proportionally to the incoming flux. The shape of the spectrum is determined by the average energy of the incoming particles. The five highlighted areas show spectral regions typically considered to be diagnostic of the process. The feature at 120 nm arises from interactions of the auroral particles with atomic hydrogen in the atmosphere; features at 130 and 136 nm arise from atomic oxygen. The two broad bands are the signatures of the excitation of molecular nitrogen emissions. The 140–150-nm band is sensitive to the amount of molecular oxygen in the atmosphere above the point where the incoming particles deposit most of their energy. The change in the ratio of this band to a band unaffected by atmospheric absorption (165–180 nm) yields quantitative data about the energy of the incoming particles.

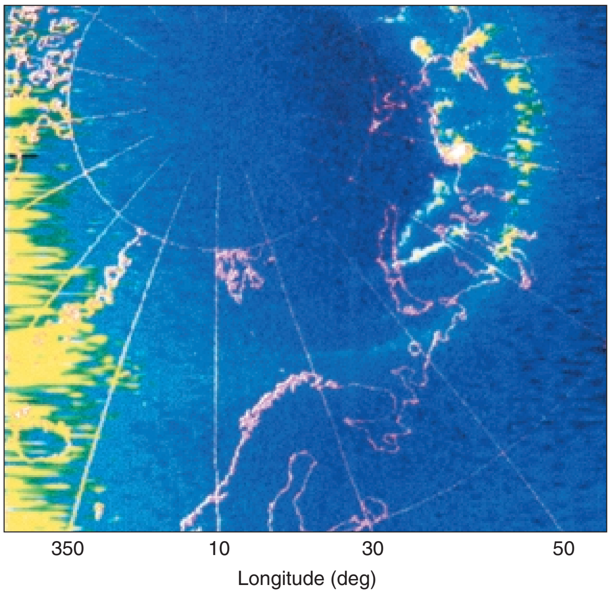

Figure 6. The first image of the aurora under sunlit conditions. A weak auroral substorm was visible on 23 July 1983 as the HILAT spacecraft passed over the Arctic coast of Russia. The Sun is toward the left-hand side of this image.[14] The image was obtained at a bandpass center wavelength of 149.3 nm. Yellow indicates highest intensities recorded; blues indicate lower intensity ranges. The entire image was sunlit. The very intense features on the left-hand side are an instrument artifact.

simple spectrograph that allowed a single wavelength to be selected. AIM, as simple as it was, proved the power of monochromatic imaging by obtaining the first image of the aurora under sunlit conditions (Fig. 6). From a research standpoint, this was significant because it allowed us to investigate another facet of the interaction of the Earth's magnetosphere and the solar wind. From an operational standpoint, UV spectral imaging was shown to provide a means for mapping the entire oval in darkness and in sunlight, thus meeting a critical requirement for resolving spacecraft anomalies.

Once the scanning imaging spectrometer concept had been demonstrated, it could be elaborated upon. The Aurora and Ionospheric Remote Sensing (AIRS) instrument on Polar BEAR[13,14] provided four-color images of the aurora. AIRS was launched on 13 November 1986 into a polar orbit. The images were obtained in two visible and two FUV wavelengths. Again, a simple spectrometer and detector system was used, but enhanced with two photomultipliers located at the spectrometer's focal plane (Fig. 2b). Placing two detectors at a fixed separation meant that they each sampled wavelengths that were of a fixed spectral separation. The use of two FUV colors allowed us to begin to characterize the energy of the precipitating auroral particles. A visible-wavelength imaging capability was provided by redirecting light from the spectrograph's telescope through a beamsplitter onto two filtered photomultipliers (essentially Fig. 2a). A typical AIRS image is shown in Fig. 7. This two-dimensional image is achieved by using the scan mirror motion in the cross-track direction and the motion of the spacecraft in the along-track direction.

The birth of the Strategic Defense Initiative (SDI) in the late 1980s fueled a tremendous increase in APL's remote sensing capabilities that laid the groundwork for new science initiatives. The first of these were the Delta 180 mission[15] and the follow-on Delta 181 mission,[16] which demonstrated the use of two-dimensional spectrographic imagers in space. MSX[17] represented the evolutionary end point of these sensors in the Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI). UVISI, with four cameras and five imaging spectrographs, is the first hyperspectral imager to fly in space. It was launched on 24 April 1996, and continues to operate.

The UVISI instruments cover the FUV through visible spectra, which provide additional spectral signatures for investigating auroral energetics (Fig. 8). Since the UVISI imagers can be pointed at a specific location on the ground or in space, they were consequently able to obtain tomographic (three-dimensional) views of the aurora. MSX is still providing data to

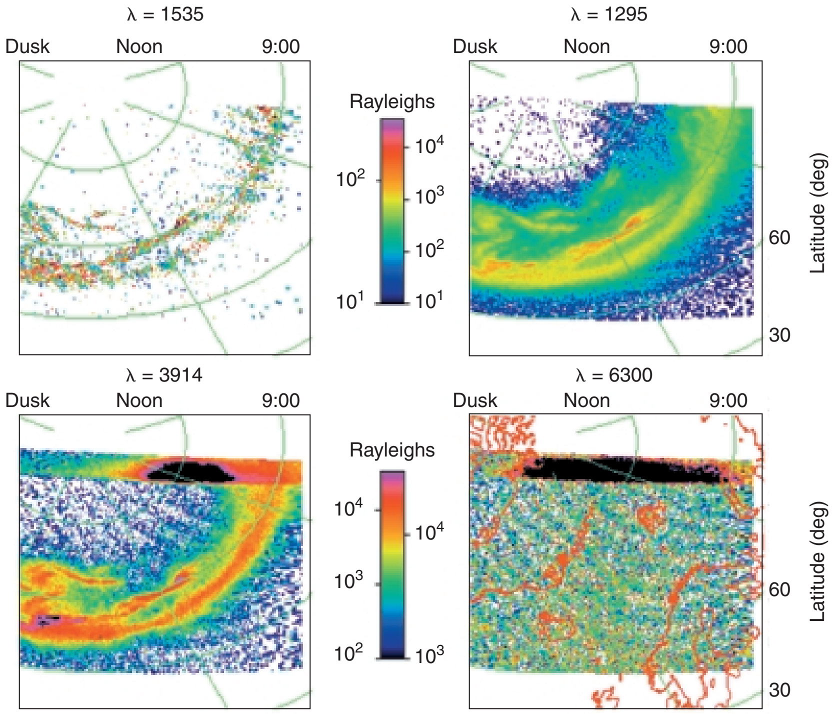

Figure 7. An AIRS image from the Polar BEAR experiment. The instrument used a beamsplitter to allow the scanner to feed an FUV spectrograph as well as two visible-wavelength photomultiplier tubes. The 630-nm system did not work as planned. The 391.4-nm system worked well but, since it was sensitive to visible light, could be saturated by sunlight or glint. The FUV channels performed as expected, although the limitations of a fixed-wavelength spacing and a fixed bandpass can be seen here and by considering Fig. 5: at some wavelengths it is desirable to accept a wider range of wavelengths in order to improve the counting statistics of the image. The wavelength λ of each image is indicated in units of Ångstroms (10^{-10} m). Just below the wavelength, the approximate local solar time is given. Color bars indicate the intensity range for each image (left-hand scale refers to image on left, and vice versa). The data were obtained at Sondrestromfjörd Station on 26 December 1996 from 1:43 to 1:51 UT.

test operational concepts and algorithms that will be used in instruments (SSUSI and GUVI) slated for flight in the next few years. These missions, like the earlier HILAT and Polar BEAR missions, were designed as survey missions: their intent was not to make high absolute radiometric accuracy measurements but to provide as much information about the broadest possible range of phenomena at the lowest cost. They were, in every sense, foundations for future quantitative instrument design efforts.

Observations of the atmosphere and the aurora have progressed significantly in the last 40 years. As these phenomena are monitored and interpreted, a more profound understanding is often engendered. With that understanding comes the next set of questions. Ideally, measurement requirements flow down from the science questions and are translated into an instrument design. The instrument itself must be calibrated. Calibration requirements have also evolved over time. In the early days, only the most rudimentary calibration was necessary because the aim was to explore an evolving frontier, and the questions often dealt with the morphology of the phenomena.

Today, detailed quantitative products are required in order to advance our understanding of the atmosphere and aurora. The next generation of sensors will have to achieve absolute radiometric accuracies of better than ±8%. The ability to meet this requirement has, in itself, spurred new research activities.

MSX/UVISI data are important to this effort, for they allow us to examine the details of the auroral energy deposition process. Simply stated, a greater number of accurate measurements more highly constrains the range of the "adjustable parameters" or unknowns in the physics-based models of the aurora. For instance, with MSX's hyperspectral wavelength coverage, we can investigate the effects of local heating on the composition of the atmosphere. This local heating, if prolonged and of sufficient intensity, can lead to departures of the atmosphere from local hydrostatic equilibrium. During geomagnetic storms, huge waves are produced in the polar region which travel toward the equator. This movement affects the amount of atmospheric drag experienced by satellites and the characteristics of the F-region ionosphere.

Auroral imagery from MSX has been used to validate the approach planned for the SSUSI and GUVI sensors. Hyperspectral images, such as those shown in Fig. 8, provide more complete information about the spectral, spatial, and temporal scales of auroral phenomena at a much higher resolution than practical to implement in an operational sensor. MSX also extended the wavelength coverage beyond the FUV into the visible and near infrared.

The ability to precisely point MSX and to examine the detailed response of the upper atmosphere to auroral energy inputs can be used to validate the techniques used by other sensors. Developing that detailed quantitative and predictive understanding of auroral phenomena is the goal of GUVI and SSUSI. These sensors, as we will discussed, are designed to survey a large portion of the Earth's upper atmosphere. "Strip" images (e.g., Fig. 9) are the first step in producing a set of environmental parameters for users.

MSX has a spatial resolution a factor of 100 times better than these routinely produced parameters but covers an area a factor of 100 times smaller. The images in Fig. 8 cover an area about the size of 25 GUVI or SSUSI superpixels. MSX data have allowed us to examine whether small-scale phenomena, such as the arcs shown in Fig. 8, are an important effect. The complete spectral coverage, illustrated by the spatial/spectral images in Fig. 8b, allows us to evaluate the value added by either full-spectral coverage (rather than just using "colors") or by extending the wavelength coverage beyond the FUV.

SSUSI and GUVI, which are built and awaiting launch, incorporate all the features shown in Fig. 4: a large instantaneous FOV, full simultaneous wavelength coverage, and imaging along the slit direction. In addition, they are accurately calibrated and fully characterized. Again, they produce horizon-to-horizon images with coverage of one limb (the one looking away from the Sun). Figure 9 illustrates the range of phenomena encountered by such a sensor and the geographic coverage available. Our earlier sensors all had very restricted data-gathering capabilities, since these exploratory missions were cost-constrained and seen by our sponsors as demonstrations rather than operational flights. SSUSI and GUVI will be our first opportunity to collect data continuously.

Both sensors benefited from our institutional experience and the development of computer codes that solve the equations for the production and transport of photons in the auroral ionosphere and the polar upper atmosphere. Armed with theoretical predictions and practical experience, we can make decisions about the implementation of these next-generation sensors.

The instrument design space is constrained by the range phenomena

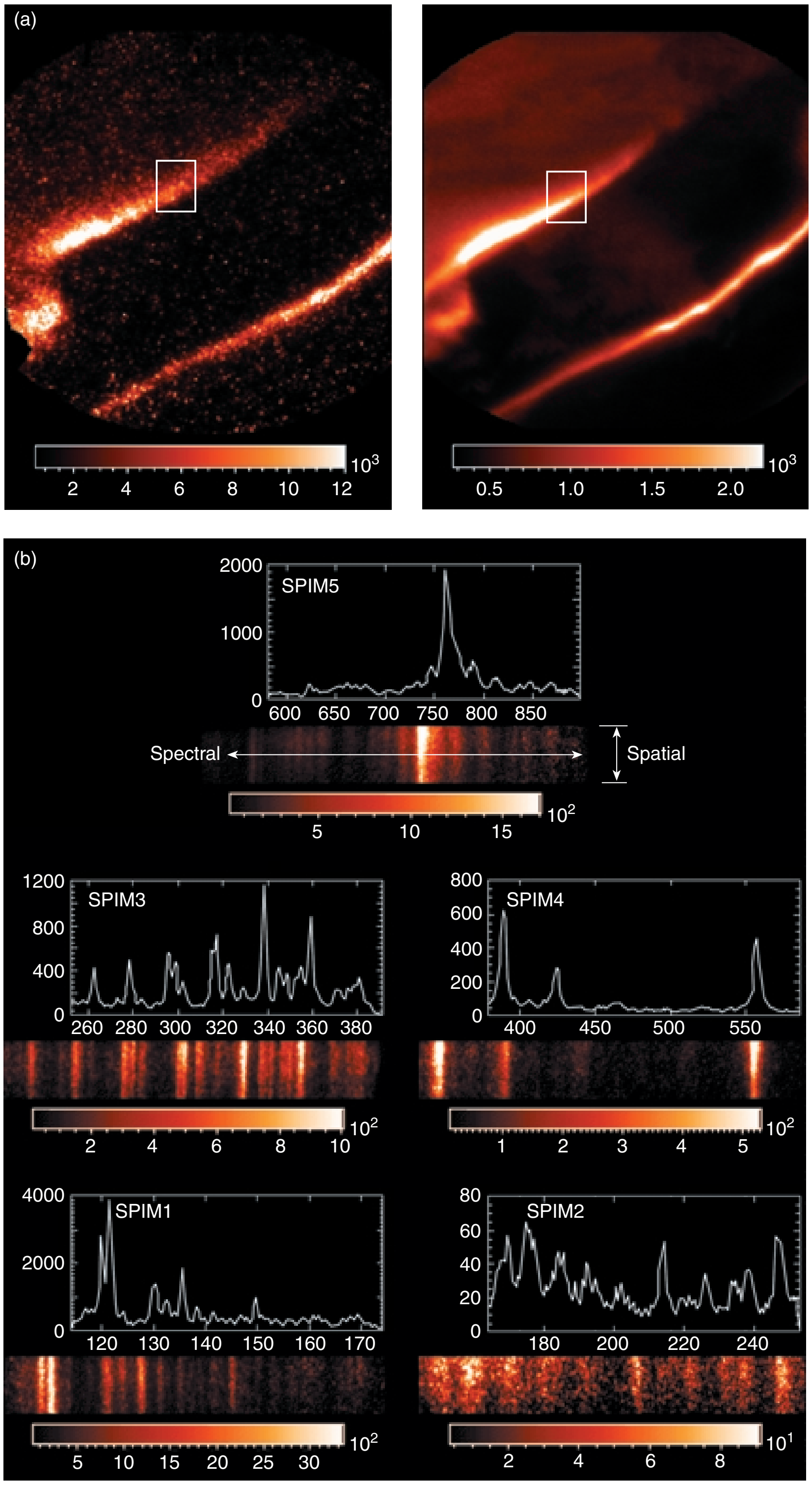

Figure 8. (a) MSX/UVISI image of an auroral arc in visible (left) and FUV (right) wavelengths. Color bars indicate intensity in Rayleighs. (b) MSX spectral images of part of the arcs shown in Fig. 8a. Each spectrographic imager (SPIM)[17] obtains spatial and spectral information (in nm), but spatial scanning ability was limited to 1°. Line plots show intensity as a function of wavelength. Images below each line plot are maps of the intensity at the image plane. Each spatial pixel is mapped vertically, and wavelength is shown horizontally. The FUV spectrum for SPIM1 shows the prominent arc features. Here the aurora has actually changed the composition of the upper atmosphere, causing a preferential enhancement of emissions from molecular nitrogen (i.e., lines at 120 and 149 nm). A significant variation in intensity along the arc can be seen, showing the spatial variation in intensity as a change in color along the vertical axis.[17] (Compare with Fig. 5.)

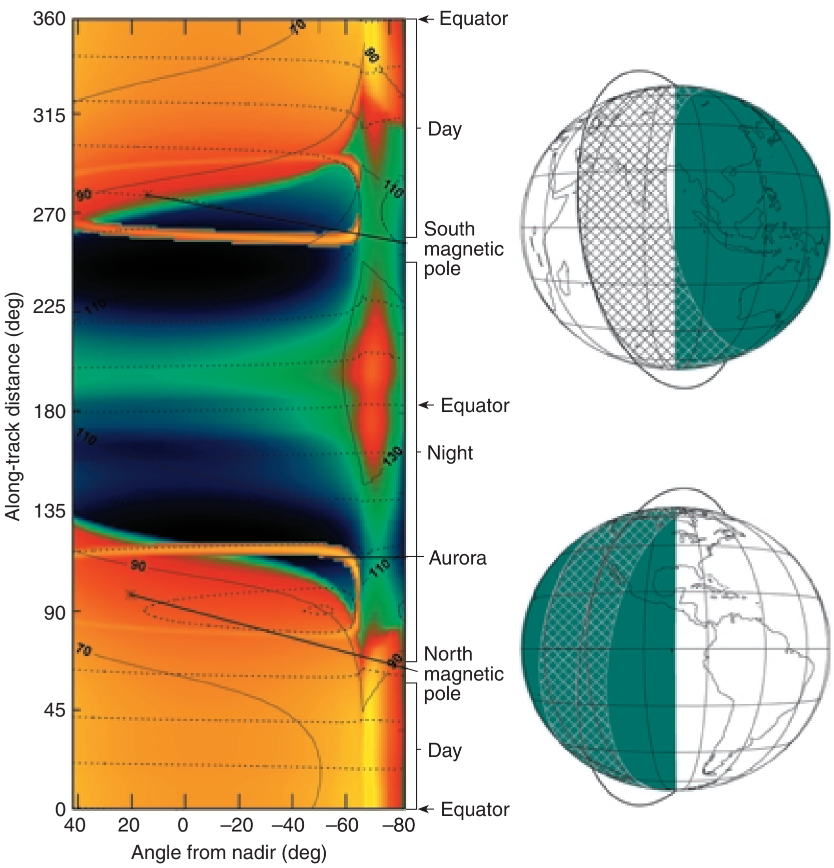

Figure 9. The view from SSUSI. In this simulation a single "color," which arises from atomic oxygen emission at 135.6 nm, is displayed as a function of position along the orbit on the left-hand side. The coverage of the horizon-to-horizon swaths is shown as the cross-hatched areas on the globes. The image swath includes a view of the limb of the Earth. SSUSI and GUVI will both be able to extract information about the altitude dependence of the neutral constituents of the atmosphere from these profiles. These sensors can image the aurora under full sunlit conditions at both poles. The intensity ranges from the brightest yellow at about 15 kR through the dark blue, which corresponds to a signal of about 10 R—a range of more than 1000 in just one emission feature. The bright feature on the nightside is the "equatorial anomaly" or "equatorial arcs," an upwelling in the nightside plasma over the magnetic equator. (Figure courtesy of D. J. Strickland, Computational Physics, Inc.)

expected to be encountered. Since SSUSI's customer, DMSP, was particularly interested in the measurement of ionospheric parameters, the system had to accommodate an interscene dynamic range of a factor of 10,000. Atmospheric physics models predicted that the dayside intensity at 130.4 nm is as great as 40,000 Rayleighs, and the nightside intensities are a few Rayleighs (Fig. 10). Using these predictions, together with a model of the instrument's end-to-end response, we were able to identify the system design drivers. A slit mechanism, which gives a factor of 4 control over the input rate, and high-speed photon-counting electronics are used to meet the measurement requirements.

SSUSI will fly aboard the DMSP Block 5D3 spacecraft, which are in Sun-synchronous or fixed local time orbits at a 830-km altitude. The orbit will cross the equator at about twilight and will pass within a few degrees of the poles. The SSUSI sensor contains an SIS covering the FUV and high-sensitivity, nadir-viewing photometers operating at 629.4 and 630.2 nm, for separate signal and ground albedo determination measurements, and at 427.8 nm. The photometers are nadir viewing and operate only on the nightside. These photometers are designed to provide information about the nightside ionosphere and confirm the FUV auroral boundary location. This latter capability is useful in reconciling space-based FUV data to the type of data routinely collected by ground-based all-sky cameras and spectrographs.

The SIS for GUVI and SSUSI has two modes of operation. The imaging mode produces horizon-to-horizon line scan images at all wavelengths in the instrument bandpass. Five "colors" or selected wavelength intervals are stored in the spacecraft data system for later downlink (see Fig. 5). In the spectrograph mode, the entire FUV spectrum is obtained at one selected look angle. The spectrograph mode is intended for instrument characterization and use during "ground truth" observing sequences. SSUSI and/or GUVI environmental parameters produced from data collected during overflights of ground-based facilities will be compared to measurements of the same parameters obtained by the ground stations. This "ground truthing" of the data is necessary to ensure that the instrument and the data reduction algorithms are performing as promised.

The SIS consists of a cross-track scanning mirror at the input to a telescope (a 75-mm focal length off-axis parabola system with a 25 × 50 mm clear aperture) and a Rowland circle spectrograph. The SIS is an *f*/3 system with a toroidal grating. Two two-dimensional photon-counting detectors are located at the focal plane of the spectrograph. The operating detector is selected by a "pop-up" mirror that is moved into or out of the optical path to direct light from the grating onto one of the two detectors. The detectors employ a position-sensitive anode to determine the photon event location. For convenience we refer to the quantization of the position determination on the detector as defining a "pixel."

The imaging spectrograph builds multispectral images by scanning spatially across the satellite track

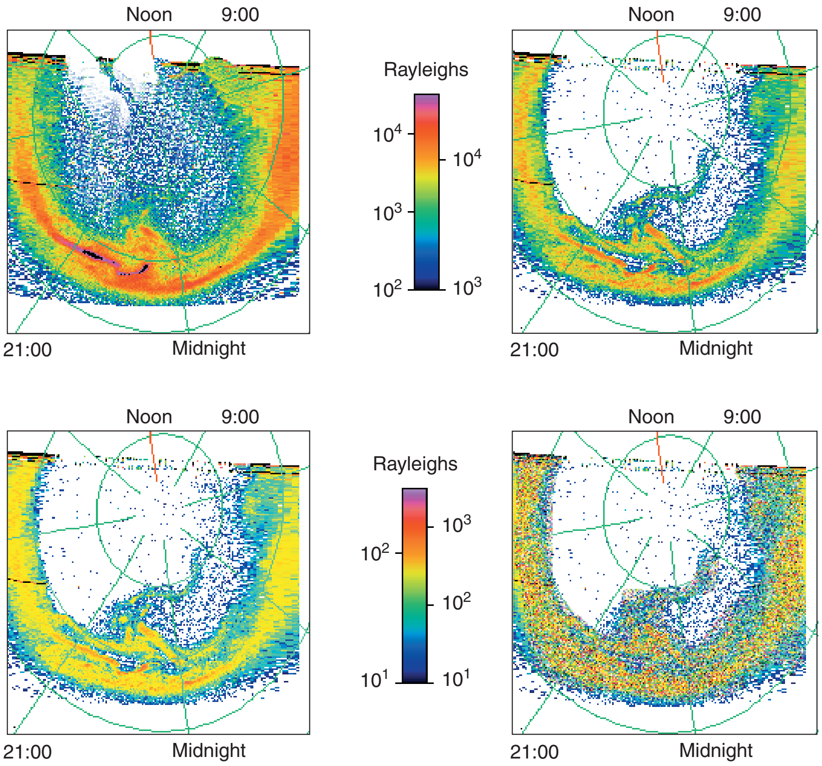

Figure 10. Simulated four-color SSUSI image. The panels, reading from top left to bottom right, correspond to atomic oxygen at 130.4 nm, atomic oxygen at 135.6 nm, N_2 emissions from 140 to 150 nm, and N_2 emissions from 165 to 180 nm. Images at 121.6 nm (not shown) indicate regions of proton precipitation. The atomic oxygen emissions are used to track changes in upper atmospheric composition. The ratio of the two N_2 emissions is indicative of the depth of the deposition of the energy of the incoming particles. Since more energetic particles penetrate more deeply into the atmosphere, the average energy of the particles can be deduced. The magnetic local time coverage of a typical image is indicated by the numbers in hours on the axes (e.g., 21:00 means that that particular part of the oval is at a magnetic local time of 21:00 h). The color bars indicate the intensity range for each image (left-hand scale refers to image on left, and vice versa).

(Fig. 4). One dimension of the detector array is binned by the detector electronics processor into 16 spatial elements (these are the spatial extent of the slit and are oriented parallel to the spacecraft track). The other dimension consists of 160 spectral bins over the range of 115 to 180 nm. The scan mirror sweeps the 16-spatial-element footprint from horizon to horizon perpendicular to the spacecraft motion, producing one frame of 16 cross-track lines in 22 s. The large FOV creates significant overlap on the disk away from nadir. This and the slower scan period increase the effective sensitivity of SSUSI and GUVI by a factor of 10 to 100 over that of AIRS and AIM.

GUVI—the imaging spectrometer on the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) spacecraft—is a modified version of the SSUSI instrument. The modifications largely reflect implementation on the TIMED spacecraft, e.g., a scan range from 80° to –60°, 14 spatial pixels rather than 16, and so on. The TIMED mission is the first in the NASA Sun–Earth Connections Program, with a launch scheduled for 18 May 2000.

TIMED will investigate the Earth's mesosphere and lower thermosphere (60–180 km), the least explored and least understood region of the atmosphere, from its 74° inclination 625-km orbit. A comprehensive global picture is needed to understand this region, where *in situ* measurements are difficult. The basic physics that control the region are understood, but the details are difficult to model: the inputs from above and below are not well known. Here, the atmospheric temperature and temperature gradients reach their largest values, the composition changes from molecular to predominantly atomic, and complex chemical and electrodynamic processes become the major determinants of composition. The combination of these effects prevents an adequate global description of upper atmospheric "weather." It is known that the global structure of this region can be perturbed during stratospheric warming events and solar-terrestrial storms, but the structure and dynamics of the response are not understood.

An important component of this overall question is that of energy balance. To begin to understand this issue we must determine the auroral inputs and be able to specify the neutral atmosphere; GUVI will provide these key parameters. The fundamental difference between TIMED and the DMSP mission is the difference between exploration and monitoring: TIMED seeks an understanding whereas DMSP focuses on knowledge of current conditions.

Key Parameters

GUVI and SSUSI ground software will process the data into key environmental parameters. Each of the five colors downlinked by SSUSI and GUVI is related to a geophysical phenomenon (Table 2). Conversion of instrument counts into radiance units requires some attention to detail and an in-depth knowledge of the instrument; transforming the engineering data into useable information is much more complex. For the SSUSI Program, over 50,000 lines of operational

Table 2. Environmental parameters measured by different colors.

	H (121.6 nm)	O (130.4 nm)	O (135.6 nm)	N_2 (LBH 1)[a]	N_2 (LBH 2)
Dayside limb	H profile and escape rate	O profile	O altitude profile	Solar EUV[b]; inputs	N_2, O_2, temperature
Dayside disk	H column	Composition	O/N_2	O/N_2	
Nightside limb	H column	F-region electron density profile	F-region electron density profile		
Nightside disk	H column	F-region total electron content	F-region total electron content		
Auroral zone	Proton auroral boundaries	Auroral boundaries	Effective energy flux Q	Effective average energy of precipitating particles	Effective average energy of precipitating particles

NOTE: No emissions occur in the N_2 LBH bands from the Earth's nightside upper atmosphere.

[a] LBH = Lyman-Birge-Hopfield.

[b] EUV = Extreme ultraviolet.

software were written and delivered to our sponsors to enable this transformation. Since DMSP supports space weather users through the 55th Space Weather Squadron (Schriever AFB, Colorado Springs, CO), they also required that the code be documented to Mil Spec 2167A standards, quite a departure from common practice for a scientific mission. As part of the operational data flow, the SSUSI software must manage data intake, decompression, calibration, gridding and geolocation, and product generation as well as the graphical interface to the data. These tasks are to be accomplished from a small workstation within about 20 minutes of the receipt of the data!

GUVI measures essentially the same quantities but has a different emphasis. Whereas DMSP focused on the development of ionospheric assessment techniques, the emphasis of TIMED is on energy inputs and the response of the atmosphere to those inputs, be they solar or auroral. This changed emphasis is reflected in the choice of orbit. DMSP flies in a Sun-synchronous orbit where the local time of the observations is essentially fixed. Conversely, TIMED is interested in unraveling the complex structures resulting from the action of atmospheric tides and waves and so must separate local time effects from seasonal ones. Again, with TIMED's 74° inclination circular orbit at 625 km, a 720°/year nodal regression rate is implied, i.e., the local time of the equator crossing will vary from dawn to dusk in 3 months.

The GUVI software is being written to reuse as much existing SSUSI software as possible while allowing for the explosive growth in distributed, network-based processing. Since TIMED data users are widely dispersed, a Web presence is a key component of GUVI's data distribution scheme. The algorithms and display software are designed to run on small PC-class computers, which greatly reduces the cost not only of the CPU but also all of the associated peripherals.

The synergy between GUVI and SSUSI exemplifies how the APL Space Department has been able to bridge the gap between operational and basic research programs to the benefit of all concerned. Not only have the individual projects realized significant cost savings, but each flight opportunity provides unique corroborative data sources that aid in the interpretation of the FUV data obtained by the APL sensors. For instance, on the DMSP spacecraft, SSUSI will determine auroral energy inputs at the same time the DMSP J5 sensor makes *in situ* measurements of the energy distribution of precipitating electrons and protons. This combination provides "space truth" at the spacecraft for the auroral information deduced from the SSUSI images. On TIMED, GUVI will measure the composition of the thermosphere as the TIMED Doppler Interferometer measures the upper atmospheric winds. This combination increases the accuracy of our estimate of the F-region ionospheric electron density profiles, which is of great interest to DoD.

SUMMARY

APL has an extensive heritage in imaging the aurora and a bright future in making new and innovative measurements that carry on that tradition. The Space Department has a tradition of providing end-to-end services to "customers"—from the design and construction of optimized sensors to the production of scientific results. Our heritage in auroral imaging demonstrates that we have helped our customers define the sensors required to produce better environmental data products.

Both GUVI and SSUSI will routinely produce environmental data products that will fuel future scientific studies and test our understanding of space weather phenomena. These products (Table 2) are to be provided to their respective user communities within minutes of receipt of the instrument data at the processing site. The key problem is to go from measurements of segments of the spectrum to a product that is meaningful to other users. Over 50,000 lines of code have been written and tested for GUVI and SSUSI, and we have every expectation that the scientific accuracy of the products will meet our customers' requirements. This is possible because of the extensive scientific, instrument, and data processing heritage that APL has brought to bear on the mission requirements.

The TIMED and DMSP missions offer opportunities as well as challenges. Other co-manifested instruments provide important collaborative or corroborative measurements that extend our scientific reach. This increases the value of SSUSI and GUVI to APL and to our customers. TIMED, for example, carries instruments to measure the solar inputs and thermospheric wind fields. These measurements are not provided on the DMSP satellites but do enable GUVI to produce a better forecast of ionospheric conditions, even though TIMED is not an ionospheric mission. Thus TIMED will help prove new measurement concepts for DMSP. DMSP, on the other hand, does fly *in situ* particles and fields experiments that provide important information on auroral electrodynamics. This is not a DMSP interest but it is very important to TIMED.

APL staff members are working on the next generation of FUV instruments, ones that incorporate new detector technologies to facilitate exploration of other planets and to better understand our own. The next 10 years may see new APL instruments that build on our past successes exploring other planets and flying in constellations of microsats probing the Earth's aurora. We also expect that by the 50th anniversary of the Space Department we will have collected over 1 terabyte of FUV data that will have fueled new investigations into the Earth's relationship to the Sun and its plasma environment.

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