MSX—A Multiuse Space Experiment

Larry J. Paxton, Ching-I. Meng, Donald E. Anderson, and Gerald J. Romick

The Midcourse Space Experiment (MSX) has the potential to address environmental issues and demonstrate that a mission for the DoD can fulfill nondefense, or dual-use, data collection requirements. MSX differs from conventional satellite investigations in that the spacecraft does not have a routine data collection mode, and it has a hyperspectral imaging capability. In this article we explore what these differences imply for dual-use applications. Examples of how MSX can be used for atmospheric remote sensing, determining ocean color, and identifying surface composition are discussed. A brief description of the MSX instruments is also provided.

INTRODUCTION

The Midcourse Space Experiment (MSX) represents what is probably the single most versatile suite of optical instruments ever to be flown in space. It is unique in the breadth of activities contemplated. A review of the experiment plans shows that almost every optical phenomenon is to be investigated. This breadth is dictated by the Ballistic Missile Defense Organization's (BMDO's) requirement that MSX characterize targets against realistic backgrounds and that a representative set of background data be acquired. Much of the data will have a profound impact on how we view our world and will be a "proof-of-concept" of the next step in the evolution of environmental remote sensing instrumentation.

Remote Sensing

Photography is the most accessible way of remotely sensing the world by mechanical means. A monochrome, or black-and-white, photographic emulsion records the intensity of light falling on it during its exposure by undergoing a chemical change. Black-and-white film has a spectral response: the silver crystals embedded in the emulsion respond not only to intensity but also to the color, or wavelength, of the light falling on the film.

Photographic reconnaissance and targeting from airborne platforms began in the late 1800s, when they were used during the Civil War to augment information from human observers. By the First World War, users realized that the ability to locate targets or to detect changes in terrain could be enhanced by selecting a specific combination of film and filter. This procedure can broadly be described as panchromatic imaging. In this type of imaging much of the available light is used to form an image. Color film divides this response into three different emulsions that respond to different wavelengths of light to a greater or lesser degree. Color films are intended to mimic how the human eye responds to a given scene. By the 1950s, multiband photography came into widespread use as a technique for mapping the distribution of terrain features and types. Typical bandpasses were coarse (about 60–100 μm). The same scene looks different to each of these sensor systems. In fact, one of the principles of camouflage is to arrange the reflective or radiative characteristics of an object so that the contrast between the object and the background is minimized based upon the spectral sensitivity of the anticipated observing system.

Film was also put to use for environmental applications. Film has many limitations, though, particularly where global coverage is required. For global coverage, space-based platforms are the best option, but film-based systems, while feasible, present many special handling problems.

These problems can be ameliorated by using an electronic medium to record the image. The Applied Physics Laboratory's Dodge satellite, which returned the first color image of the full Earth, demonstrated how such an image could be achieved. A new era was entered in 1972 with the launch of the first Landsat Multispectral Scanner.[1] It had an 8-bit radiometric resolution, a spatial resolution of 79 m, and a swath width of 185 km. There were four channels: two in the visible (each 100 nm wide) and two in the infrared (one 100 nm and the other 300 nm wide). This arrangement enabled the Landsat satellite to synthesize "color" images, which enhanced the user's ability to identify surface features. Landsat 4, launched on 16 July 1982, carried the Thematic Mapper, which had six channels covering visible through thermal infrared (IR) wavelengths. The Landsat series and the National Oceanographic and Atmospheric Administration (NOAA) Polar Orbiting Environmental Satellite series (in particular, its Advanced Very High Resolution Radiometer) have continued to refine this concept.[1] Identification of surface features has proved to be complex: there has been a steady push to increase the number of spectral bands that are used in imaging systems in the belief that the presence of more spectral features will enable the user to identify surface features more confidently. Several aircraft now provide hyperspectral imaging systems with hundreds of colors available in their images.

Airborne sensors have been the proving ground for technological innovation: they were the first to demonstrate the utility of hyperspectral remote sensing. Hyperspectral imaging implies the imaging of hundreds or even thousands of spectral bands. For example, the NASA Airborne Imaging Spectrometer, first flown in 1982, obtained 128 bands with 9.3-nm bandwidth and 12-m resolution.[1] The trend toward increasing spectral resolution is exemplified by the Hyperspectral Digital Imagery Collection Experiment, which records 206 channels over a 1-km swath at about 10-nm resolution, and the Airborne Visible/Infrared Imaging Spectrometer, which records 224 channels in an 11-km swath at about 10-nm resolution.[1]

The MSX Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) constitutes a great leap forward by demonstrating the application of hyperspectral imagers from space. UVISI records data in 1360 spectral channels simultaneously, with an average spectral resolution of about 1 nm in a swath about 18 km across.

The spectrum of the Earth is complex. It is determined by the spectral reflectivity of surface features, the solar spectrum, and the properties of the atmosphere. Figure 1 shows an example of how the reflectivity of a sample measured in the laboratory is changed by solar illumination and the interaction of the incident and reflected light with the atmosphere. For an observer outside the atmosphere, the radiation field is altered by the absorption and scattering of sunlight as it passes through the atmosphere to illuminate the scene. Photons scattered by the surface feature can then be absorbed or scattered as they travel from the surface out toward the observer. In scattering, a photon's direction is changed; in absorption, a photon is removed from the radiation field, causing a change in the internal energy of the material that absorbs it. The relative and absolute magnitudes of the two processes depend on the composition of the atmosphere as well as the locations of the observer and the Sun. These processes have to be correctly accounted for if the observer is to

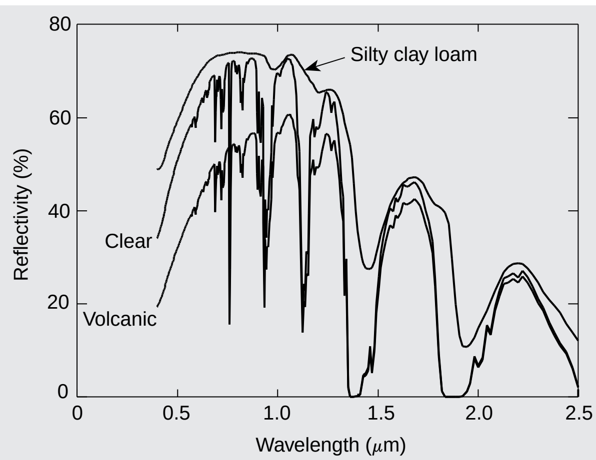

Figure 1. Comparison of the spectral signature of silty clay with that as seen through a "clear" atmosphere and one that contains fresh volcanic aerosols. These signatures have been normalized to remove the variation in the solar spectrum. The structure in the clear and volcanic aerosol cases is a result of water vapor and O_2 absorption features. CO_2 is a relatively minor absorber in this spectral region; the 2.0-μm band is its only absorption feature in this spectrum. O_3 absorption in the Chappuis bands contributes around 0.6 μm, but it absorbs only about 7% of the solar signal. At short wavelengths molecular, or Rayleigh, scattering is the dominant broad-band absorber in the clear case. Particle, or Mie, scattering is seen in the volcanic case.

determine with any certainty the nature of the material being viewed.

Each region of the spectrum of the Earth has unique scattering and absorption characteristics. In the far ultraviolet (0.1–0.2 μm), solar radiation is stopped high in the atmosphere as a result of absorption by molecular oxygen (O_2). In the middle ultraviolet (0.2–0.32 μm), ozone (O_3) blocks solar radiation from reaching the ground. In the visible (0.4–0.7 μm), Rayleigh scattering, absorption by O_3, and dust and haze affect the transmission of light. In the near IR (0.7–0.8 μm), O_2 is the principal absorber. At longer wavelengths, polyatomic molecules start to become important absorbers. Out to about 4.0 μm, the radiation observed from space is dominated by sunlight reflected from the atmosphere and the surface. At longer wavelengths, thermal radiation from the atmosphere and surface becomes the most important source. The thermal radiation spectra are shown in Fig. 2. The major constituents of the atmosphere, N_2, O_2, and A, are nearly transparent to light of a wavelength longer than 4.0 μm. Trace polyatomic constituents such as CO_2, H_2O, O_3, CO, CH_4, and N_2O have complex absorption spectra and are present in large enough amounts that they absorb much of the terrestrial radiation field in some spectral bands. Clouds absorb and scatter radiation throughout the entire spectrum, and dust, haze, and aerosols contribute as well. Calculating the radiation field or interpreting observations is even more complicated in the thermal IR; terrestrial radiation is transferred from layer to layer in the atmosphere and altered by the differences between these layers. Theory describes the scattering of light by water droplets and molecules quite well, but aerosols vary in complex ways and are difficult to relate to other meteorological phenomena. Looking down in the IR at wavelengths longer than about 3.5 μm reveals a radiation field that has a complex dependency on the atmosphere.

MSX

MSX was designed to perform a task with a direct connection to environmental remote sensing: to characterize the optical backgrounds for viewing geometries typical of those seen during target encounters. The optical background is produced by three general effects: where the Sun is relative to the observer's line of sight, what is in the atmosphere (both within and outside of the field of view), and what is behind the atmosphere (whether it is the celestial scene or the Earth's disk). MSX has the unique ability to look at the effects caused by all three phenomena. A catalog of data, while it may represent typical scenes, does not constitute a predictive capability. A predictive capability requires an understanding of the underlying phenomenology, i.e., an understanding of why the observed scene changes.

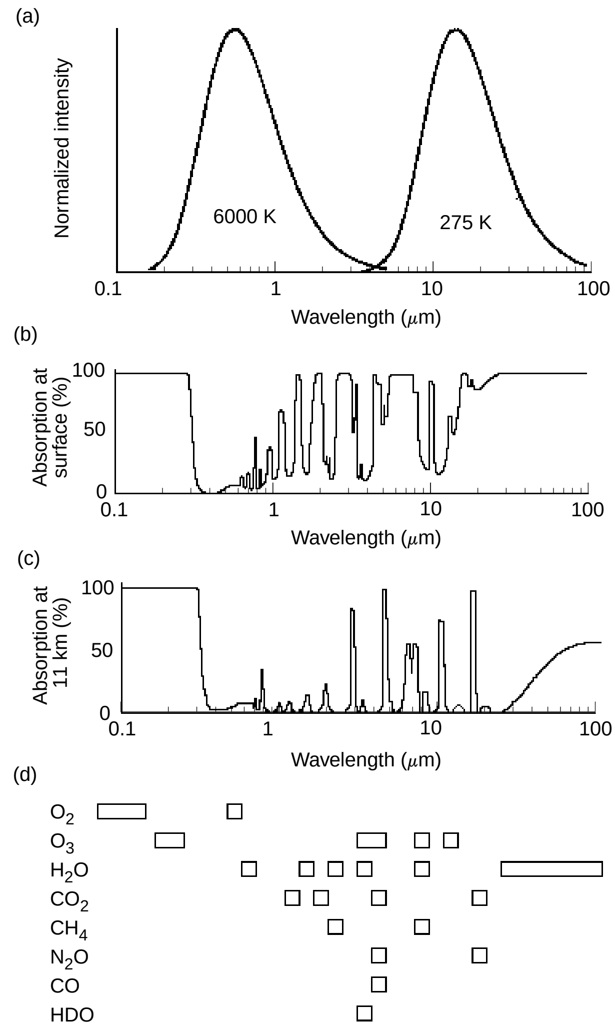

Figure 2. Radiative characteristics of the atmosphere. (a) Blackbody radiation curves for an object at 6000 K (representative of the effective temperature of the Sun) and at 275 K (typical of the Earth). The crossover region at about 4.3 μm is readily apparent. At this point the measured signal will be in approximately equal proportions of solar backscattered radiation and thermal emission from the Earth. (b) Percent absorption at the Earth's surface. (c) Percent absorption at about the altitude of cloud tops (11 km). Details of the absorption and transmission of atmospheric radiation dramatically affect the observed spatial and temporal variability of the scene (its "clutter"). (d) Approximate spectral range of the atmospheric species that result in significant absorption. (Adapted from Ref. 2.)

MSX can contribute toward building that required predictive capability. First, a comparison of the observed radiances with those predicted by models can indicate areas in which the models are less accurate. Second, by going beyond the radiances and retrieving the atmospheric and environmental parameters that give rise to the radiation field, we can compare the deduced environmental parameters with data obtained from other sources. MSX is in an enviable position; it will make early, unique measurements before the flight of the first of the Earth Observing System (EOS) satellites.

USING MSX FOR ENVIRONMENTAL STUDIES

The combined instrument suite on MSX is very powerful. The primary MSX instruments—the Spatial Infrared Imaging Telescope III (SPIRIT III), UVISI, and the Space-Based Visible experiment—are described in detail elsewhere.[3–5] Here we address features that are particularly important to the problem of obtaining environmentally relevant data; the two environmentally relevant instruments are SPIRIT III and UVISI. There are two important differences between SPIRIT III and UVISI. First, the spectrographic part of SPIRIT III (the interferometer) does not image; second, we do not anticipate using the radiometer to image the surface since its detectors are expected to saturate when viewing below horizon on the disk of the Earth. The radiometer does have 90-μrad angular resolution, which is equivalent to a spatial resolution of about 200 m on the limb. Thus, SPIRIT III's utility lies in its observations of targets, the Earth-limb, and the celestial scene.

Figure 3 illustrates the range of wavelengths covered by the MSX instruments. Table 1 summarizes the characteristics of SPIRIT III and the estimated tangent altitude (or altitude of the closest approach of the line of sight to the Earth) at which the detectors will become saturated. The UVISI instruments are all expected to be able to obtain valid data at all tangent altitudes, including viewing the fully illuminated disk of the Earth. The UVISI spectrographs are summarized in Table 2, and the imagers are summarized in Table 3. Figure 4 shows the UVISI and the SPIRIT III fields of view (FOVs). The instruments are all expected to be co-aligned to within about 0.1° of a spacecraft boresight. The SPIRIT III radiometer and interferometer

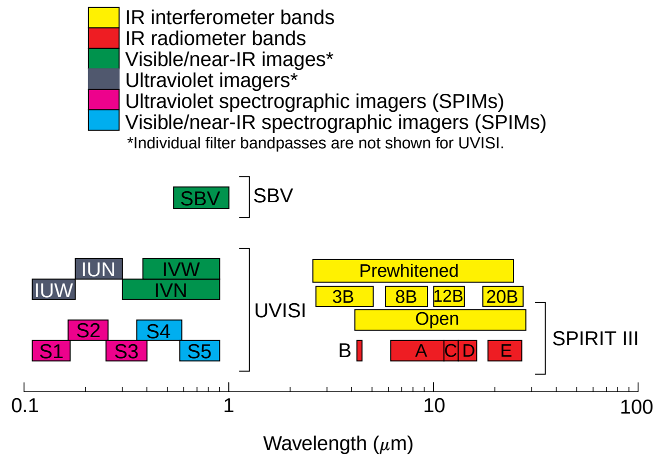

Figure 3. Schematic representation of the MSX optical instrument bandpasses. The MSX instruments cover the spectral range from the ultraviolet, through the visible, and into the long-wavelength IR. Each of these spectral ranges offers some unique signature of a process, feature, or constituent in the biosphere. The SPIRIT III interferometer and the UVISI/SPIMs produce spectrally resolved information. Each UVISI imager has four multispectral filters available for use. MSX offers an unmatched combination of wavelength coverage and resolution. This broad wavelength range includes that of many NASA, NOAA, and DoD sensors. SBV = Space-Based Visible experiment.

Table 1. SPIRIT III detector designations, wavelength coverages, and sensitivities.

Detector designation	Range (μm)	Noise equivalent signal radiance ($W \cdot cm^{-2} \cdot sr^{-1}$)	Vertical FOV[a] as viewed on the limb (km)	Minimum tangent height before saturation (km)
SPIRIT III Interferometer				
20B	17.2–28.0	10^{-12}	14	53
3B	2.6–4.9	5×10^{-10}	6.7	<0
8B	5.8–8.9	5×10^{-11}	14	23
Open	4.0–28.0	$5 \times 10^{-9} - 5 \times 10^{-12}$	6.7	52
12B	10.6–13.0	10^{-9}	4	<0
Prewhitened	2.5–24.0	$5 \times 10^{-9} - 5 \times 10^{-12}$	6.7	39
SPIRIT III Radiometer				
A	6.03–10.91	4×10^{-11}		
B_1	4.21–4.36	2×10^{-10}		
B_2	4.20–4.45	2×10^{-10}		
C	11.1–13.4	2×10^{-11}		
D	13.5–16.0	1.5×10^{-11}		
E	18.1–26.0	2×10^{-11}		

[a]Field of view.

Table 2. Characteristics of the UVISI spectrographic imagers (SPIMs).

Characteristic	SPIM 1	SPIM 2	SPIM 3	SPIM 4	SPIM 5
Wavelength coverage (nm)	110–170	165–258	251–387	381–589	581–900
Wavelength resolution (nm)					
Wide slit	0.8	1.2	1.8	2.8	4.3
Narrow slit	0.5	0.9	1.5	2.1	3.3
Sensitivity (photon · $cm^{-2} \cdot s^{-1}$)	5	2	3	1	1
Photocathode	CsI	RbTe	Bi-alkali	Tri-alkali	Tri-alkali
Window	MgF_2	MgF_2	SiO_2	SiO_2	SiO_2
Clear aperture (cm^2)	110	110	110	110	110

FOVs do not overlap, but the spacecraft can be moved to produce overlapping data sets. The SPIRIT III radiometer and the UVISI spectrographic imagers (SPIMs) have instantaneous FOVs that are swept by scan mirrors to produce a larger field of regard. The SPIRIT III field of regard is completely within the FOV of the UVISI wide-field imagers, as is the fixed FOV of the SPIRIT III interferometer.

MSX System Capabilities

The great majority of Earth remote sensing instruments operate in a manner fundamentally different from MSX; typically, they constantly collect data and they operate in one mode most of the time. MSX is an event-driven (or episodic) spacecraft. Although this does present a number of difficulties from a mission planning standpoint, it offers the promise of extraordinary flexibility in designing a data collection event (DCE).

A DCE is the fundamental unit of operation of the MSX spacecraft. It is a sequence of events and instrument states that takes the spacecraft from its safe, or "park," state to an observation state or sequence of states, and then returns it to park. To a large extent, as long as no spacecraft or instrument constraints are violated, the line of sight is free to move in any pattern or to stare at a fixed or moving coordinate. In the following material we will give examples of several kinds of DCEs planned for MSX operations.

Sounding the Atmosphere Above a Ground Site

One of the fundamental problems of any space-based system is demonstrating consistency with ground-based observations or "ground truth." This is particularly difficult when the atmosphere plays a major role in determining the character of the observed signal. All too often recourse must be made to a climatological model, that is, one based on past experience of what atmospheric conditions are likely to be for a given location, time of year, time of day, etc. Direct observation and characterization of the atmosphere are highly desirable.

Table 3. Characteristics of the UVISI imagers.

Characteristic	Narrow FOV UV imager (IUN)	Wide FOV UV imager (IUW)	Narrow FOV visible imager (IVN)	Wide FOV visible imager (IVW)
Filter bandwidth (nm)				
Open	180–300	115–180	300–900	380–900
Closed	—	—	—	—
Attenuated[a]	180–300	115–180	300–900	380–900
Wideband-1	200–230	117–127	305–315	426–429
Wideband-2	230–260	121–122	350–440	529–631
Wideband-3	260–300	145–180	470–640	380–900
Photocathode	RbTe	CsI	Tri-alkali	Tri-alkali
Window	MgF_2	MgF_2	SiO_2	SiO_2
Clear aperture (cm^2)	130	25	130	25
FOV	1.59° × 1.28°	13.1° × 10.5°	1.59° × 1.28°	13.1° × 10.5°
Resolution on disk (m)	80	800	80	800

[a]IUN and IUW are attenuated by a factor of 1,000 with this filter; IVN and IVW are attenuated by a factor of 10,000.

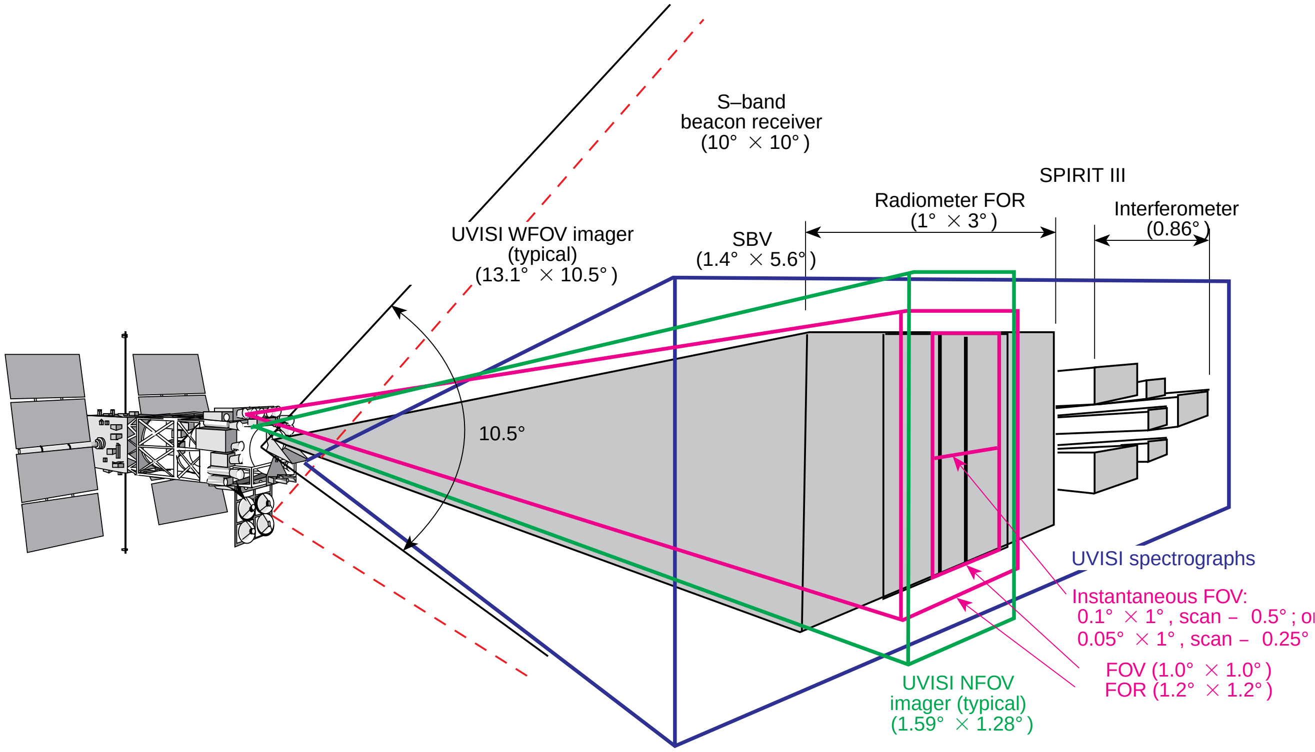

Figure 4. The fields of view (FOVs) of the MSX instruments. The SPIRIT III interferometer FOV is completely outside of the field of regard (FOR) of the SPIRIT III radiometer. The two are placed in context by the UVISI wide field of view (WFOV) imagers, IUW and IVW. The UVISI spectrographic imagers (SPIMs) and the SPIRIT III radiometer have instantaneous FOVs that are perpendicular to each other. Both the UVISI SPIMs and the SPIRIT III radiometer use a scan mirror to achieve the desired FOR. SBV = Space-Based Visible experiment.

MSX can perform a limb observation and then rotate to look down on the ground site. The limb observation allows us to determine the composition of the atmosphere and the amount and structure of clouds above a site. Looking down allows the user to obtain spatial information since the scene is not foreshortened as it is when viewed from anywhere but directly above. This is a unique capability and can be applied to a number of problems. Examples are given in the following sections.

Stellar Occultation

MSX is able to provide unique environmental data through its ability to track a point or object in space. This capability is particularly useful during stellar occultations, which give us one of the most powerful means of sounding the atmosphere. In an occultation the Sun, Moon, or a star is observed as it sets through the Earth-limb. Occultation measurements are self-calibrating, i.e., the results are largely independent of a detailed knowledge of the absolute radiometric response of the instrument since they are scaled to data when the line of sight to the star is completely outside of the atmosphere. In a stellar occultation the spacecraft line of sight is held fixed in space. This does have its limitations, however; refractive effects in the lower atmosphere will cause a star's apparent position to change by about 1°. For many systems this motion would present an insuperable problem. On MSX, however, the UVISI image processor can be used to keep the image of a star within the UVISI FOV.

Multiangle Imaging

MSX has the ability to view a scene from a variety of angles; it is a powerful tool for understanding the structure and composition of the atmosphere and its constituents or the properties of ocean or surface features. The combination of spectrographic imagers and imagers (or "cameras") is particularly powerful since the spectrographic imager provides detailed information while the imagers set the stage for the observation by providing a broader context for the data. Because the undistorted FOV of a ground-based camera is roughly the same as the projected FOV of a UVISI wide-field imager, we can use ground-based all-sky imager data information as a benchmark for interpretation of UVISI atmospheric observations.

Most sensors that image the Earth do so by looking at one fixed angle, in the nadir, to obtain their data. Multiangle viewing is particularly useful for studying the scattering characteristics of aerosols and their optical properties; this is required if we are to understand the particle size distribution and their scattering phase functions. For active volcanoes, forest fires, factories, agricultural burnoffs, rocket plumes, and clouds, MSX can obtain stereophotogrammetry from the imagers to determine plume or cloud elevations. Cloud heights are also a key issue for many systems applications, particularly for theater missile defense. One of the key sources of uncertainty in ocean color results from the inability to uniquely specify an aerosol distribution. Multiangle viewing can significantly reduce ambiguity in the aerosol characterization.

Remote Sensing Applications

Land surface processes are key components of the coupled global biogeochemical cycle. Modeling is one of the ways that we develop and test our understanding of the environment. Models require the specification of inputs, which can include fluxes of energy, mass, and momentum. These inputs are also the predicted outputs of models. Since these fluxes are defined or influenced by local and nonlocal variability in vegetation, landform, cloud cover, etc., they are difficult to define because of the paucity of data. Ground sites can collect very detailed data, but only for very small areas. A more general data set is required to specify the boundary conditions as well as the values within a given model "cell." For instance, simple models of tree canopy radiative transfer and leaf physics have demonstrated that, if the hemispherical albedo is known for a site, one can determine self-consistent photosynthesis, transpiration, evaporation, respiration, and radiative absorption rates, but this information is missing for much of the world's forests.[6,7] Hemispherical albedo measurements are required for ice and snow fields; the cryosphere is affected by natural and anthropogenic contaminants, yet plays a crucial role in determining the short-wavelength radiation flux that is coupled to the atmosphere.[8]

Numerical modeling suffers the fundamental limitations of memory and speed; any global model that can reproduce effects at "small" sizes, say 100 km, must handle millions of data points and preferably perform those calculations at a rate significantly faster than a day of model time per day of computer usage time. If we are to project anthropogenic change into the future, the models must simulate many years or even hundreds of years of processes. Increasing the spatial fidelity of models to a degree sufficient to reflect the natural surface variability is not possible at this time. Commonly, models that study local phenomena are "nested" within the results of coarser models; the large-scale models provide boundary conditions for the finer-scale models. A key problem, then, is to improve the fidelity of these models. That is achieved by providing subgrid-scale parameterizations of surface roughness, composition, etc. MSX can provide unprecedented spectral coverage at relatively high spatial resolution. Figure 5 demonstrates how UVISI compares with other space-based imaging systems.

Atmospheric Remote Sensing

The atmosphere is a dynamic, complex entity. It responds to changes in the amount and type of solar radiation reaching it from above and the variation in the absorption and emission characteristics of the surface below. Differences in the solar heating rate and the rotation of the Earth produce winds that are further changed by surface or orographic features. The atmosphere is divided into the lower (troposphere), middle (stratosphere and mesosphere), and upper (above 80 km and consisting of the thermosphere and ionosphere) atmospheres. Above about 600 km, in the exosphere, collisions between individual atoms or molecules are no longer important or common. The temperature profile throughout the lower and middle atmospheres is controlled by trace constituents that cool and heat the atmosphere. In the stratosphere and mesosphere, solar energy is absorbed primarily by ozone. This energy is rapidly converted to thermal energy through chemical reactions. The thermal energy is balanced by cooling as a result of IR emission from CO_2

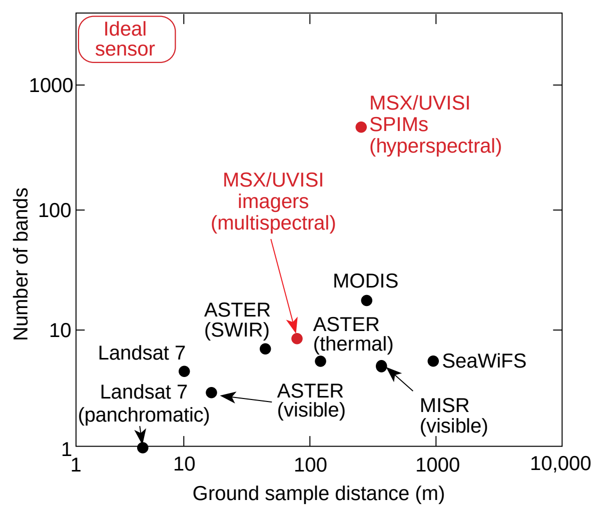

Figure 5. The MSX/UVISI sensor's ground sample distances are compared with those of several civilian sensors. The Moderate Resolution Imaging Spectroradiometer (MODIS), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and the Multi-angle Imaging Spectroradiometer (MISR) are expected to fly in June 1998 on Earth Observing System (EOS) AM-1. The Sea-viewing Wide Imaging Field Sensor (SeaWiFS) is scheduled for a Pegasus XL launch on the SeaSTAR satellite in the summer of 1996. MSX/UVISI's unique capability is a result of the combination of a very large number of spectral bands (>1000) with relatively high spatial resolution. For purposes of mapping the distribution of biogeochemical features, a resolution of 800 m is adequate. No such high-spectral-resolution database of space-based data exists.

(15-μm band), O_3 (9.6-μm band), and H_2O (primarily 8.0-μm band). The upper atmosphere is heated by the absorption of solar ultraviolet radiation of wavelengths shorter than 0.31 μm. In the high thermosphere, conduction redistributes this energy, and the lack of efficient radiators leads to very high temperatures, often as high as 1200 K, that are nearly altitude independent. The thermosphere is strongly influenced by the sunspot, or solar, cycle, which is associated with large changes in the short-wavelength solar output. Satellites orbit in the thermosphere, which expands in response to increased solar radiation; consequently, they experience a variable drag force that is difficult to forecast more than a few days ahead. The ionosphere, which has a tangible effect on communications, also varies as a result of changes in the solar spectrum.

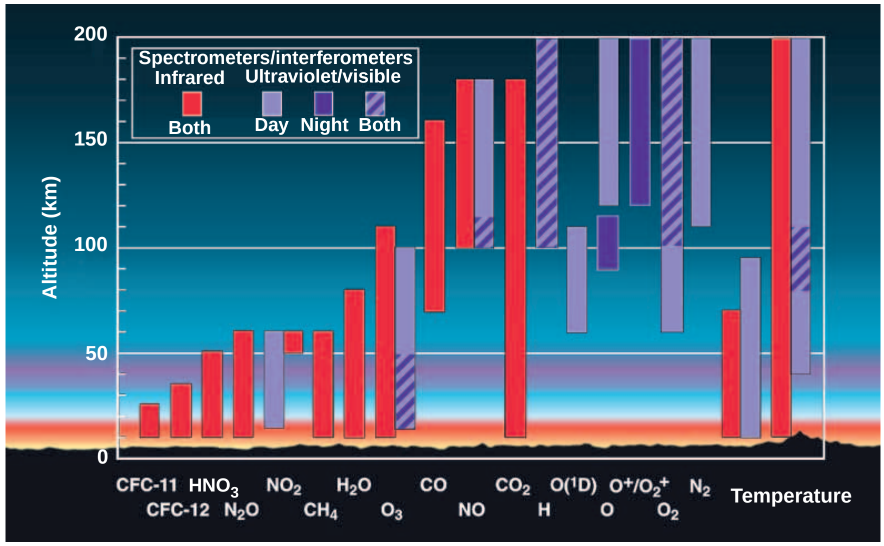

Figure 6. Altitude range over which MSX is expected to provide number density profiles of atmospheric constituents. The infrared observations are predicted on the basis of the performance of the CIRRUS 1A instrument (Robert O'Neil, private communication, 1995). "Both" indicates that, since the infrared radiation field is present during the day and at night, SPIRIT III will see the optical signatures of these species both day and night. In the ultraviolet and visible the emission mechanisms vary; a species may have one signature during the day and another at night.

MSX can sense the spectral signatures of a wide range of species, as shown in Fig. 6. This figure indicates only those species that are observed in emission. UVISI should be able to extend its observations into the troposphere and determine column densities of trace species such as SO_2, OClO, ClO, and BrO under certain conditions.

The Upper Atmosphere

MSX can collect high spatial, spectral, and temporal resolution data in support of the DoD operational environmental monitoring. The Air Force Defense Meteorological Satellite Program (DMSP) collects environmental data relevant to the DoD. The current Block 5 satellites, which began in early 1970, include the Operational Linescan System (OLS), which collects horizon-to-horizon visible and IR imagery, including pictures of the aurora in darkness. The data are now available through NOAA's World Geophysical Data Center and have been used to study the aurora. The next generation of auroral imager will be the Special Sensor Ultraviolet Spectrographic Imager (SSUSI).[9,10] SSUSI has a spatial resolution of a few kilometers but obtains its images in about 165 spectral elements and can image the aurora in full sunlight. MSX will be able to provide ultraviolet images at very high spatial resolution (80 m) and at a high temporal resolution (up to four frames per second). Horizon-to-horizon imagers, such as OLS and SSUSI, typically image a location only once an orbit, but MSX can stare at a particular location or volume of space for the entire 10 min of an overflight. Figure 7 compares a typical OLS image with about 2.7-km resolution to one that would be obtained with the MSX/UVISI narrow-FOV camera with a resolution of about 80 m. These data, in correlation with ground-based radar data, should provide operational users with that important connection between optical imagery and the propagation characteristics of the aurora. MSX will also provide operational users with an opportunity to validate SSUSI data-reduction algorithms before that imager's first flight, which is projected to occur in 1999. This technology transfer will provide a demonstrable benefit to the DMSP.

The upper atmosphere (the mesosphere, thermosphere, and ionosphere) is also the focus of a number of NASA programs, including the first element in NASA's planned Solar-Terrestrial Connections satellite program (Thermosphere–Ionosphere–Mesosphere Energetics and Dynamics, or TIMED), the ongoing Global Geospace Science (GGS) program, the Fast Auroral Snapshot Explorer (FAST), and the National Science Foundation's Coupling Energetics and Dynamics of Atmospheric Regions program. The upper atmosphere is also addressed by instruments carried on the DMSP Block 5D2 and 5D3 spacecraft.

The TIMED Mission will study the least explored region of the Earth's atmosphere. This region, between 80 and 180 km, is poorly characterized because of the difficulty in accessing it. TIMED represents the new "small sat" approach to doing science at NASA and, as such, requires collaborative measurements to fill in

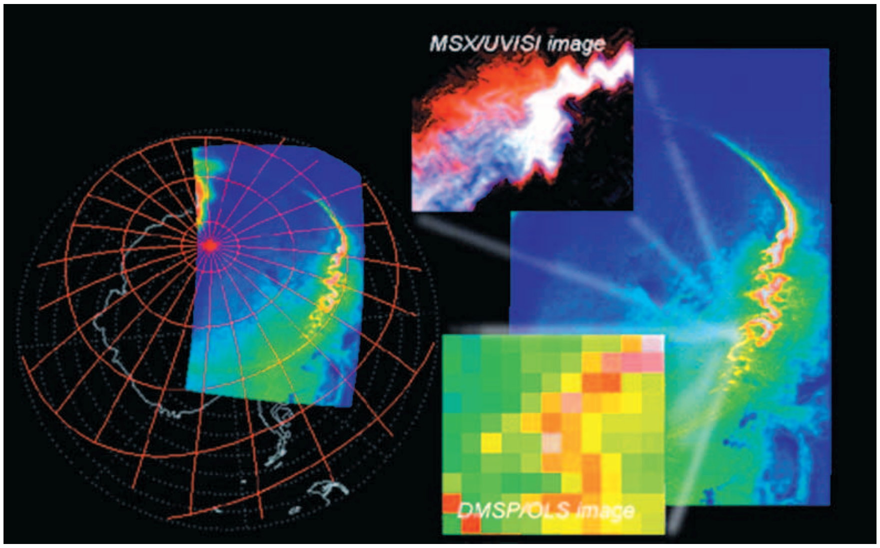

Figure 7. Comparison of Operational Linescan System (OLS) imagery of the southern aurora to a simulation of the same scene as imaged by the UVISI narrow FOV imager. The left-hand portion of the image shows how OLS imagery can be draped over a map of the world as viewed in an orthographic projection. The right-hand portion is an expanded view of part of that image. The OLS image has an effective resolution of about 2.7 km. The UVISI image simulation has a spatial resolution of about 80 m. These small-scale features have never been imaged from space.

gaps in data collection. For instance, it has been suggested that polar mesospheric clouds can be imaged in the far ultraviolet by TIMED.[11] MSX, with its unique combination of imagers and SPIMs, will be able to validate this technique by obtaining visible data, where the technique has been proven, and correlating visible to far ultraviolet observations. MSX can also obtain phase angle variation measurements of the scattering properties of these clouds, which will enable us to determine the size distribution of their particles.

MSX can make an important and unique contribution to studies of the Earth's geospace environment. The Wind spacecraft, launched on 31 October 1994, is the first of two space missions of the GGS initiative, which is the U.S. portion of a worldwide collaboration called the International Solar-Terrestrial Physics program. This program focuses on the response of the Earth's atmosphere to changes in the solar wind. The second GGS satellite, Polar, is scheduled for launch in the winter of 1995 to study the magnetospheric plasma. FAST is designed to study the variation in the electric and magnetic fields, the flow of electrons and protons in the auroral zone, and the physics and electrodynamics of the aurora. It is to be launched on a Pegasus XL. MSX will be able to provide coordinated observations with GGS and FAST. It will also provide a key piece of information that FAST and Wind do not produce: optical images of the aurora. While Polar will obtain ultraviolet and visible images, MSX will be able to tie these observations to those produced at ground sites by "staring" at a ground site during overflights. MSX will provide corroborative information that is at a higher spatial resolution.

The Lower Atmosphere

The lower atmosphere, especially the troposphere, is the part of the atmosphere we are most aware of. We experience the changes in the energy balance of the atmosphere locally as weather, and we rely to a greater extent every year on our ability to predict the weather through a forecast. The temperature at the surface is higher than would be expected by just equating the incident solar flux to the radiated energy. The difference of about 35°C is a result of the so-called greenhouse gases (CO_2, H_2O, N_2O, and CH_4), which trap radiant heat in the atmosphere. The amount of these gases affects the amount of heat trapped in the lower atmosphere. To truly understand the entire global climate system requires an enormous investment, for to do so one must have a profound understanding of the myriad interactions between the Earth's surface, oceans, and atmosphere. NASA's EOS was intended to be just such a comprehensive survey, but recent budgetary pressures have led to a considerable reorganization of that effort. MSX can make a unique contribution toward understanding the state of the atmosphere and the coupling between the atmosphere and the surface by focusing on a few key problems and demonstrating new techniques for the acquisition and interpretation of optical remote sensing data.

Ozone

A major problem, of great societal relevance, is determining the amount and distribution of ozone in the atmosphere and monitoring it for long-term trends. As can be seen in Fig. 2, ozone is the principal absorber of solar ultraviolet radiation with wavelengths shorter than about 0.32 μm. This cutoff coincides nearly exactly with the cutoff in the absorption spectrum of deoxyribonucleic acid (DNA). Without the protection of ozone, life as we know it could not exist on the Earth. Thus, when the "ozone hole" over Antarctica was reported[12] there was some cause for concern. At the time, the observation was quite surprising since most scientists had expected the first anthropogenic ozone loss to occur in the upper stratosphere (30–50 km). If that had been the case, the change in the total column amount would have been small. It turns out that the answer lay in the occurrence of polar stratospheric clouds, which act as chemical factories to destroy nearly all ozone between about 12 and 26 km.[12,13] MSX can, in concert with other observations, form the basis for a detailed investigation of the physics and chemistry of these clouds. Stellar occultations, particularly in austral spring when the ozone depletion begins, can clarify the mechanism for creating that depletion.

Figure 8 shows how the fraction of transmitted starlight varies as a star sets through the atmosphere. The transmission efficiency decreases as a result of the increasing amount of absorption encountered along the path of the line of sight. Ozone (O_3) is the principal absorber, but water vapor and O_2 also show absorption features low in the atmosphere. Figure 8 also shows the positions of the bandpasses of two important space-based sensors: the Total Ozone Mapping Spectrometer (TOMS) and Stratospheric Aerosol and Gas Experiment III (SAGE III). In these experiments the bandpasses are fixed; i.e., no new experiments or techniques can be examined. For instance, the depth of the O_2 absorption feature is a sensitive indicator of the presence of clouds, a source of important uncertainty in the TOMS algorithms. TOMS cannot produce an altitude-dependent profile of ozone; it provides a measure of the total column amount of ozone. UVISI can be used to validate new ideas for operational instruments, including the production of high-spatial-resolution altitude profiles from a nadir viewing geometry. MSX/UVISI has about 1000 spectral elements in this range. SAGE III can make only solar or lunar occultation measurements. Solar occultations are always twilight measurements. MSX/UVISI is sensitive enough that it can see between 10 and 100 suitable occultation targets on each orbit. This allows MSX/UVISI to determine the ozone profile over almost any geographic location. MSX/UVISI's image processor can be used to supply pointing information to the spacecraft. Therefore, the star can be followed into the troposphere, where refraction effects usually end an occultation. The expected error in these retrievals is much less than 10%.

MSX/UVISI can contribute to our understanding of the relationships between human activities and human needs. For example, much of the world's population is at risk from hunger, and this risk is expected to increase with global warming. In much of the developing world, one-third of the daily intake of protein comes from the sea; phytoplankton is the foundation of this food source. Phytoplankton productivity in the southern oceans may be adversely affected by the Antarctic ozone hole, which can lead to increases in harmful UV-B radiation at the sea surface.[14–16] MSX can provide a unique monitoring capability at much higher spatial resolution than current ozone-monitoring systems (i.e., TOMS or solar backscatter UV) and tie that directly to an ocean productivity measurement at higher spectral resolution and better temporal resolution than currently envisioned ocean color monitoring systems (i.e., Sea-viewing Wide Imaging Field Sensor [SeaWiFS], which may fly in 1996).

Global Change Gases

Global change gases are those gases that are either radiatively or chemically active and whose concentrations have been enhanced significantly by human activities. The greenhouse effect, in which globally averaged surface temperature has risen as a result of the trapping of solar radiation by the atmosphere, is associated with increasing concentrations of CO_2 and other radiatively active gases. (A radiatively active gas is one that has a significant impact on the instantaneous altitude-dependent atmospheric heating or cooling rate.) Chlorofluorocarbons can be monitored from the

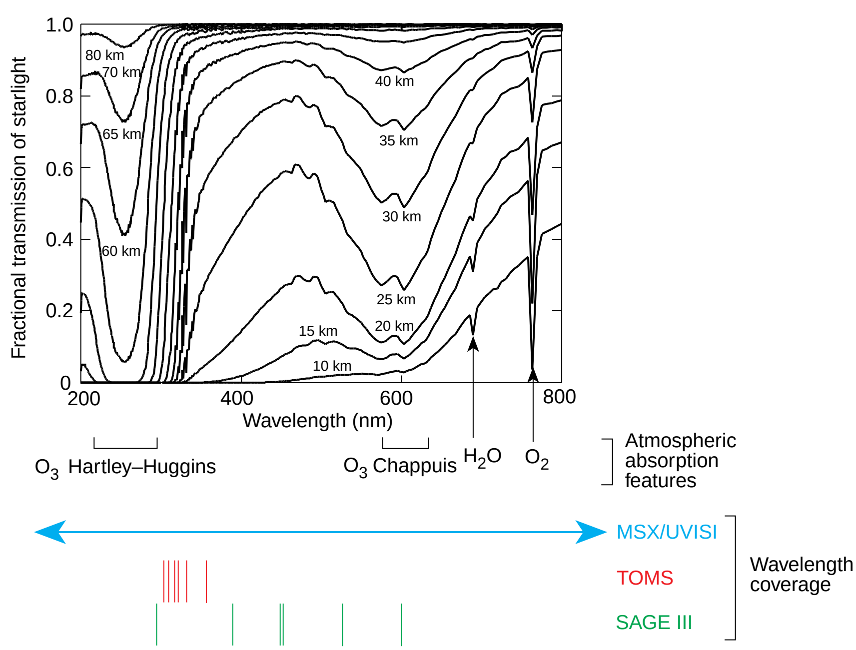

Figure 8. Determination of an ozone profile through a stellar occultation. Determining the altitude distribution of an atmospheric constituent through an occultation measurement is self-calibrating. The sensor observes the unattenuated spectrum of the object (Sun, Moon, or a star) when it is outside of the atmosphere. As the object "sets" through the atmosphere as a result of the spacecraft's orbital motion, atmospheric absorption changes the distribution of the observed radiation. This figure shows how important it is to be able to look over a broad range of wavelengths; some spectral regions become saturated and no more information can be retrieved. The bands used for the Total Ozone Mapping Spectrometer (TOMS) and the Stratospheric Aerosols and Gases Experiment (SAGE III) are indicated.

ground but show a marked altitude dependence caused by their dissociation by ultraviolet photons, which produces free chlorine. Chlorine can then destroy ozone in a catalytic cycle.

MSX can play an important role in monitoring global change gases. The design driver for most space-based applications is to provide the capability for continuous global monitoring of trace species. MSX cannot map their global distribution, but it can provide local data in the interim between major elements in NASA's Mission to Planet Earth program (Upper Atmospheric Research Satellite and the EOS Chem mission; see Fig. 9). MSX will also make measurements during solar minimum; variation in the solar flux has a profound impact on the upper atmosphere.

Biomass Burning

Agricultural burnoffs are a yearly activity throughout much of the developing world. This burning releases soot and important trace species such as CO_2, carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), and hydrocarbons. Burning fossil fuels, such as coal, has also led to a dramatic increase in the amount of trace gases in the atmosphere. Acid rain, a phenomenon we associate with industrialized areas, has been observed in the nonindustrial tropics. There, nitric acid (HNO_3) is produced by the release and chemical interaction of NO, NO_2, and hydrocarbons. Wet deposition (acid rain) is not the only way that nitric acid ends up on the surface. Acid can be deposited as gases or in microscopic particles. Dry deposition may, in fact, be more damaging than acid rain. CO also decreases the ability of the atmosphere to remove contaminants since CO destroys the hydroxyl radical (OH), which reacts with almost every trace gas, including some that would otherwise remain inert.

Photochemical smog is also a problem in the tropics. In large areas of the world it is produced on a vast scale by the burning of savanna grasses. Under the bright tropical sun, photochemistry proceeds very rapidly; ozone levels can exceed normal values by a factor of 5. Tropospheric ozone has a deleterious effect on agricultural productivity, which leads to more biomass burning in response to the need to increase agricultural productivity.

The global extent of biomass burning is monitored by instruments such as the DMSP OLS, but these instruments provide only a crude indication of the extent of the actual burnoff and the local effects since they provide a local nadir view of the phenomenon with no spectroscopic information. The OLS resolution is also much poorer (about 1–2 km) than that required to image individual sites. Biomass burning observations are extended through aircraft campaigns, which have an important advantage: they can make detailed in situ measurements of particle size and composition. MSX can make important ancillary measurements by mapping the spatial distribution of the plume and monitoring its dispersion. MSX observations can also provide phase functions and, consequently, the particle size distribution. These observations will be unique and cost-effective in that the widely distributed plume can be mapped and the distribution of trace constituents and any local

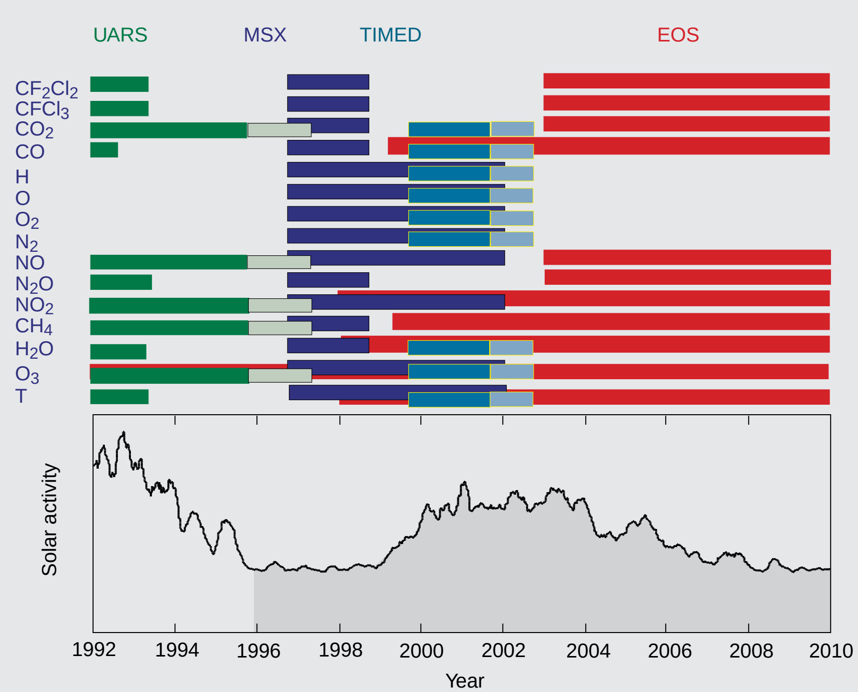

Figure 9. MSX measurements of atmospheric composition compared with NASA mission coverage. The Upper Atmosphere Research Satellite (UARS), which was launched on 13 September 1991 aboard the space shuttle *Discovery*, has been measuring the composition, chemistry, and dynamics of the stratosphere and mesosphere. The first element of the NASA Solar-Terrestrial Connections program, TIMED, will fly in 1999 and will focus on the energetics in the mesosphere and lower thermosphere. The EOS mission shown is EOS Chem, the earliest mission to focus on atmospheric chemistry, which is scheduled for a December 2002 launch. Other Mission to Planet Earth elements and sensors on EOS platforms contribute some additional information. Extended mission operations for UARS and TIMED are indicated by the extensions on their timelines. The lower panel indicates the approximate expected range of solar variability during the next 15 years. This curve is an extrapolation based on the history of solar cycle variability as traced through the number of sunspots. The shaded area is estimated activity level and shows representative intracycle variability.

enhancements determined. SPIRIT III will make an important measurement of several trace gases, for example, CO, NO, O_3, CH_4, and CO_2. The stereoscopic mapping capability inherent in the spacecraft design will allow MSX to map the injection of particulates into the stratosphere.

The Biosphere

Relevance and Issues

Global environmental change is occurring. A key element in monitoring that change is satellite data. Evaluating the quality of the data, determining and eliminating calibration drifts, optimizing data collection modes, and rapidly disseminating the products of the analysis of the data are major problems. MSX can serve as a paradigm for future government or commercial ventures by virtue of its ability to tailor a data product from its hyperspectral imagery, its capacity for point-and-stare data collection, and its demonstration of new approaches to on-orbit calibration.

Another key area of potential contribution is public education. Although the data collected during MSX operations will certainly be of considerable interest to a broad segment of society, the combination of spectrally resolved data and images should enhance the presentation of biosphere data to the public. Increasing emphasis has been placed on demonstrating to the American public a return from their investment. There is now, at NASA, a renewed emphasis on elementary and secondary education. MSX has the flexibility to address focused problems that are tied to a particular location or phenomenon and that can be used to demonstrate to students the utility of space-based observations as well as to establish a larger context for their classroom activities.

Ocean Color

Marine phytoplankton are the basic link in the ocean food web. A key problem in assessing the health of the oceans and the productivity of fisheries is that of determining the concentration of chlorophyll *a* and its breakdown products. This is usually accomplished by using a few spectral bands in the range from 400 to 800 nm. The Coastal Zone Color Scanner mapped ocean productivity using six fairly broad bands.[1] The next-generation ocean color sensors, SeaWiFS and Moderate Resolution Imaging Spectroradiometer, still have fairly large bandpasses.[1] MSX/UVISI has nearly 500 bands covering this spectral range, which will allow MSX/UVISI data to characterize additional biogeochemical signatures in the oceans, for example, the signatures of gelbstoff, diatoms, phycoerythrin, and sediments (see Fig. 10).

MSX/UVISI will be the first of a new generation of space-based sensors capable of making ocean color measurements. These include sensors on the European Space Agency's Polar Orbit Earth-Observation Mission Environmental Satellite and the Japanese National

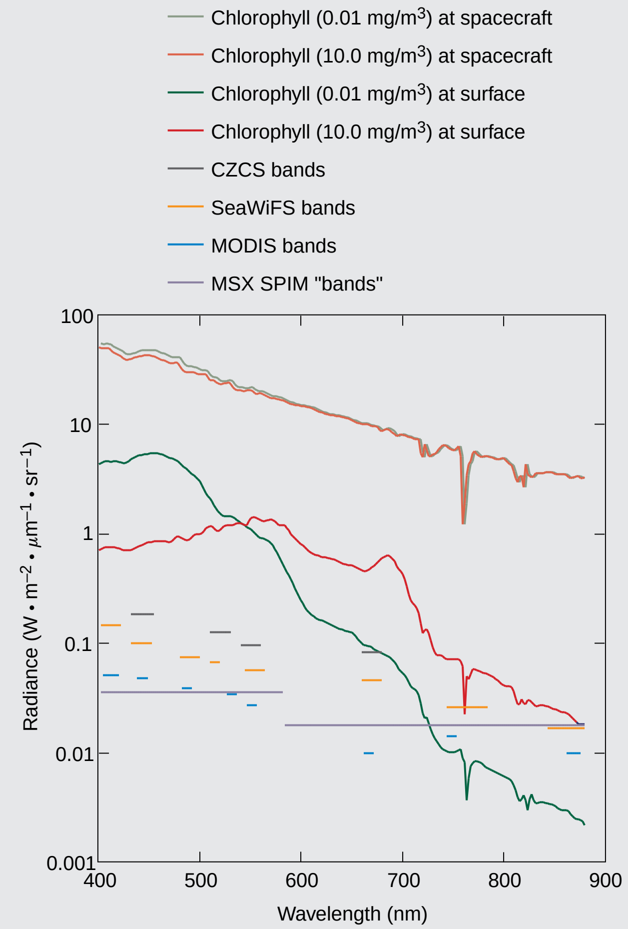

Figure 10. MSX/UVISI utility for ocean color measurements. MSX has unique capabilities for measuring ocean productivity. MSX/UVISI will obtain about 500 spectral band observations between 400 and 900 nm as compared with the 6 bands obtained from the Coastal Zone Color Scanner (CZCS), the 8 bands obtained from SeaWiFS, and the 9 relevant bands from the EOS AM-1 MODIS experiment.[1] Surface observations show a significant dependence of the observed water-leaving radiance on the concentration of chlorophyll (see curves labeled "Chlorophyll . . . at surface"). The problem for space-based observations is that the atmosphere is the dominant source of emission; the ocean has an albedo of only a few percent (illustrated by the two curves labeled "Chlorophyll . . . at spacecraft"). The radiances observed at the spacecraft for the two cases are now nearly indistinguishable. The spectral coverage of CZCS, SeaWiFS, MODIS, and MSX/UVISI instruments is indicated. The anticipated UVISI performance is indicated in terms of the noise equivalent radiance and compared with CZCS, SeaWiFS, and MODIS. Since the UVISI SPIM wavelength coverage is contiguous rather than in a few discrete bands, UVISI coverage is indicated as a solid line. Only UVISI obtains an actual spectrum of the ocean color. UVISI SPIM bands consist of over 500 spectral measurements taken by two separate imaging spectrographs.

Table 4. Utility of MSX to other users.

	Potential users of MSX data					
Area of study	Other areas of DoD[a]	NASA	NOAA	Other agencies[b]	Commercial[c]	International[d]
Distribution of greenhouse gases		x	x	x		x
Structure and composition of the atmosphere	x	x	x	x	x	x
Composition and size distribution of polar mesospheric clouds	x	x				x
Role of polar stratospheric clouds in the formation of the ozone hole		x	x			x
Atmospheric circulation by measuring trace gases and diffusion of plumes	x	x	x			x
Effects of natural and man-made aerosols on the biosphere	x	x			x	x
Ocean color measurements to determine biomass	x	x	x	x	x	x
Characterization of the oceanic aerosol budget	x	x	x			x
Development of new ocean color algorithms for coastal zone measurements	x	x	x	x	x	x
Impact of deforestation on coastal-zone and oceanic biological productivity		x		x	x	x
Earth resources evaluation and improved atmospheric correction algorithms	x	x		x	x	x
Coupling of the biosphere to the atmosphere		x	x			x
Effects of aircraft and their plumes on the atmosphere	x	x	x	x		x
Determination of forest canopy characteristics by multiangle viewing	x	x	x	x	x	x
Impact of acid rain on forest productivity		x		x	x	x
Determination of oil spill boundaries and characteristics	x	x	x	x	x	x
Demonstration of emergency management support from space	x	x	x	x	x	x
Identification of volcanic plumes and possible intrusions into aviation routes	x	x	x	x	x	x
Assessment of the impact on people of changes in the local environment		x		x	x	x
Evaluation of instrument concepts by simulating their operation	x	x	x	x	x	x
Development of new measurement techniques	x	x	x	x	x	x
Demonstration of the efficacy and cost-effectiveness of hyperspectral imaging	x	x	x	x	x	x

[a] DoD activities outside of BMDO including but not limited to DMSP, Defense Mapping Agency, Topographic Engineering Center, and Space Forecast Center.
[b] Other government agencies, organizations, or activities not included in previous categories.
[c] Indicates potential utility of data, derived techniques, or the outcome of technology transfer to the commercial sector.
[d] Potential utility of data to any segment of the international scientific community.

Space Development Agency Advanced Earth Observing Satellite. A key element in all space-based programs is ground truth measurements. The ocean sciences community has a significant monitoring program. For example, the Joint Global Ocean Flux Study coordinates global long-term observations of phytoplankton biomass through field experiments. NOAA programs such as the Marine Optical Buoy provide water-leaving radiances as well as the surface irradiance. These, and other programs, will provide key information to validate MSX DCEs. They will, in turn, benefit from the ability of MSX to remotely sense the altitude profile of the atmosphere above a site, image the site and its surroundings, correct for atmospheric transmission, and produce a water-leaving radiance.

MSX/UVISI can also connect different aspects of the biosphere. For example, as described earlier in this article, MSX can provide unique observations of ozone during Southern Hemisphere spring. The impact of increased solar UV-B radiation on phytoplankton productivity can be evaluated using MSX/UVISI observations of changes in the biological productivity of the southern oceans.

Fisheries evaluation and protection are of growing concern to many governments. This concern has grown from the realization that the fisheries industry is overcapitalized; there are far more modern, efficient fish-catching and -processing ships than there are fish to catch. This overcapitalization leads to depletion of fish stocks, increased waste due to bycatch in which non-targeted species are caught and killed, and the growth of short-term economic concerns that maintain pressure to sustain yields that prevent recovery of fish stock. Conflicts also arise between different types of users: commercial and sport fishermen, ecotourists and fishermen, and long-liners and trawlers.

The productivity of a marine resource is dictated by its biological characteristics and its environment. Many near-shore species have been affected by pollution and a decrease in wetlands and unaltered coastal areas. The shrimp industry, for example, is affected by the reduction in marshes and estuaries, which play a key role in the early part of the shrimp life cycle. Shrimping also produces a very high bycatch, which further affects productivity.

MSX can serve as a prototype for a future space-based system. It combines hyperspectral sensors that can monitor biological productivity and relatively high-spatial-resolution visible imagers (80 m). These imagers can be targeted to a particular region during overflights. MSX/UVISI data can be used to demonstrate the production of tailored signature data (a report of where a specific atmospheric-effects-corrected signature was observed) by combining spectral data into synthetic color bands and passing those data through special algorithms.

Surface Typing

The interaction of the surface of the Earth with the atmosphere is complex. The character of this interaction is tied to the hydrological cycle (the transport of water through the atmosphere and on the surface) and to the vegetation that covers the Earth. Exchanges between the atmosphere and the surface are controlled by soils, overlying vegetation, land management practices (fertilizers produce nitrates that are transported into the stratosphere as N_2O, rice paddies produce methane, and biomass burning produces photochemical smog, for example), precipitation, and the interaction of the surface with solar radiation. Characterizing the forest canopy is a key problem in the specification of the radiative interaction in forested areas. Other notable needs are for studies of the surface albedo over land, the distribution of soils, and vegetation characteristics. Down-looking, multiangle data from MSX/UVISI can be used to produce spectra of a wide range of terrestrial surface features. These observations can be tied to ongoing measurement and interpretation programs such as the Landsat atmospheric correction studies, the U.S. Army Topographic Engineering Center, and the focused programs in NASA, the U.S. Department of Agriculture, and the U.S. Department of the Interior. For example, the Boreal Ecosystem Atmosphere Study is a large-scale international, interdisciplinary experiment in the boreal forests of Canada. Its focus is the exchanges of water, CO_2, energy, and trace gases between the boreal forest and the lower atmosphere. These data will be incorporated into computer models to evaluate their accuracy and to predict the response of the boreal ecosystem to global warming. These kinds of investigations are highly focused and so are well suited to the unique characteristics of MSX.

CONCLUSION

The true value of MSX to users from outside the BMDO will be determined through the demonstrated applicability of the data collected. In this article we have touched upon only a few of the areas to which MSX data can contribute. Some other areas of potential utility are summarized in Table 4. At this writing, only about one-third of the available time for MSX observations is subscribed. New DCEs can be accommodated within the constraints of the program objectives of the BMDO.

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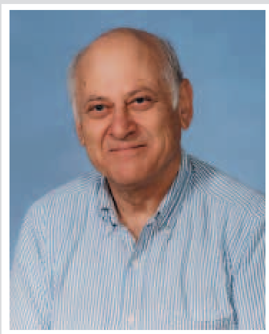
THE AUTHORS

LARRY J. PAXTON received his Ph.D. in astrophysical, planetary, and atmospheric sciences from the University of Colorado in 1983. He has been involved in the modeling and interpretation of ultraviolet and visible data from the Earth, Mars, and Venus. He joined APL in 1990 as a member of the Senior Professional Staff. In 1995, he became a member of the Principal Professional Staff. Dr. Paxton is the Principal Investigator for the Special Sensor Ultraviolet Spectrographic Imager (SSUSI) instrument for DMSP, Associate Principal Investigator for the Global Ultraviolet Imager (GUVI) on the NASA TIMED mission, and UVISI Chief Scientist. He is the Atmospheric Analysis and Evaluation Section Supervisor in the Near-Earth Environmental Remote Sensing Group of APL's Space Department. His research interests focus on the application of optical remote sensing techniques. Dr. Paxton's e-mail address is Larry.Paxton@jhuapl.edu.

CHING-I. MENG received a B.S. in physics from Tunghai University in Taichung, Taiwan, China in 1961 and an M.S. and Ph.D. in geophysics from the University of Alaska in 1965 and 1968, respectively. After serving as an Assistant Professor at the Geophysical Institute at the University of Alaska and an Associate Research Physicist at the Space Sciences Laboratory at the University of California, Berkeley, he joined APL in 1978, where he is Supervisor of the Space Sciences Branch. Dr. Meng is the Principal Investigator or Co-Investigator of more than 10 NASA and DoD spacecraft experiments and is also the Principal Investigator of numerous research grants and has published over 200 articles in magnetospheric physics, ionospheric physics, atmospheric physics, and optical remote sensing from NSF, AFOSR, and AFGL. He serves on many committees at the national level. Dr. Meng's e-mail address is Ching.Meng@jhuapl.edu.

DONALD E. ANDERSON has been active in atmospheric science research for more than 25 years. He received his Ph.D. in aerospace engineering from the University of Colorado in 1977. His early work involved modeling and analysis of emissions from the atomic hydrogen coronae of Mars, Venus, and Earth. He has also been involved in modeling and analysis of atomic and molecular dayglow and nightglow emissions from the thermosphere and ionosphere. His current research focuses on modeling and analysis of the UV-visible radiation field data in the troposphere and stratosphere, with application to photochemical modeling. He is co-principal investigator on the MSX Shortwavelength Terrestrial Backgrounds team and leads the Atmospheric Modeling and Radiative Transfer Section in the Near-Earth Environmental Remote Sensing Group of APL's Space Department. His e-mail address is Donald.Anderson@jhuapl.edu.



GERALD J. ROMICK received his Ph.D. at the University of Alaska in 1964 and subsequently became an Assistant Professor of Geophysics at the Geophysical Institute of the University of Alaska. His research career primarily focused on topics using optical remote sensing techniques, including spectroscopic, photometric, and imaging observations of the aurora, nightglow, and chemical releases. He retired as a full professor in 1982 and consulted in the area of optical aeronomy until 1988 when he became the Program Director for Aeronomy at the National Science Foundation. In 1990, he joined The Johns Hopkins University Applied Physics Laboratory as a Senior Professional Staff member and became the Principal Investigator for Shortwavelength Terrestrial Backgrounds in the MSX program. He became a member of the Principal Professional Staff in 1995. His primary interests are in the use of optical observations of atmospheric emissions to understand the dynamics, energetics, and excitation mechanisms that occur in the atmosphere. His e-mail address is Gerald.Romick@jhuapl.edu.