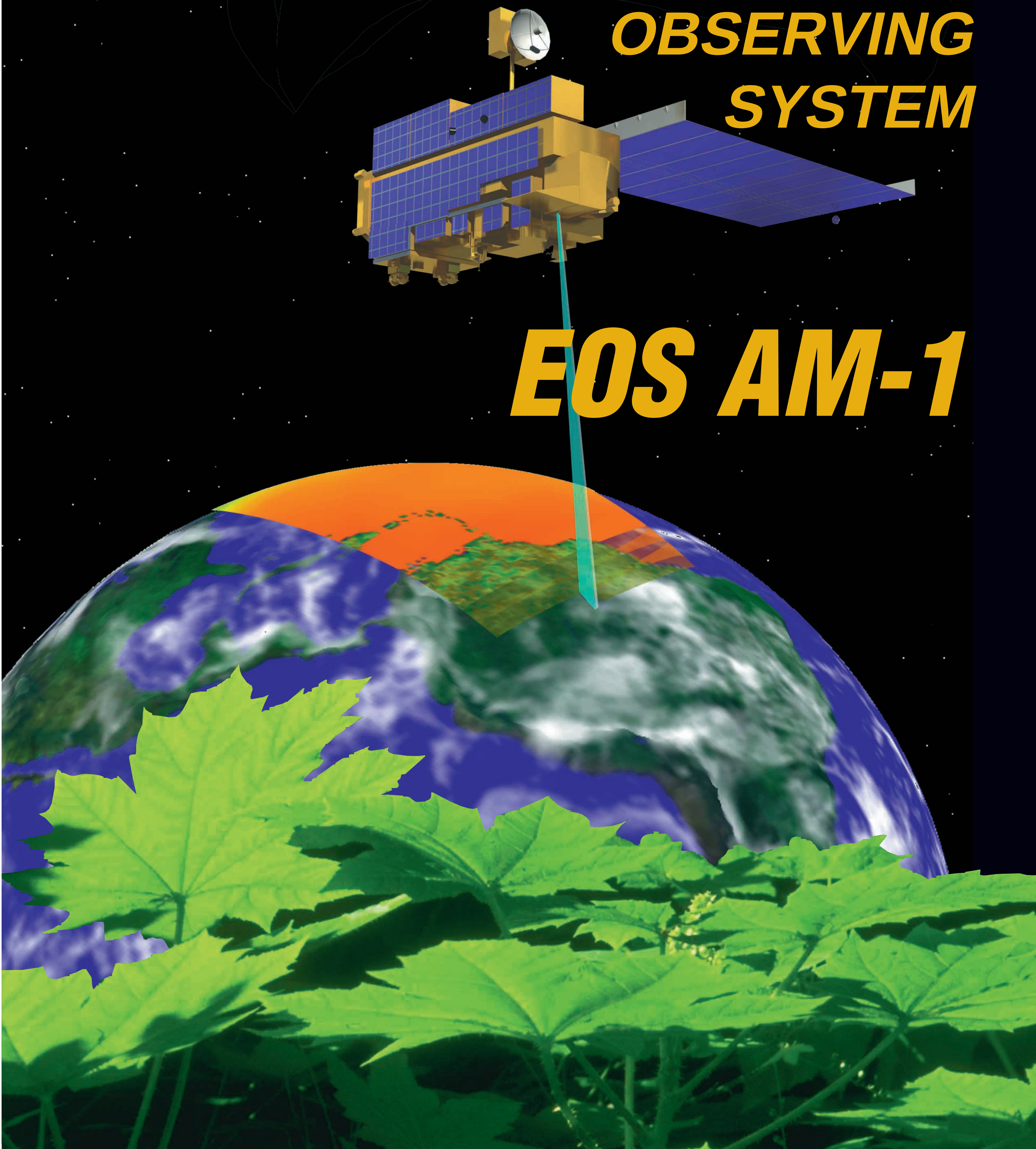
THE FIRST EOS SATELLITE

NASA'S EARTH OBSERVING SYSTEM

EOS AM-1



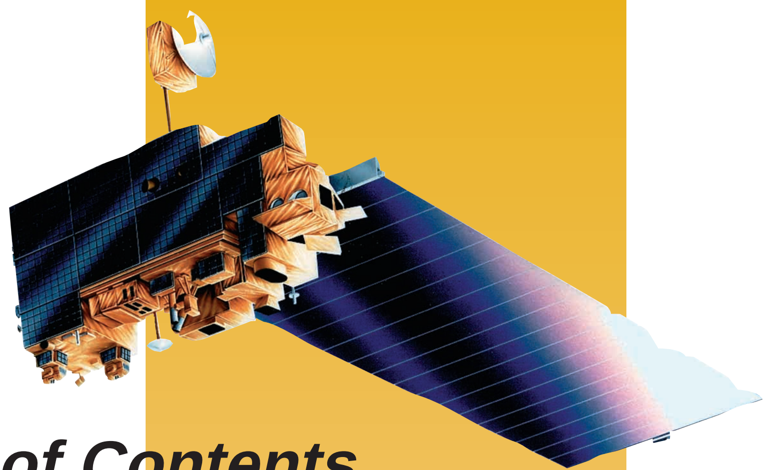


Table of Contents

Spacecraft art on front cover by Barbara Summey, Scientific Visualization Studio, NASA Goddard Space Flight Center

"Is the mean temperature of the ground in any way influenced by the presence of the heat-absorbing gases in the atmosphere?"

Svante Arrhenius, Philosophical Magazine and J. of Science, 1896

Background and Science Objectives

The EOS AM-1 satellite is the flagship of NASA's Earth Science Enterprise. It will be the first EOS platform and will provide global data on the state of the atmosphere, land, and oceans, as well as their interactions with solar radiation and with one another.

One century ago, Swedish scientist Svante Arrhenius asked the important question "Is the mean temperature of the ground in any way influenced by the presence of the heat-absorbing gases in the atmosphere?" He went on to become the first person to investigate the effect that doubling atmospheric carbon dioxide would have on global climate.[1] The question was debated throughout the early part of the twentieth century and is still a main concern of Earth scientists today. Other equally important questions have arisen concerning the "health" of our planet that also require further scientific investigation and are discussed in this brochure.

Arrhenius' first climate model was based on Samuel Langley's infrared measurements of the temperature of the moon, from which Arrhenius derived the infrared transmissions of carbon dioxide and water vapor. Since then, climate models were developed to include other trace gases and many processes in Earth's atmosphere, lands, and oceans. But scientists now recognize that climate models using trace gas forcing alone cannot adequately explain temperature trends. To predict future climates we need to introduce into the models Earth parameters that are highly varying in space and time, such as clouds, aerosols, water vapor, land use, ocean productivity, and the interactions between these parameters. Today, the prime tools for measuring these parameters are highly precise satellite sensors. Consequently, the World Climate Research Program, the International Geosphere-Biosphere Program, and the U.S. Global Change Research Program formed the framework for NASA's Earth Science Enterprise. The design and construction of the Earth Observing System (EOS) and its associated scientific efforts are the Enterprise's main foci.

In 1998, NASA will launch the first EOS satellite—EOS AM-1—with five state-of-the-art instruments to observe and measure the state of the Earth system, and to monitor global environmental changes over time. Each instrument is uniquely designed to provide data with unprecedented precision, quality, and scope. These data will be processed into continuous long-term measures of the state of the land, ocean, and atmosphere. EOS AM-1's measurements, together with those of other satellite systems launched by NASA and other international space agencies, begin a new self-consistent data set that is expected to revolutionize climate change models. Follow-up missions are planned to extend this data set continously for at least the next 18 years.

What is the reason for this large investment in understanding our planet from space and what do we expect to gain?

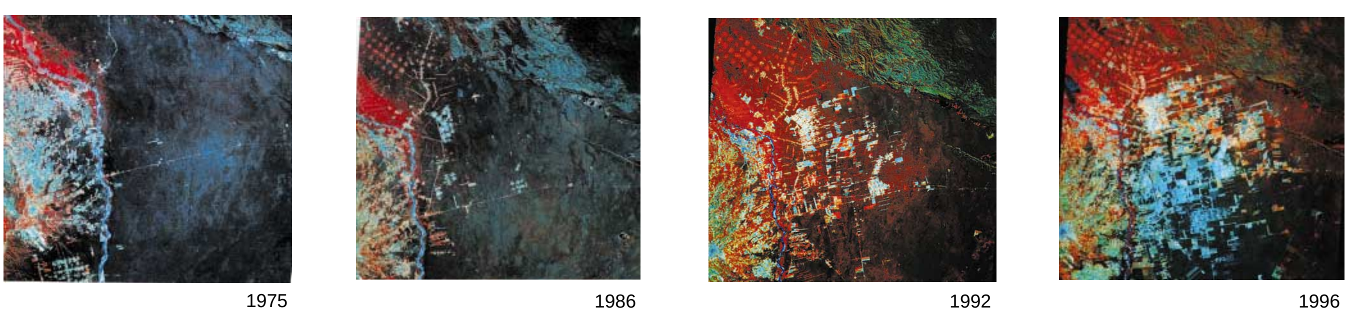
In order to understand the Earth as a whole, integrated system, we need long-term measurements of its various environments at specific temporal, spectral, and spatial intervals. Current satellites play an increasingly important role in global environmental monitoring, but often were not designed for the tasks to which they are applied. Yet, the instruments on EOS AM-1 are uniquely designed for "comprehensive" Earth observations and scientific analysis. "Comprehensive" refers to the wide spectral coverage provided by the satellite's instruments, its wide spatial coverage as it collects image data daily over the entire Earth's surface, and its long temporal coverage as EOS AM-1 begins a series of Earth observing satellites designed to measure global climate change over a minimum of 18 years. "Comprehensive" also refers to the multi-disciplinary applications of its science data products; to the large number of researchers worldwide who will utilize EOS AM-1's freely distributed global data; and to the existing global data sets—such as those of AVHRR, CZCS, and Thematic Mapper—that will be extended by EOS AM-1. With the 1998 launch of EOS AM-1, we enter a new era in global environmental change detection.

Why should we look for global change?

Changes in the land-ocean-atmosphere-biosphere system are caused by both natural and human influences. Solar output fluctuations, volcanic emissions, and El Niño are examples of natural processes that cause interannual variations in global climate. Dramatic climate changes have been documented during historical times. In the 15th century, the climate began to cool suddenly by about 1.5°C during the 'little ice age,' causing disruption of agricultural and social systems. New evidence continues to accumulate showing large and abrupt (decadal) climate changes in the past.

Human activity has had an increasing impact on the global environment. Since Arrhenius' 1896 prediction, the Earth's population has almost quadrupled and the per capita use of natural resources (energy, water, and land) has also grown. Increased population, deforestation and forest fires, and energy and land use in the last century have resulted in transformation of one-third to one-half of the land surface; increases in concentrations of greenhouse gases (carbon dioxide, for instance, has risen by 30 percent); more aerosol particles in the atmosphere; and use of more than half of all accessible surface fresh water.[2] These changes are associated with increases in global surface temperature, as well as changes in spatial and diurnal distribution of temperature.

The Intergovernmental Panel on Climate Change recently concluded that "...the balance of evidence suggests that there is a discernible human influence on global climate." Now we need to gather data—on a global scale over a long period of time—to quantify the causes and predict the magnitude of the effects of

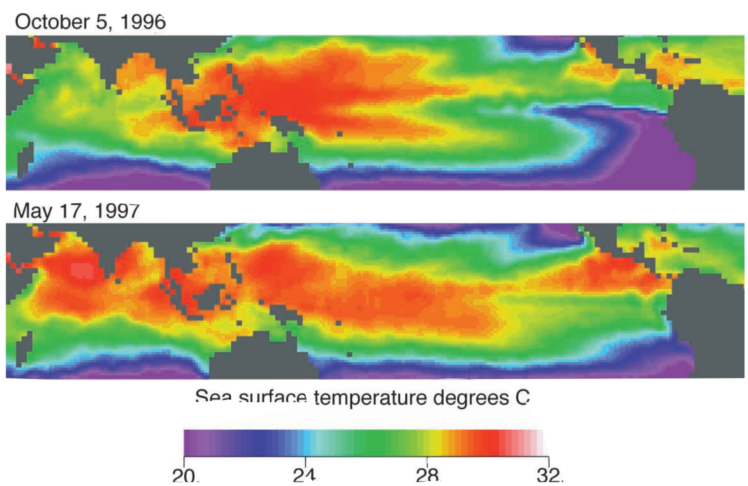


This series of visible and infrared image data was taken over Bolivia by Landsat satellites 1, 4, and 5. The series shows the rapid conversion of tropical dry forest into large-scale agriculture (Compton Tucker, NASA Goddard Space Flight Center).

natural and human impacts on climate and the environment. In short, the ability to differentiate between natural- and human-induced climate and environmental change will empower us to better act as stewards of our home planet.

Signals of global change and their causes that are under investigation

Scientists have proven that there has been a steady increase in the amount of carbon dioxide in the atmosphere since the beginning of the industrial revolution. There is mounting evidence that this and other atmospheric greenhouse gas increases are causing the average annual global temperature to rise. If so, climate warming may result in melting of continental ice and snow, as well as rising sea levels and increasing weather instabilities. Over the last 20 years, satellite observations have shown that the extent of snow cover in the Northern Hemisphere has decreased in conjunction with increases in surface air temperature.[3] Satellites have also revealed recent deterioration of major ice sheets and an increase in atmospheric water vapor, both possible indicators of current global climate warming.[4] Increases in air temperature are expected to cause changes in agricultural practices. Current models suggest that productivity is likely to increase where low temperatures are limiting plant growth and to decrease where the climate is currently warm and dry.[5]



These NOAA AVHRR data products show normal sea surface temperatures (Oct. 1996) and, those near the peak (May 1997) of the 1997 El Niño, one of the most severe in this century. Under normal conditions the western tropical Pacific Ocean is a large "warm pool" of water, while relatively cool waters occur off the South American coast. During El Niño, warm waters spread across the entire tropical Pacific (Jet Propulsion Laboratory).

What are the benefits of better understanding our planet?

A global monitoring system, coupled with other measurements and data analysis, will give us the tools to measure the environmental impacts of population expansion, overgrazing, and biomass burning in the tropics. To what degree do droughts, overgrazing, and deforestation affect generation of dust, change in the land radiative and hydrological properties, and forcing of climate? Do we know what the effects of global climate change have been so far and can we predict them in the future? How does human use of resources like energy, land, and water, contribute to climate change? Today's climate models are developed to a stage where, coupled with global observations—starting with EOS AM-1—they are expected to be useful for predicting the impact of natural and anthropogenic forcing of climate.

Besides detecting longer term climate and land use change, there are more immediate economic and societal advantages to be gained by the implementation of an extensive Earth monitoring system. Better information on the state of the surface and the atmosphere will lead to more accurate extended weather forecasts affecting health, safety, commerce, recreation, agriculture, and natural hazard prediction. For instance, El Niño is known to disrupt the patterns of life of plants and animals in the Pacific Ocean, and is second only to the changing seasons in its impact on world climate. The term El Niño (Spanish for "the Christ Child") was coined by South American fishermen in reference to the warm ocean currents that periodically appear around Christmas-time and can last for months. Nine El Niños have occurred during the past 40 years—with each came warmer ocean temperatures, reduced oceanic productivity, and heavy rainfall in many areas of the Earth.

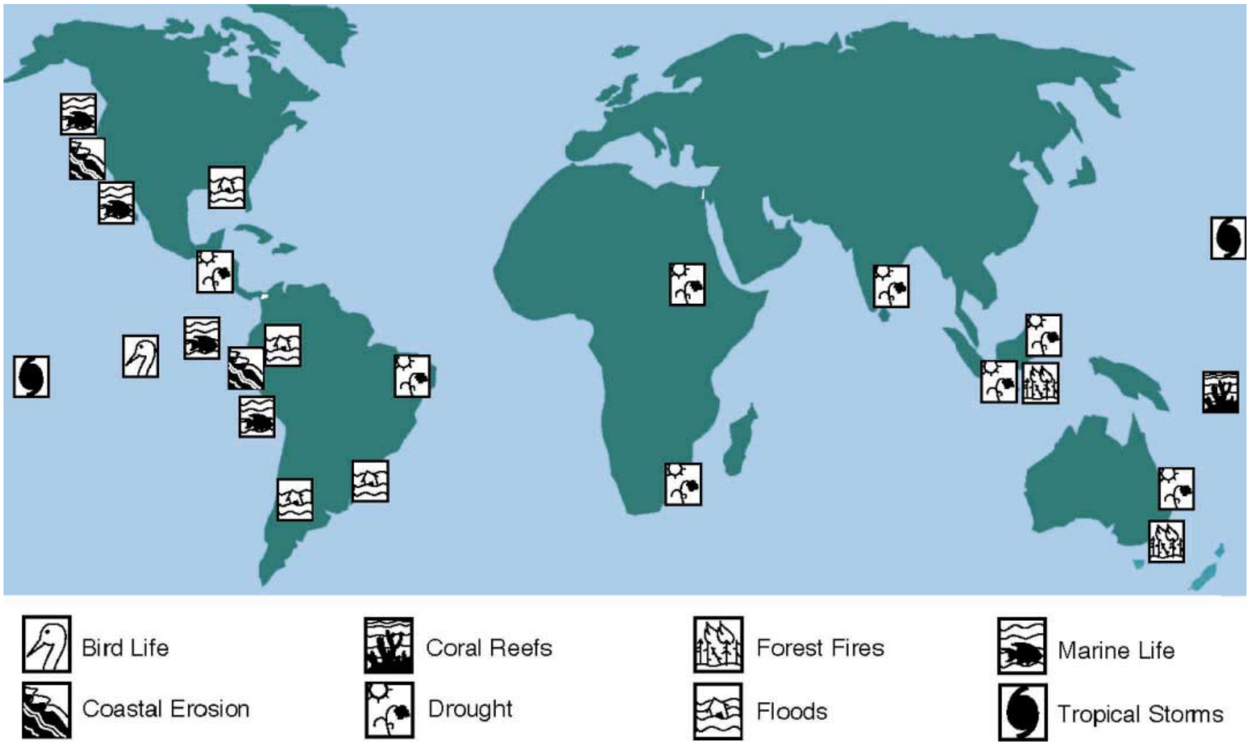
Scientists have shown that El Niño causes droughts in Africa, Australia, and Southeast Asia, while reducing the productivity in the Pacific Ocean and thus impacting the fisheries it supports.[6] These dry conditions in Africa, coupled with extensive increases in local land use, generate a large amount of dust that is transported thousands of miles westward over the Atlantic Ocean by prevailing winds. In the atmosphere, dust alters the radiation budget of the Earth and, as it settles out, fertilizes the biota in the Atlantic Ocean, the Atlantic islands, and even the Amazon rain forest.

El Niño has been linked to '93 and '95 flooding in the midwestern United States.[7, 8] Crop yields have been found to be correlated with El Niño events. The economic gains due to improved El Niño forecasts in the southeastern United States alone are estimated to be more than $100 million a year. The ability to forecast El Niño events is another example of the benefits that are expected from EOS.

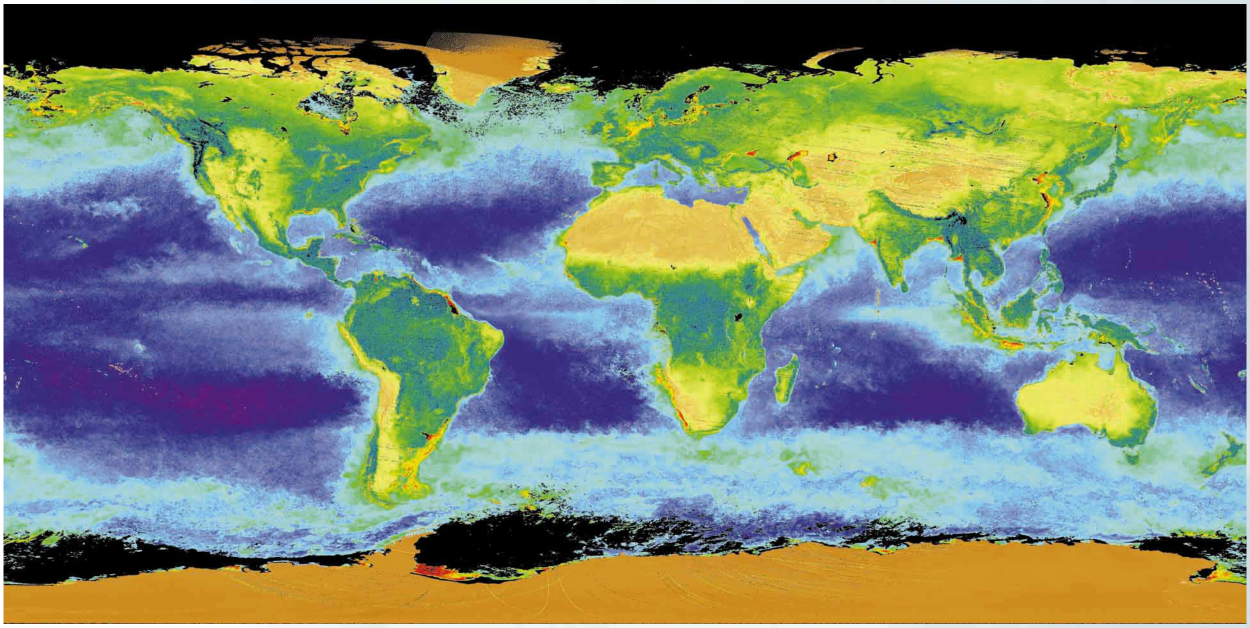
Alarm systems using satellite observations to monitor fire, famine, floods, and volcanoes are currently under development. For example, NASA scientists are processing data from meteorological satellites in near real time to provide the Famine Early Warning System (FEWS) with measurements of the condition of vegetation in Africa. Efforts like FEWS to mitigate the effects of disaster events will be more effective as more accurate and timely observations become available.

The Mt. Pinatubo eruption in 1991 gave scientists an opportunity to predict the expected global temperature impact and, subsequently, validate their predictions with real data. They predicted and confirmed that for the 2 years following the eruption the resulting stratospheric sulfate cloud intercepted and reflected back into space a significant part of the incoming solar radiation. Mt. Pinatubo caused, nearly as predicted, a 0.5°C reduction in the surface and tropospheric temperatures.[9]

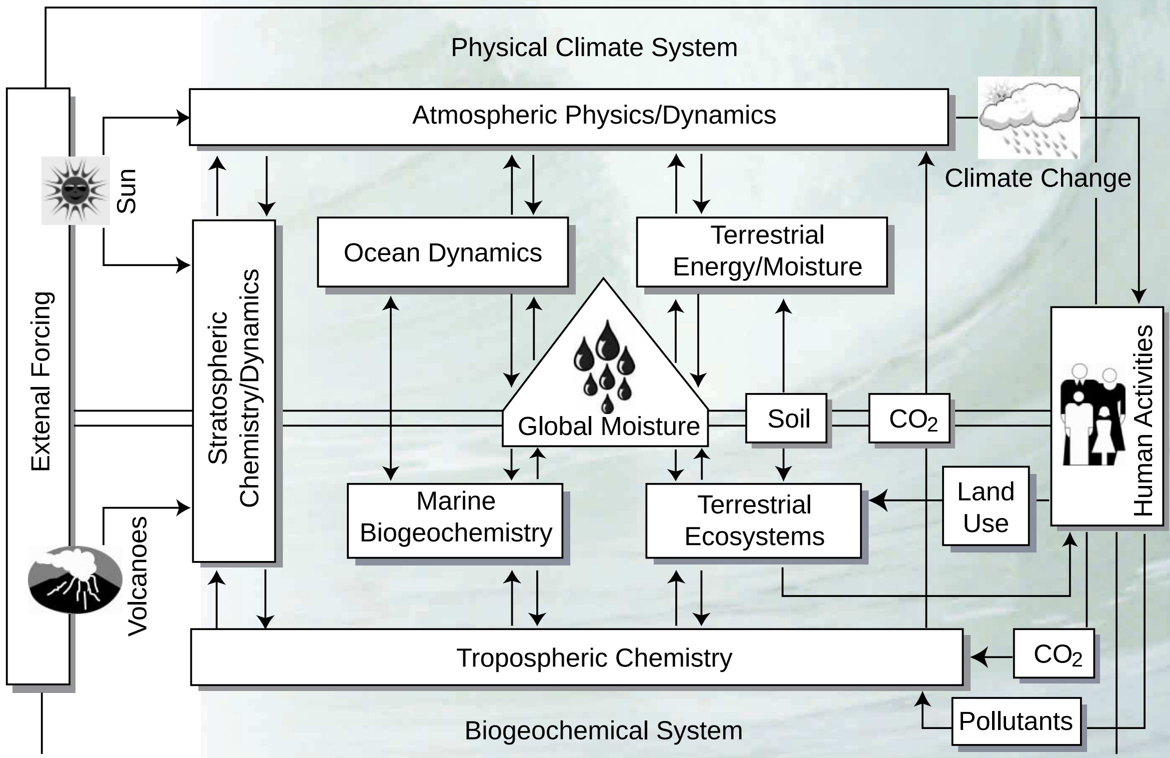
The EOS AM-1 mission will be complemented by Landsat-7 in 1998, Meteor-3M/SAGE III in 1999, and Jason-1 and EOS PM-1 in 2000. EOS CHEM-1, ICESat-1, and missions that will continue the AM and PM main data sequence are currently under development, or in the planning stage for launch in the next millennium. These missions will provide repetitive and additive measurements to EOS AM-1.



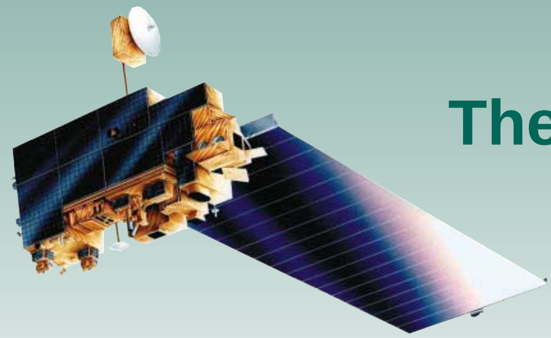
El Niño events cause fluctuations in temperature and rainfall patterns in the Pacific basin and beyond. These periodic variations that occur as a result of the interaction between the ocean and the atmosphere in the tropical Pacific region can affect ecosystems and human lives in far-flung regions of the globe. This ocean-atmosphere phenomenon, known as the El Niño/Southern Oscillation (ENSO), affects climate-sensitive human activities such as agriculture and fisheries. The symbols on this map indicate the known impacts of the 1982-83 El Niño (NOAA Office of Global Programs).



Sea-viewing Wide Field-of-view Sensor (SeaWiFS) image showing the distribution of plant life on Earth, i.e., the Global Biosphere. On land, vegetated areas are shown as dark green and areas of little or no vegetation are brown. Ocean areas rich in phytoplankton are shown as red, yellow, and green, and areas of low concentration are blue and purple (SeaWiFS Project, Goddard Space Flight Center)

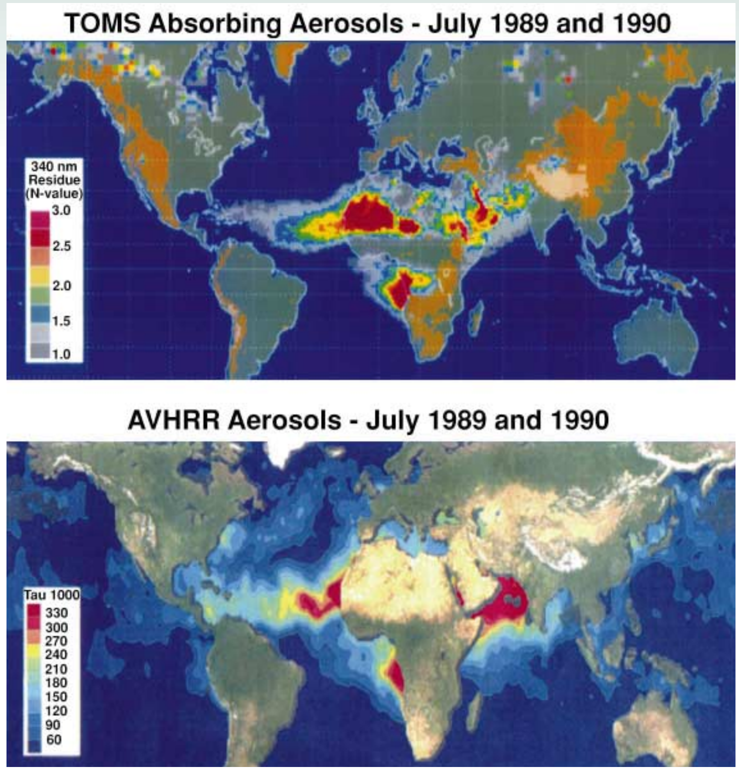


Schematic diagram of the Earth system and its interactions, encompassing the physical climate system, biogeochemical cycles, external forcing, and the effects of human activities [adapted from Earth System Science: Overview, NASA]. Projecting the future climate requires understanding and quantitatively predicting how the components and interactions will change as a result of natural and human activities.



The EOS AM-1 Mission

The launch of EOS AM-1 marks the beginning of humankind's comprehensive monitoring of solar radiation, the atmosphere, the oceans, and the Earth's continents from a single space-based platform. Its mission objectives stem from NASA's Earth Science research strategies and the EOS AM-1 instruments' capabilities. The science priorities of EOS are to provide global observations and scientific understanding of:



Global maps of the aerosol loading derived from TOMS data (top) over land and ocean, and from AVHRR data over the oceans (bottom). The regions of high aerosol concentrations are indicated by red colors. Note the dust aerosol advected westward from Africa, and the heavy dust in the Arabian Peninsula (Jay Herman, Goddard Space Flight Center and Joe Prospero, U. of Miami).

- land cover change and global productivity—including trends and patterns of change in regional land cover, biodiversity, and global primary productivity;
- seasonal-to-interannual climate predictions that improve forecasts of the timing and geographical extent of transient climate anomalies;
- natural hazards—including disaster characterization and risk reduction from wildfires, volcanoes, floods, and droughts;
- long-term climate variability, to help scientists identify the mechanisms and factors that determine long-term climate variation and trends, including human impacts; and
- atmospheric ozone, to help scientists detect changes, causes, and consequences of changes in atmospheric ozone.

Specific objectives of EOS AM-1 and their implementation include the following:

1. Provide the first measurements of the global/seasonal distribution of key Earth and atmosphere parameters, which include global bio-productivity (land and oceans); land use; land cover, snow and ice; global surface temperature—day and night; clouds (macrophysics, microphysics, and radiative effects); radiative energy fluxes; aerosol properties and water vapor, fire occurrence, and trace gases.

   Begin to assimilate data from EOS AM-1 and Landsat-7 into regional process studies and models. Begin to detect annual changes in land use and deforestation.

   Generate a new set of state distributions of geophysical parameters in combination with Jason-1 and EOS PM-1 data.

2. Improve our ability to detect human impacts on climate, identify "fingerprints" of human activity on climate, and predict climate change by using the updated global distributions of land use change, aerosols, water vapor, clouds and radiation, trace gases, and oceanic productivity in global climate models.

   Later, these comparisons will be repeated together with Landsat-7, SAGE-III, Jason-1, and EOS PM-1 data.

3. Provide observations that will improve forecasts of the timing and geographical extent of transient climatic anomalies. Investigate the correlation between the regional and annual variations of clouds, aerosols, water vapor, biota in land and oceans, fires and trace gases, the radiation field, and major climatic events such as El Niño, volcanic activity, etc.

4. Improve seasonal and interannual predictions using EOS AM-1 (and later Jason-1 and EOS PM-1) data.

5. Develop technologies for disaster prediction, characterization, and risk reduction from wildfires, volcanoes, floods, and droughts.

6. Start long-term monitoring of the change in global climate and environmental change.

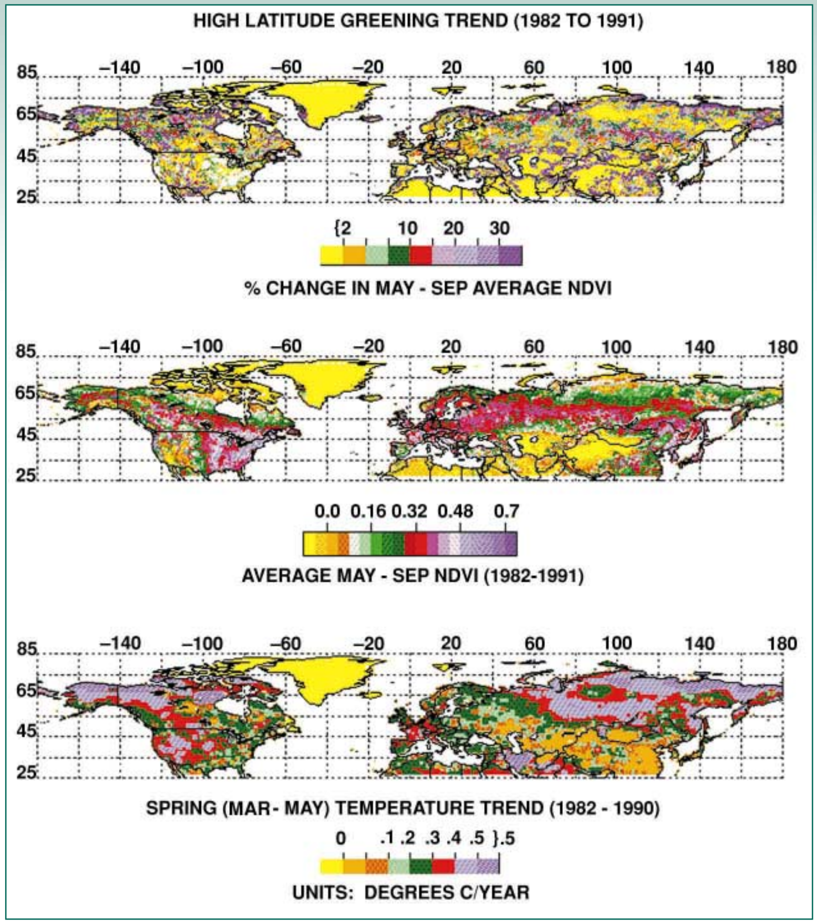
EOS identified high-priority measurements needed for a better understanding of each of the Earth system components—the atmosphere, the land, the oceans, the cryosphere, and the solar driving force. To quantify changes in the Earth system, EOS will provide systematic, continuous observations from low Earth orbit for the bulk of these measurements for a minimum of 18 years. The following is a list of these key measurements; those that will be provided specifically by EOS AM-1 instruments are in bold text.

Discipline	Measurement	EOS-AM Instruments
ATMOSPHERE	**Cloud Properties**	MODIS, MISR, ASTER
	Radiative Energy Fluxes	CERES, MODIS, MISR
	Precipitation	
	Tropospheric Chemistry	MOPITT
	Stratospheric Chemistry	
	Aerosol Properties	MISR, MODIS
	Atmospheric Temperature	MODIS
	Atmospheric Humidity	MODIS
	Lightning	
LAND	**Land Cover and Land Use Change**	MODIS, MISR, ASTER
	Vegetation Dynamics	MODIS, MISR, ASTER
	Surface Temperature	MODIS, ASTER
	Fire Occurrence	MODIS, ASTER
	Volcanic Effects	MODIS, MISR, ASTER
	Surface Wetness	
OCEAN	**Surface Temperature**	MODIS
	Phytoplankton & Dissolved Organic Matter	MODIS, MISR
	Surface Wind Fields	
	Ocean Surface Topography	
CRYOSPHERE	**Land Ice Change**	ASTER
	Sea Ice	MODIS, ASTER
	Snow Cover	MODIS, ASTER
SOLAR RADIATION	Total Solar Irradiance	
	Ultraviolet Spectral Irradiance	

EOS Interdisciplinary Science Investigations

To ensure that the scientific potential of EOS is fully exploited, NASA is sponsoring Interdisciplinary Science (IDS) investigations under the EOS program. More than 70 teams of scientists from various institutions and disciplines are developing technologies and models in anticipation of the launch of EOS AM-1. Each team is composed of specialists in different disciplines ranging across the atmospheric, biospheric, and marine sciences. Indeed, important advances in the field of Earth science have already been achieved by IDS investigators so that when EOS AM-1 launches, many of the IDS Teams will already be prepared to assimilate their first products into models.

The following sections discuss just a few examples of ongoing research by IDS investigators and team members contributing to EOS science.



Geographic distribution of the change from 1982 to 1991 in normalized difference vegetation index (NDVI) of land areas north of 27.75° N, expressed as the average over the northern active growing season of May through September. The top panel shows NDVI increase in percentage over 10 years, determined by linear regression of year-to-year northern growing season averaged NDVI. The middle panel shows climatological NDVI of the active growing season. The bottom panel shows change in spring temperature (March through May) over a 9-year period during the 1980s (1982 to 1990) determined from the average daily thermometer observations. It can be seen that spring-time warming (bottom panel) over vegetated areas (middle panel) has caused increased plant growth in the northern high latitudes (top panel) during the 1980s (Myneni et al., 1997).[10]

Detection of global change and its causes

Vegetation

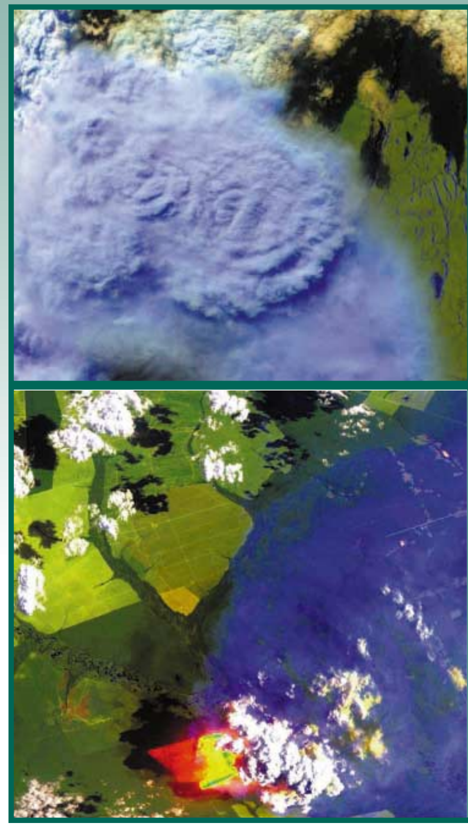
We are beginning to realize the scientific benefits of long-term Earth observations from space. After more than a decade of experience using AVHRR data, scientists are now able to measure year-to-year variations in important properties of the Earth's surface, such as vegetation, snow cover, and sea surface temperature.

MODIS and MISR Science Team member Ranga Myneni, together with EOS IDS investigators and other collaborators, detected an increase in surface greenness (NDVI) in the northern hemisphere during the 1980s using specially processed AVHRR data. An increase in the duration of the growing season was also detected. This increase is correlated with a decrease in satellite-measured snow cover, surface-measured increases in air temperature, and the seasonal amplitude in the atmospheric carbon dioxide concentration.

In conducting this work, Myneni has had to overcome problems associated with detection of small year-to-year changes, using measurements of limited accuracy. Uncertainty in instrument calibration, interference from atmospheric and surface conditions, and coarse spatial and spectral resolution are some of the problems that have had to be dealt with when using AVHRR data for change detection. These issues are addressed in the design of the EOS AM-1 (MODIS, MISR) platform, making change detection more accurate than in the past.

Clouds

Low clouds over the ocean affect the energy balance of the Earth because they strongly reflect solar radiation, but are warm enough to have only a small effect on the amount of emitted thermal radiation. Low clouds are abundant over the oceans, especially in high latitudes and over the eastern margins of the oceans where low sea surface temperatures (SST) and atmospheric subsidence promote their formation and persistence. The amount and optical properties of low stratiform clouds are determined by atmospheric and oceanic conditions, as well as by the abundance of cloud condensation nuclei such as those arising from the burning of fossil fuels and biomass. These sensitivities and the strong effect on the radiation balance give low clouds the potential to play a major role in climate change.



Severe thunderstorm, composed of ice particles (blue) over the Brooks Range, Alaska, June 7, 1995 (top). Tropical biomass burning and smoke plume, Central Brazil, near the Xingu River, August 23, 1995 (bottom). These images were created from multispectral MAS data with 50-meter nadir pixel resolution. Each image represents a composite of three different MAS spectral bands, each assigned to a different red/green/blue (RGB) color (Paul Hubanks, RDC/Goddard Space Flight Center).

Dennis Hartmann's IDS Team is studying long-term trends in low clouds and their relation to SST and other variables to estimate how low-cloud changes have been related to natural changes in the climate system. The figure below shows the correlation between low-cloud abundance and SST over the North Pacific and North Atlantic oceans during the three decades from 1952 to 1981. During this period, rather significant downward trends in SST over the mid-latitude oceans have been accompanied by significant upward trends in the abundance of low clouds. More recent data from the 1980s, however, suggest that these trends have reversed—oceans are warming while low-cloud amounts are decreasing.

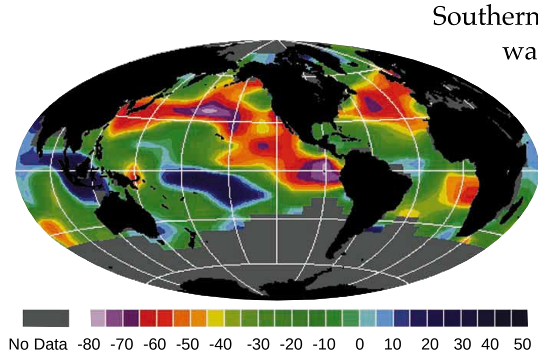
The CERES, MISR, MODIS, and ASTER Instrument teams, as well as other EOS IDS teams, are preparing for the new era of multi-spectral, multi-angle, high-resolution cloud measurements beginning with EOS AM-1 and extending through the next decade with the launch of other EOS satellites. With these new measurements, scientists expect to distinguish between natural variability and multi-year trends in global climate, as well as to identify the underlying causes of these dynamics.

Aerosols

Aerosols—liquid or solid particles suspended in the atmosphere—can affect climate by intercepting or reflecting incoming solar radiation, and by affecting cloud microphysics, cloud brightness, and precipitation. Atmospheric aerosols are produced by a number of natural and anthropogenic processes, such as volcanism, fossil fuel burning, fires, and soil erosion.

Using models of dust generation, an EOS Interdisciplinary Investigation (Ina Tegen, Principal Investigator) calculated emissions and transport of mineral dust in the atmosphere arising from regions with soils disturbed both by natural processes and by human activities, such as over-grazing, deforestation, and cultivation. Compar-ing the models with satellite data, the team found that about half of the mineral aerosols present globally in the atmosphere arise as a result of human activities.

The effect of human-made aerosols on the planetary albedo can delay or compensate for carbon dioxide-induced greenhouse warming. In fact, it is suspected of slowing the increase in the global temperature, decreasing the diurnal temperature range, decreasing warming in the Northern Hemisphere relative to the Southern Hemisphere, and decreasing warming of continents relative to oceans. But there are large uncertainties in the aerosol loading



This graphic shows the coefficient of correlation between anomalies of stratus plus-stratocumulus cloud amount and sea surface temperature during the summer season (June-August) over the period from 1952 to 1981 (Dennis Hartmann, U. of Washington).

and properties, as well as their spatial and vertical distribution and variability with time. Consequently, the uncertainties in the aerosol forcing and the influence of aerosols on clouds are considered to be major weaknesses in current models of climate change.

Identifying the sources of aerosols and their impact on climate is an important component of EOS and climate research in general. Analysis of global daily satellite data from EOS AM-1 can provide the overall assessments of the interdependence and interactions among aerosols, water vapor, clouds, and the radiative forcing. All these quantities are measured from EOS AM-1 instrumentation. MODIS measures simultaneously global aerosols, water vapor, and clouds; MISR provides independent measures of aerosol amounts, composition, and radiative properties along with three-dimensional cloud characterizations; CERES measures the resulting radiative forcing; and ASTER and Landsat-7 can provide a zoomed image of the aerosol and cloud properties in specific locations of major interest. The Aerosol Robotic Network (AERONET) of ground-based, autonomous instrumentation will make coincident aerosol measurements and provide information on their properties for validation of EOS AM-1 aerosol products (Brent Holben's IDS Team).

Assessment of the dust's climate effects requires use of a fully interactive climate model. Other EOS Instrument and IDS Teams (e.g., Fung, Dickinson, Hansen, Hartmann, Kiehl, Toon, Holben, Ghan, and Pickering) will be ready to assimilate aerosol measurements from EOS AM-1 into atmospheric and global climate models to assess the impacts of aerosols on climate.

Biospheric productivity

Photosynthetic organisms, like land plants and phytoplankton, convert solar energy into the chemical energy that drives the rest of the biosphere. The magnitude of this process is hinted at when one considers that all of the Earth's coal and oil comes from ancient photosynthesis. This solar-energy-driven biospheric productivity provides food, fuel, and shelter for humans. Natural or human processes that reduce productivity will have potentially harmful social and economic consequences. Thus, the ability to monitor and model productivity at regional-to-global scales is a high priority in the EOS Program.

The Inez Fung IDS Team has processed the AVHRR record to produce continuous, time-varying global maps of land surface parameters needed as input into climate and biosphere productivity models. A vegetation model coupled with an atmosphere/ocean/ice model and forced by observed seasonality in vegetation is being used to study the interplay among vegetation, climate, and the composition of the atmosphere. Comparisons between measured carbon dioxide concentrations from a global observation network and model simulations indicate that the land biosphere of the Northern Hemisphere is storing a large part of the carbon dioxide generated by fossil fuel and biomass burning every year. The possibility of a connection between the satellite observations of a longer, greener growing season (Myneni, MODIS and MISR Instrument Team member) and the terrestrial carbon sink in the Northern Hemisphere is intriguing.

Soon after the launch of EOS AM-1, the Fung Team will use the MODIS land cover and vegetation index data, together with EOS Data Assimilation Office (DAO) (Richard Rood's Team) meteorological products, to generate near-real-time predictions of productivity at 0.25° resolution for the whole globe. Simulations will be tested against ground observations of atmospheric carbon dioxide concentration and meteorology and used to predict near-term agricultural and forest production rates.

Other IDS Teams are focusing on the productivity of continents (e.g., Moore, Schimel, and Foley) and oceans (e.g., Abbott and Barton).

Human impacts

Large-scale Earth processes, such as climate variability and land cover change, have obvious impacts on agricultural productivity. The economic and social costs of disruption of human activities by these processes are often huge. Efforts to monitor and predict these events and their human consequences will greatly reduce these costs. The EOS Program has, therefore, invested in the development of approaches that will exploit the unique global, near-instantaneous measurements that satellite remote sensing can provide for the purposes of monitoring and forecasting the impacts of these events.

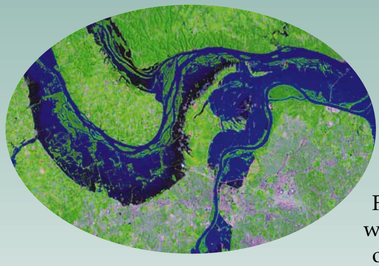
El Niño and food production

The Rosenzweig IDS Team is developing a set of tools for prediction and assessment of the impacts of large-scale seasonal-to-interannual climate fluctuations, including El Niño Southern Oscillation (ENSO) events, on important food-producing systems around the world. Improving the quality of such predictions should permit farmers, policymakers, and other food-system decision-makers to take appropriate actions to mitigate human deprivation and economic disruption resulting from changes in food production caused by wide swings in climate.

Specifically, this involves coupling a biological production model with an ENSO prediction model and a General Circulation Model (GCM). Retrospective analysis of satellite data over the past two decades is being used to improve ENSO and crop yield models. With the launch of EOS AM-1, the models will use MODIS surface temperature and vegetation products to predict the ENSO cycle and its impact on global agriculture productivity.

Urban land cover change

Urbanization significantly affects regional air quality and climate. Higher temperatures in cities in the summer result in increased health risks, energy consumption, and air pollution. The Dale Quattrochi IDS Team is using satellite observations now from Landsat-4 and -5 and AVHRR, and later from MODIS, ASTER, and Landsat-7, together with regional climate models to address issues such as how urban planners might mitigate these deleterious consequences of urbanization. Studies so far have shown that vegetation cover and surface albedo of urban areas can have a significant impact on air temperatures and ozone pollution levels, which suggests that appropriate urban planning can reduce energy consumption, ozone pollution, and human discomfort. The team is collaborating with the EPA, Atlanta Regional Commission, and the Georgia Department of Natural Resources, and is developing an EOS data user base among regional municipalities in the United States.



Flood waters of the Illinois, Mississippi, and Missouri Rivers near St. Louis, Missouri on July 29, 1993 (Gumley and King, 1993).[11]

Volcanism

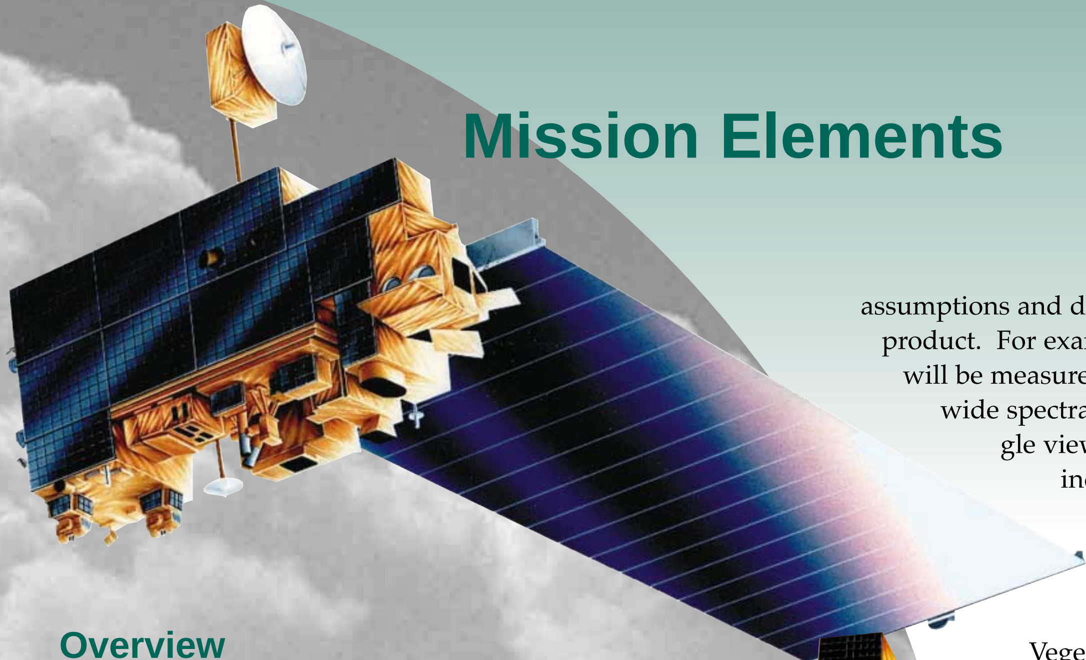
Volcanic activity not only injects aerosols into the atmosphere, but also can directly threaten human activities. Remote sensing offers an approach for measuring the activity of volcanoes globally in near real time for hazard detection and climate impact assessment.

The Volcanology (Peter Mouginis-Mark) IDS Team will produce an almost real-time fire and volcanic eruption alert using MODIS data to look for nighttime hot spots. A list of alarmed pixels will then be mapped globally and updated continuously on the Internet to be used for scientific analysis and human impact mitigation. Additionally, this team will generate weekly global inventories of lava flows, forest fires, and the thermal output of human development (e.g., power plants). MODIS data will be used in conjunction with ASTER, MISR, and Landsat-7 data to track the level of activity at specific volcanoes at higher spatial resolution.

Floods

Flooding is a serious hazard to both humans and natural resources. Each year, the cost of floods increases as humans alter surface hydrology and populate flood-prone regions. Climate variability, such as El Niño cycles, and trends, such as global warming, affect the frequency and intensity of flooding. Satellite observations provide a unique way of measuring flood vulnerability and assessing the damage caused by flooding. The Robert Brakenridge IDS Team will use EOS AM-1 sensors (MODIS and ASTER), as well as Landsat-7 and other global data sets, to study interannual-to-interdecadal global variations in flooding and its resulting societal effects. For individual extreme flood events, the research team will measure: land area inundated, contributing basin area, peak discharge, suspended sediment concentration, meteorological conditions, and geomorphological factors. The team will also identify conditions conducive to flooding before such events occur and monitor conditions during the events.

Mission Elements



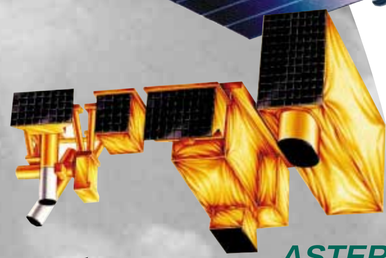
Overview

The EOS AM-1 platform will fly in a near-polar, sun-synchronous orbit so that it descends across the equator at 10:30 a.m. when daily cloud cover over the land is minimal. It will be followed by its PM counterpart in the year 2000; however, EOS PM-1 will fly in an ascending orbit with a 1:30 p.m. equatorial crossing time to represent the diurnal variability.

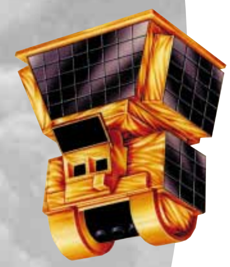
EOS AM-1 is designed to house five instruments for simultaneous geolocated measurements and for intercomparison of the new measurement techniques. For example, MODIS' detailed internal calibrations will be used, through simultaneous geolocated measurements, to help in the calibration of ASTER. The MODIS and ASTER high-resolution multi-channel observations of clouds will be used by CERES' low-resolution radiative flux measurements, and by MOPITT to determine the location of clouds as well as their distribution and properties. MISR's multi-angle measurements will determine the angular reflectance properties of land surface features, aerosols, and clouds, all of which will be used by the MODIS, ASTER, and CERES Teams in their data analyses.

Since EOS AM-1 is a research facility, some of the geophysical products will be derived using more than one instrument and more than one pathway, each with a different set of assumptions and different properties of the product. For example, aerosol properties will be measured by MODIS using its wide spectral range and 1-2 day single view coverage, and also independently by MISR using its multi-angle data, narrower spectral range, and 2-9 day coverage. Vegetation properties will be derived from both MODIS and MISR data. Water vapor will be derived independently from MODIS measurements of reflected near infrared sunlight and emitted terrestrial infrared radiation. The simultaneously geolocated products will allow the EOS instrument teams to develop broad science approaches to specific problems. For instance, in the case of deforestation resulting from biomass burning, fires and emitted smoke particles will be observed by MISR and MODIS, deforestation and burn scars will be observed by ASTER and MODIS, emitted trace gases—carbon monoxide and methane—will be measured by MOPITT, and the radiative forcing of climate will be observed by CERES.

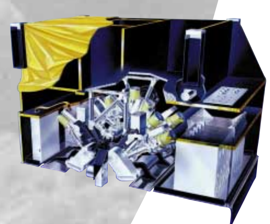
Each instrument was developed under the supervision of a science team that also developed algorithms for analysis of the data and derivation of Earth system measurements. The science teams also will validate these products and use them in their respective scientific investigations.



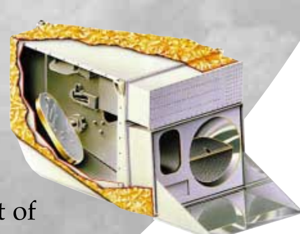
ASTER



CERES



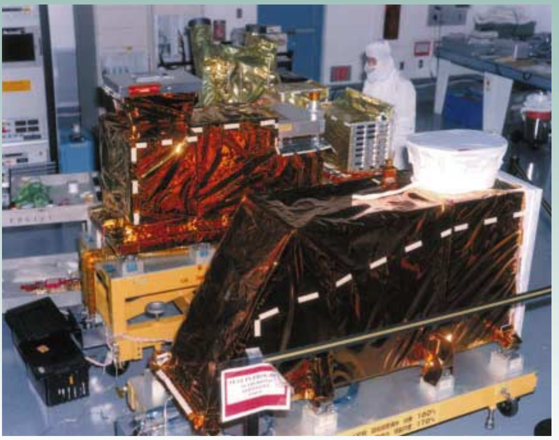
MISR



MODIS

MOPITT

A Advanced
S Spaceborne
T Thermal
E Emission and Reflection
R Radiometer



ASTER will obtain high resolution (15 to 90 m) images of the Earth in the visible, near-infrared (VNIR), shortwave-infrared (SWIR), and thermal infrared (TIR) regions of the spectrum.

ASTER is a cooperative effort between NASA and Japan's Ministry of International Trade and Industry (MITI), with the collaboration of scientific and industrial organizations in both countries. Management of the ASTER Team is provided by the Japan Resources Observation System Organization (JAROS). As shown in the figure, ASTER consists of three distinct telescope subsystems: VNIR, SWIR, and TIR. It is a high spatial, spectral, and radiometric resolution, 14-band imaging radiometer. Spectral separation is accomplished through discrete bandpass filters and dichroics. Each subsystem operates in a different spectral region, has its own telescope(s), and is built by a different Japanese company.

The VNIR subsystem, built by NEC Corporation, consists of two telescopes—one that looks backward (along track) and one that looks at nadir. The nadir-looking telescope is a reflecting-refracting improved Schmidt design and pairs with the backward looking telescope to produce same-orbit stereo images. The VNIR subsystem operates in three visible and near-infrared bands with 15 m resolution and a 60 km swath width. The telescope pair is pointable cross-track over a ± 24° angle to increase the revisit frequency of any given Earth location and special targets of opportunity (e.g., volcanic activity and natural disasters). Light from either of two onboard halogen lamps will be used periodically for calibration of this subsystem.

The SWIR subsystem, built by Mitsubishi Electric Company (MELCO), operates in six shortwave infrared channels with 30 m resolution and a 60 km swath width. It contains a pointing mirror that can point ± 8.54° from nadir to allow coverage of any point on Earth over the spacecraft's 16-day cycle. This mirror is also periodically used to direct light from either of two onboard calibration lamps into the subsystem's telescope—a fixed, aspheric refracting telescope.

The TIR subsystem, built by Fujitsu Ltd., operates in five thermal infrared channels with 90 m resolution and a 60 km swath width. It contains a scan mirror that is used for both scanning and pointing up to ± 8.54° from nadir. As in the SWIR, this mirror is also periodically used to view the onboard blackbody for calibration. Light from the TIR scan mirror is reflected into a Newtonian catadioptric telescope system with an aspheric primary mirror and lens for aberration correction.

The ASTER instrument operates for a limited time during the day and night portions of an orbit. The full configuration (all bands plus stereo) collects data for an average of 8 minutes per orbit. Reduced configurations (limited bands, different gains, etc.) can be implemented as requested by investigators.

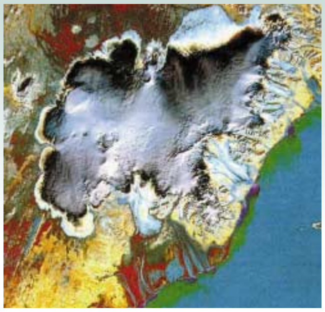
The ASTER Team Leaders are Hiroji Tsu in Japan and Anne Kahle in the U.S. For more information about the instrument, see http://asterweb.jpl.nasa.gov.

ASTER is the highest spatial resolution instrument on the EOS AM-1 spacecraft, and the only one that does not acquire data continuously. ASTER data products include:

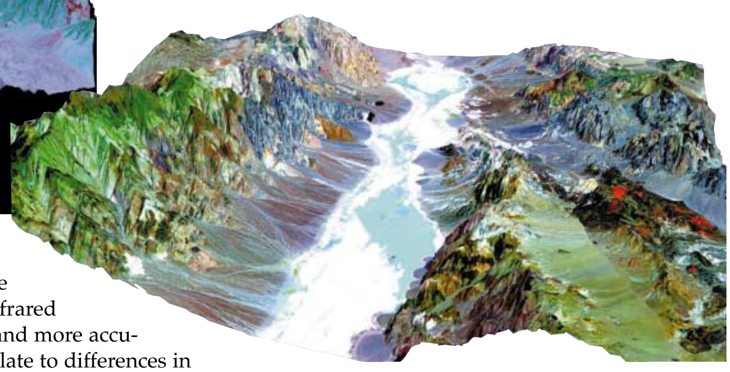
- spectral radiances and reflectances of the Earth's surface;
- surface temperature and emissivities;
- digital elevation maps from stereo images;
- surface composition and vegetation maps;
- cloud, sea ice, and polar ice products; and

- observation of natural hazards (volcanoes, etc.).

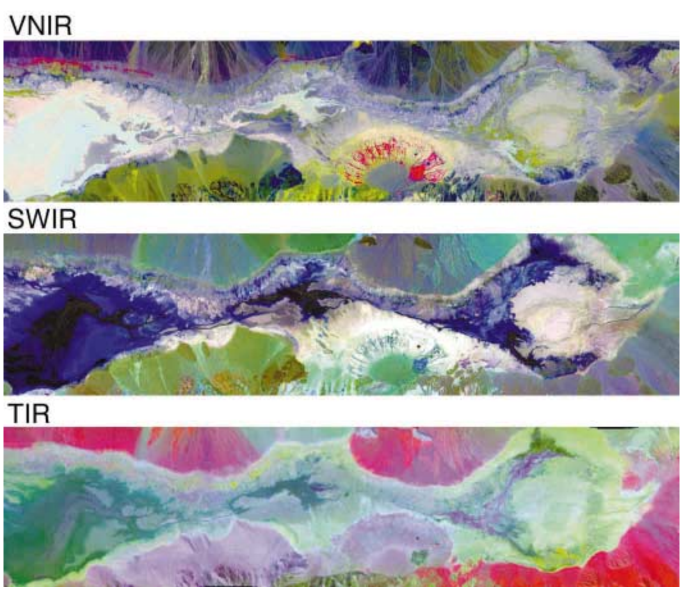
ASTER Instrument Characteristics	
Spectral range VNIR SWIR TIR	 0.5-0.9 µm 1.6-2.5 µm 8-12 µm
Spatial resolution	15 m (VNIR: 3 bands), 30 m (SWIR: 6 bands), 90 m (TIR: 5 bands)
Duty cycle	8%
Data rate	8.3 Mbps (avg), 89.2 Mbps (peak)
Mass	450 kg
Power	525 W (avg), 761 W (peak)



ICELAND ICE CAP. The Vatnajokull ice cap and its glaciers are clearly shown in this simulated ASTER image created from Landsat data. Monitoring of glacial movement contributes to understanding climate change.



These are simulations of an ASTER scene, 60 × 60 km, taken from an aircraft over Death Valley, CA. The images are draped over digital elevation data to produce the 3-D perspective view. The left image illustrates ASTER's multispectral thermal infrared bands that will provide new surface compositional information and more accurate surface temperature determinations. Colors on the image relate to differences in surface materials—red areas are quartz-rich outcrops and alluvial fans; dark green, gray, and blue areas are other volcanic and sedimentary rock types; light green areas are salt deposits on the valley floor. The right image was produced using the visible, middle infrared, and short wavelength infrared bands that are used for the color display of the surface compositional information. Image colors depict different surface materials—green areas are vegetated; blue areas are wet or have standing water; orange areas are iron-rich volcanic rocks; brown, pink, blue gray areas are volcanic and sedimentary rocks (ASTER Team, Jet Propulsion Laboratory).



These simulated ASTER images were made from coregistered AVIRIS imaging spectrometer data (the VNIR and the SWIR images), and Thermal Infrared Multispectral Scanner data (the TIR image). The VNIR image has a spatial resolution of 15 m, and combines ASTER bands 3, 2, and 1 in red, green, and blue (RGB). The SWIR image has a resolution of 30 m, and combines SWIR bands 8, 6 and 4 as RGB. The TIR image uses bands 14, 12 and 10 displayed as RGB, and has a resolution of 90 m. (Images displayed here are reduced in resolution.) The size of the area depicted is 12 × 50 km.

Bad Water in Death Valley is the lowest place in the United States. It is in the right middle of each image. The three versions of ASTER data illustrate the different compositional information available in various wavelength regions. For example, the bright red areas in the top image are vegetation patches at Furnace Creek Ranch and on the Furnace Creek Fan. The turquoise area in the left corner of the middle image depicts ground covered by limestone fragments. In the thermal image (bottom), surfaces with the mineral quartz present are depicted in red (ASTER Team, Jet Propulsion Laboratory).

C Clouds and the E Earth's R Radiant E Energy S System

CERES consists of two broadband scanning radiometers that will measure the Earth's radiation balance and provide cloud property estimates to assess their role in radiative fluxes from the surface to the top of the atmosphere.

CERES is a broadband scanning thermistor bolometer package with extremely high radiometric measurement precision and accuracy. The EOS AM-1 spacecraft will carry two identical instruments: one will operate in a cross-track scan mode and the other in a biaxial scan mode. The cross-track mode will essentially continue the measurements of the Earth Radiation Budget Experiment (ERBE) mission as well as the Tropical Rainfall Measuring Mission (TRMM), while the biaxial scan mode will provide new angular flux information that will improve the accuracy of angular models used to derive the Earth's radiation balance.

Each CERES instrument has three channels—a shortwave channel for measuring reflected sunlight, a longwave channel for measuring Earth-emitted thermal radiation in the 8-12 µm "window" region, and a total channel for total radiation. Onboard calibration hardware includes a solar diffuser, a tungsten lamp system with a stability monitor, and a pair of blackbody sources. Cold space and internal calibration looks are performed during each normal Earth scan.

Both CERES scanners operate continuously throughout the day and night portions of an orbit. In the cross-track scan mode, calibration occurs biweekly. In the biaxial scan mode, calibration also occurs biweekly, and sun-avoidance short scans occur twice per orbit.

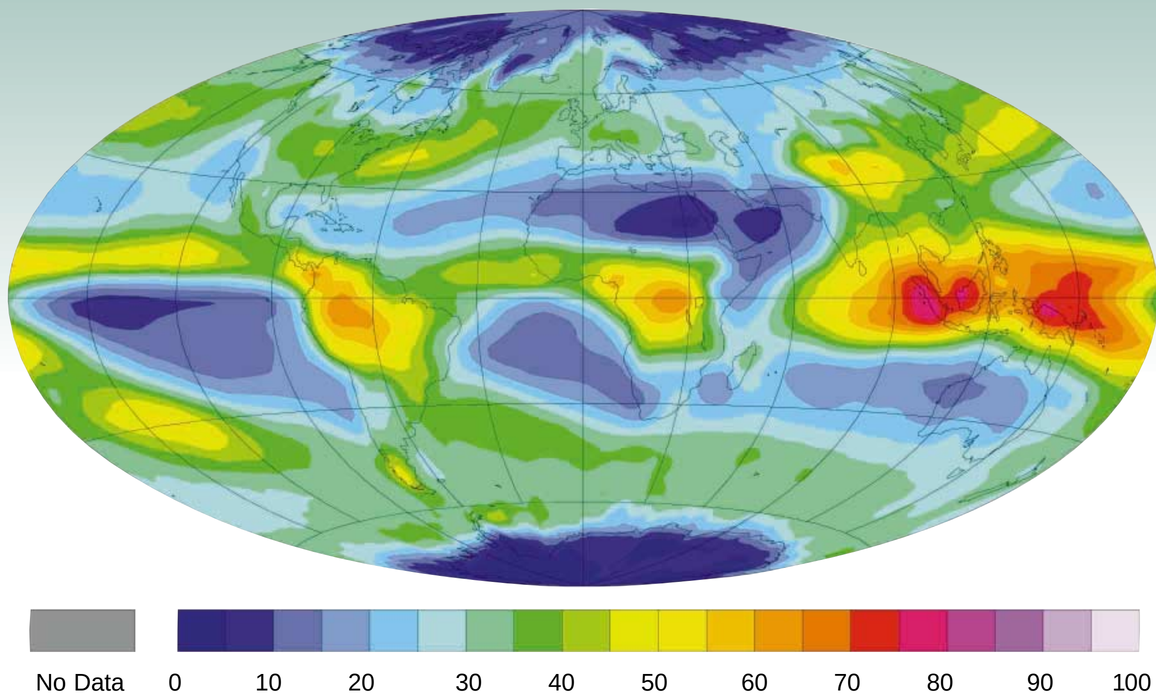
CERES is a Principal Investigator instrument provided by NASA and managed by NASA's Langley Research Center (LaRC) in Hampton, Virginia. The instrument was built by TRW in Redondo Beach, California. The CERES Team Leader is Bruce Barkstrom. More information may be obtained on the CERES Web Page at http://asd-www.larc.nasa.gov/ceres/ASDceres.html.

CERES data will be used to:

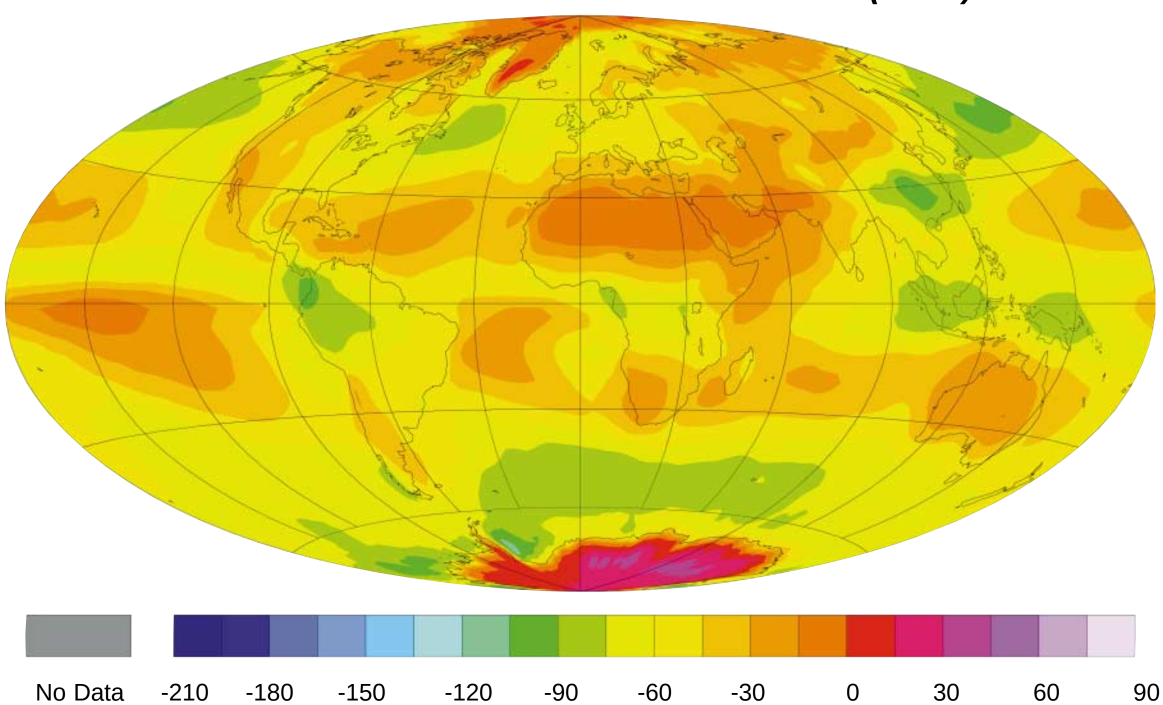
- study cloud radiative forcing and feedbacks;
- develop an observational baseline of clear-sky radiative fluxes;
- determine radiant input to atmospheric and oceanic energetics models;
- validate general circulation models; and
- enhance extended-range numerical weather predictions.

CERES Instrument Characteristics	
Spectral bands	Shortwave: 0.3-5.0 µm Longwave: 8-12 µm Total: 0.3 to >200 µm
Spatial resolution at nadir	20 km
Duty cycle	100%
Data rate	20 kbps (two instruments)
Mass	90 kg (two instruments)
Power	95 W (two instruments)

LONGWAVE CLOUD FORCING 1985-1986 (Wm^{-2})

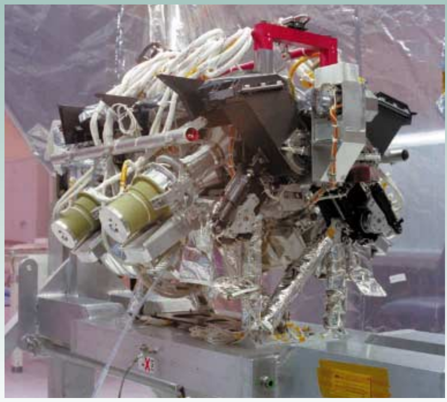


SHORTWAVE CLOUD FORCING 1985-1986 (Wm^{-2})



These global data products were taken by the Earth Radiation Budget Experiment (ERBE)—the heritage instrument for CERES. The data show a one-year average (from 1985-86) of the cloud forcing of incoming solar radiation and outgoing longwave radiation. The colors represent ERBE's measurements in Watts per meter squared (Dennis Hartmann, U. of Washington).

M Multi-angle
I Imaging
S Spectro-
R Radiometer



Most satellite instruments look only straight down, or toward the edge of the planet. To fully understand Earth's climate, and to determine how it may be changing, we need to know the amount of sunlight that is scattered in different directions under natural conditions. MISR is a new type of instrument designed to address this need—it will view the Earth with cameras pointed at nine different angles. One camera points toward nadir, and the others provide forward and aftward view angles, at the Earth's surface, of 26.1°, 45.6°, 60.0°, and 70.5°. As the instrument flies overhead, each region of the Earth's surface is successively imaged by all nine cameras in each of four wavelengths (blue, green, red, and near-infrared).

In addition to improving our understanding of the fate of sunlight in the Earth's environment, MISR data can distinguish different types of clouds, aerosol particles, and surfaces. Specifically, MISR will monitor the monthly, seasonal, and long-term trends in:

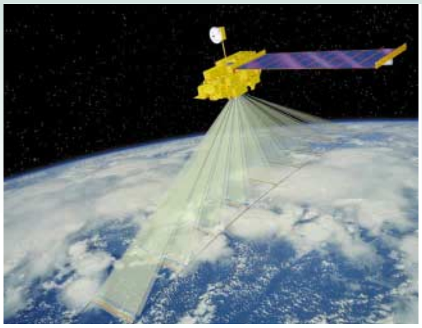
- the amount and type of atmospheric aerosol particles, including those formed by natural sources and by human activities;
- the amount, types, and heights of clouds; and
- the distribution of land surface cover, including vegetation canopy structure.

These data will be used to investigate the influence of aerosol, cloud, and surface properties on the Earth's reflected radiation budget and climate. Spatial samples are acquired every 275 m. Over a period of 7 minutes, a 360 km wide swath of Earth comes into view at all nine angles. Special attention has been paid to providing highly accurate absolute and relative radiometric calibration using onboard hardware consisting of deployable solar diffuser plates and several types of photodiodes. To complement the onboard calibration effort, a validation program of *in situ* measurements is planned, involving field instruments such as PARABOLA III, which automatically scans the sky and ground at many angles, and a multi-angle aircraft camera (AirMISR). Global coverage by the space-based MISR will be acquired about once every 9 days at the equator. The nominal mission lifetime is 6 years.

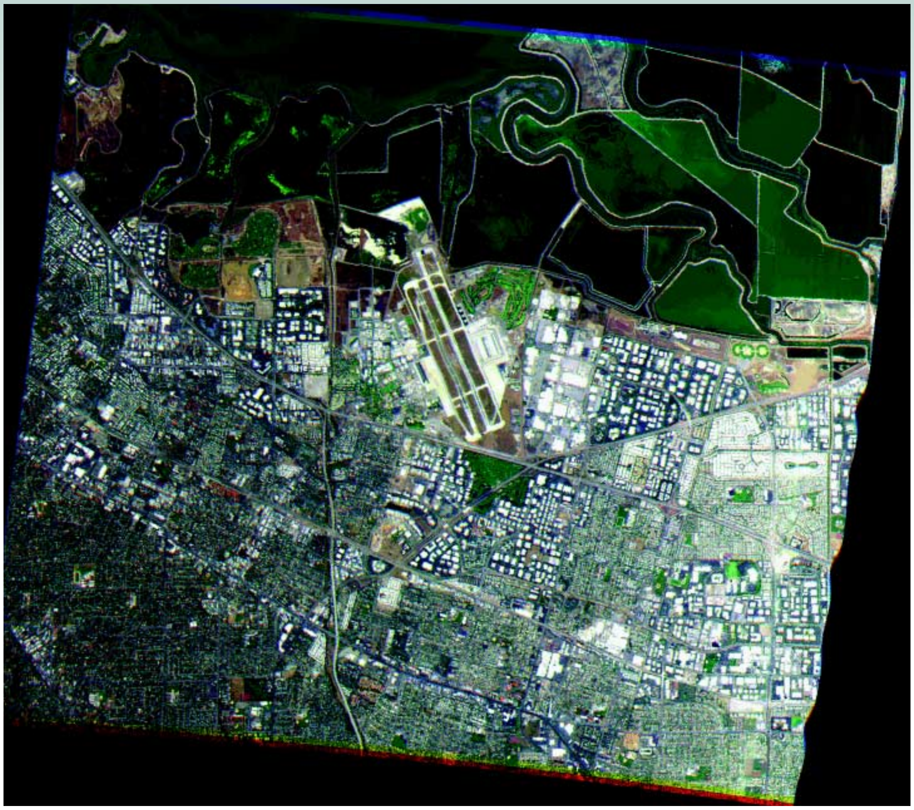
MISR is being built for NASA by the Jet Propulsion Laboratory in Pasadena, California. The Principal Investigator is David J. Diner. For more information, check out the MISR Web Site at http://www-misr.jpl.nasa.gov.

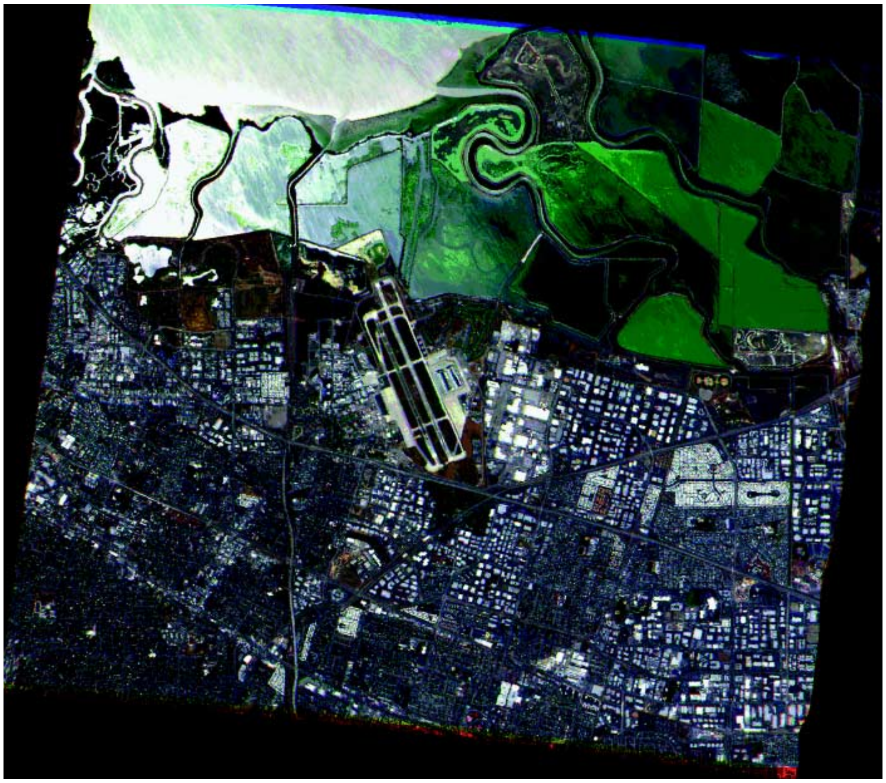
MISR Instrument Characteristics	
Swath width	360 km
Spectral bands	446, 558, 672, 866 nm
Cross-track pixel size	275 m off-nadir, 250 m nadir
Duty cycle	50% (day only)
Data rate	3.3 Mbps (avg), 9.0 Mbps (peak)
Mass	149 kg
Power	72 W (avg), 135 W (peak)

The MISR Optical Bench (photo top right on this page)
This is the "science part" of the MISR instrument, which includes the cameras and calibration equipment. The photograph was taken in October 1996, as MISR was being assembled. Subsequently, the parts that supply power, communications, and temperature control were added. The entire package was then encased in a protective housing, which was covered with highly reflecting thermal blankets.



This computer-generated image shows the EOS AM-1 spacecraft, with the MISR instrument on board, orbiting the Earth. Direction of flight is toward the lower left. The actual locations imaged by the 9 cameras, each with 4 color bands, along the Earth's surface are illustrated here with translucent surfaces. The background star field is also realistic (Shigeru Suzuki and Eric De Jong, Solar System Visualization Project, Jet Propulsion Laboratory).





This pair of red/green/blue color composite images was taken by the AirMISR instrument on August 25, 1997, over the area surrounding Moffett Field, California. They each cover an area approximately 10 km on a side and were acquired from a NASA ER-2 aircraft flying at 20 kilometers altitude in an approximately southward direction. Radiometric scaling using pre-flight calibration coefficients and a simple line-by-line roll correction algorithm have been applied. The imaged area straddles the waters of San Francisco Bay near the inlet of Coyote Creek, mudflats, marshes, tidelands that are in part utilized as salt evaporation ponds, and urban areas of Mountain View, Sunnyvale, and adjacent communities that provide a grid of city streets, buildings, and freeways. North is toward the top of these images, and the sun is shining roughly from the south. For the left image, the camera was pointing at 26.1 degrees forward of nadir, whereas the top image was taken with the camera pointing 26.1 degrees aftward of nadir. The rivers and tidal areas are brighter in the forward-viewing (left) image, illustrating that these wet surfaces produce mirror-like reflections that are observable at this viewing geometr (MISR Team, Jet Propulsion Laboratory).

MODIS
MODerate-resolution Imaging Spectroradiometer

MODIS will view the entire surface of the Earth every 1-2 days, making observations in 36 co-registered spectral bands, at moderate resolution (0.25 - 1 km), of land and ocean surface temperature, primary productivity, land surface cover, clouds, aerosols, water vapor, temperature profiles, and fires.

MODIS is a whisk broom scanning imaging radiometer consisting of a cross-track scan mirror, collecting optics, and a set of linear arrays with spectral interference filters located in four focal planes. MODIS has a viewing swath width of 2330 km (the field of view sweeps □ 55° cross-track) and will provide high-radiometric resolution images of daylight-reflected solar radiation and day/night thermal emissions over all regions of the globe. Its spatial resolution ranges from 250 m to 1 km at nadir, and the broad spectral coverage of the instrument (0.4 - 14.4 µm) is divided into 36 bands of various bandwidths optimized for imaging specific surface and atmospheric features. The observational requirements also lead to a need for very high radiometric sensitivity, precise spectral band and geometric registration, and high calibration accuracy and precision.

The MODIS instrument has one of the most comprehensive onboard calibration subsystems ever flown on a remote sensing instrument. This onboard calibration hardware includes a solar diffuser, a solar diffuser stability monitor, a spectroradiometric calibration assembly, a plate-type black body, and a space viewport.

MODIS operates continuously during the day and night portions of each orbit. In normal science mode, data from all bands are collected during the day portion of an orbit, whereas only the thermal infrared band data are collected during the night portion of an orbit. The instrument is calibrated periodically using the three internal targets—solar diffuser, blackbody, and spectroradiometric calibration assembly.

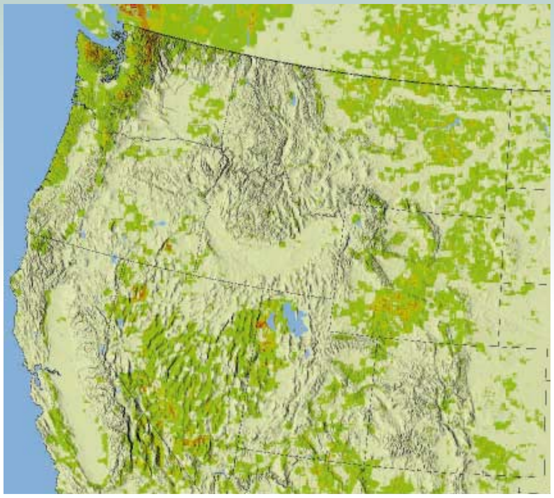
MODIS is a facility instrument provided by NASA and managed by NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. It was built by Hughes Corporation's Santa Barbara Remote Sensing (SBRS) in Santa Barbara, California. The MODIS Team Leader is Vincent V. Salomonson. For more details, refer to the MODIS Web Page at http://modarch.gsfc.nasa.gov.

MODIS will measure:

- surface temperature (land and ocean) and fire detection;
- ocean color (sediment, phytoplankton);
- global vegetation maps and change detection;
- cloud characteristics;
- aerosol concentrations and properties;

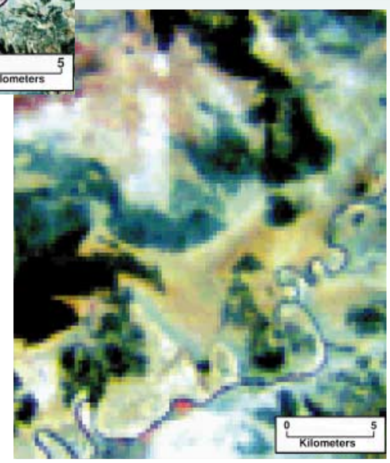
MODIS Instrument Characteristics	
Spectral range	0.4-14.4 µm
Spectral coverage	± 55°, 2330 km swath (contiguous scans at nadir at equator)
Spatial resolution	250 m (2 bands), 500 m (5 bands), 1000 m (29 bands) at nadir
Duty cycle	100 %
Data rate	6.2 Mbps (avg), 10.8 Mbps (day), 2.5 Mbps (night)
Mass	274 kg
Power	162.5 W (avg for one orbit), 168.5 W (peak)

- temperature and moisture soundings;
- snow cover and characteristics; and
- ocean currents.



(a) Landsat Thematic Mapper (TM) false color image for a region around Choma, Zambia (WRS: 173/071, acquisition date July 27, 1992) with fire burn scars clearly identified as the large dark/black polygons (Jacqueline Kendall, Goddard Space Flight Center).

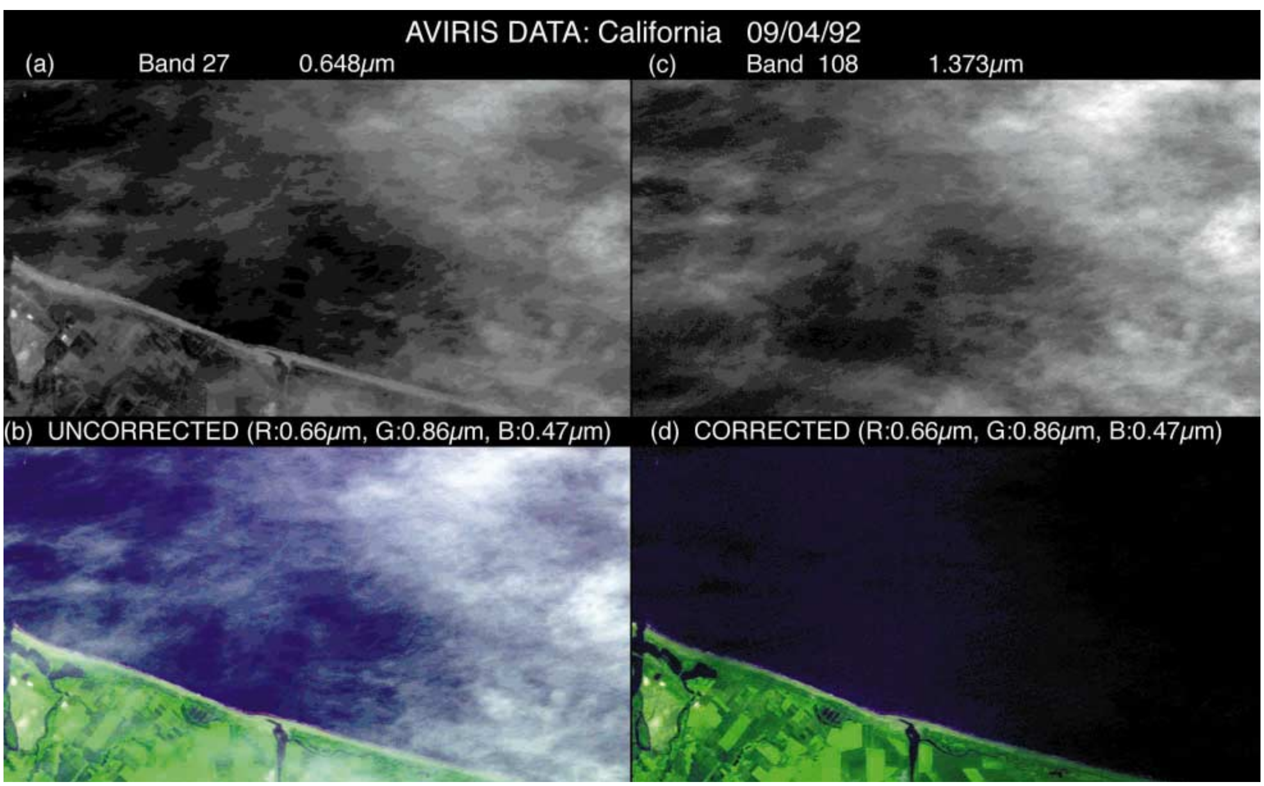
(a)



(b)

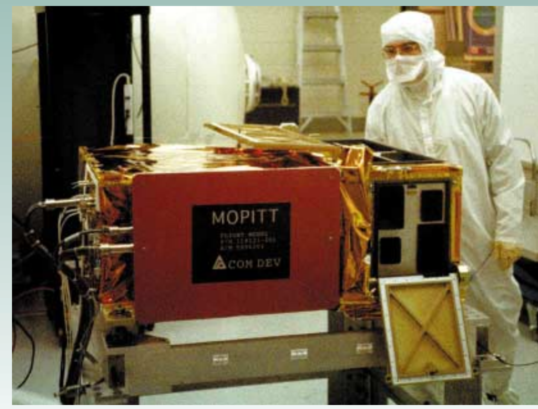
(b) Simulated MODIS 250 m data derived from the Landsat TM image described in figure (a).

This fire potential index was derived from weekly composites of AVHRR Normalized Difference Vegetation Index (NDVI) and surface temperature data obtained from NOAA-14 (processed and provided by EROS Data Center). The image shows regions in 11 of the midwestern United States that are moderately (orange) to highly (brown) susceptible to the outbreak of a wildfire due to dry conditions on the ground. There is low fire susceptibility in those regions colored light tan and green. Although this particular image product is still at the experimental stage, the Land Discipline Group plans to provide global fire susceptibility maps to the public once MODIS data become available (Ramakrishna Nemani, Lloyd Queen, Jim Plummer, and Steve Running, U. of Montana).



These images illustrate a planned application of MODIS ’ new 1.375 μm cirrus channel (using AVIRIS data): (a) image taken over an ocean-land interface region where the presence of thin clouds obstructs the view of the surface (0.65 μm band alone); (b) the same image using three bands (red - 0.65 μm, green - 0.86 μm, blue - 0.47 μm), uncorrected; (c) the same image (1.375 μm cirrus band alone), observing high clouds only due to the strong water vapor absorption in the lower troposphere in this band; (d) the same image as the one in (b) but corrected to provide an unobstructed view of the surface (Bo-Cai Gao, Naval Research Laboratory).

M Measurements
O Of
P Pollution
I In
T The
T Troposphere



MOPITT is an instrument designed to enhance our knowledge of the lower atmosphere and to particularly observe how it interacts with the land and ocean biospheres. Its specific focus is on the distribution, transport, sources, and sinks of carbon monoxide and methane in the troposphere.

MOPITT is a scanning radiometer employing gas correlation spectroscopy to measure upwelling and reflected infrared radiance in three absorption bands of carbon monoxide and methane. The instrument modulates sample gas density by changing the length or the pressure of the gas sample in the optical path of the instrument. MOPITT has a spatial resolution of 22 km at nadir and a swath width of 640 km.

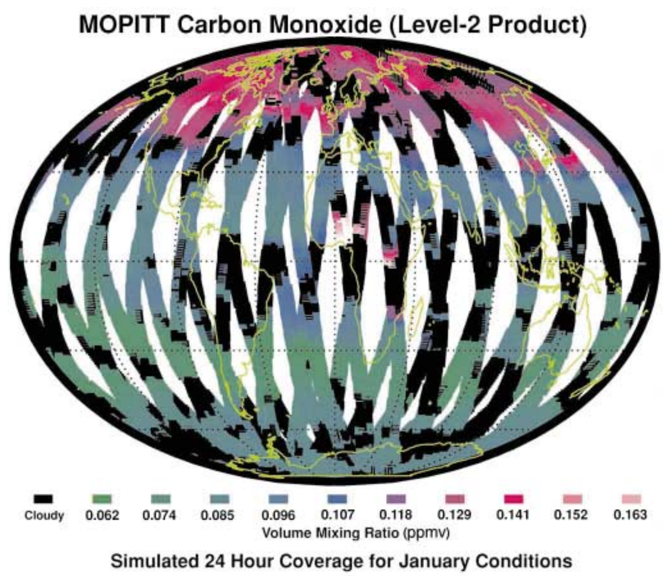
MOPITT operates continuously, providing science data on both day and night portions of an orbit. Calibration, using the onboard blackbodies and a space look, occurs during each normal scan. A long calibration occurs monthly and provides calibration at an elevated blackbody temperature.

MOPITT is a Principal Investigator instrument provided by Canada, managed by the Canadian Space Agency, and built by COM DEV Ltd. in Cambridge, Ontario. The MOPITT Team Leader is James R. Drummond. Refer to the MOPITT Web Site for more details at http://eos.acd.ucar.edu/mopitt/home.html.

MOPITT data will be used to:

- measure and model carbon monoxide and methane concentrations in the troposphere;
- obtain carbon monoxide profiles with a resolution of 22 km horizontally and 3 km vertically, with an accuracy of 10 percent;
- measure the methane column in the troposphere with a resolution of 22 km and a precision of better than 1 percent; and
- generate global maps of carbon monoxide and methane distribution, and provide increased knowledge of tropospheric chemistry.

MOPITT Instrument Characteristics	
Spectral bands	2.3 (CH_4), 2.4 (CO), and 4.7 µm (CO)
Swath	640 km
Spatial resolution	22 km
Duty cycle	100 %
Data rate	25 kbps (avg), 40 kbps (peak)
Mass	184 kg
Power	250 W



This image represents a simulation of MOPITT Level 2 data showing mid-tropospheric carbon monoxide mixing ratios. The image represents the coverage of MOPITT for one day. The atmospheric conditions are for January (Paul Bailey, NCAR).

EOS AM-1

The First EOS Morning Satellite

The EOS AM-1 spacecraft supports the operation of the five instruments on the mission. All instruments are mounted on the nadir-facing deck of the spacecraft for a clear view of the Earth.

To support the cooling requirements of ASTER and MOPITT, the spacecraft provides an advanced technology capillary-pumped heat transport system that transports heat from the instruments to the passive radiators mounted on the spacecraft. This advanced heat transport system, developed at NASA's Goddard Space Flight Center, was tested on the Space Shuttle and is expected to yield significant benefits to this and future spacecraft.

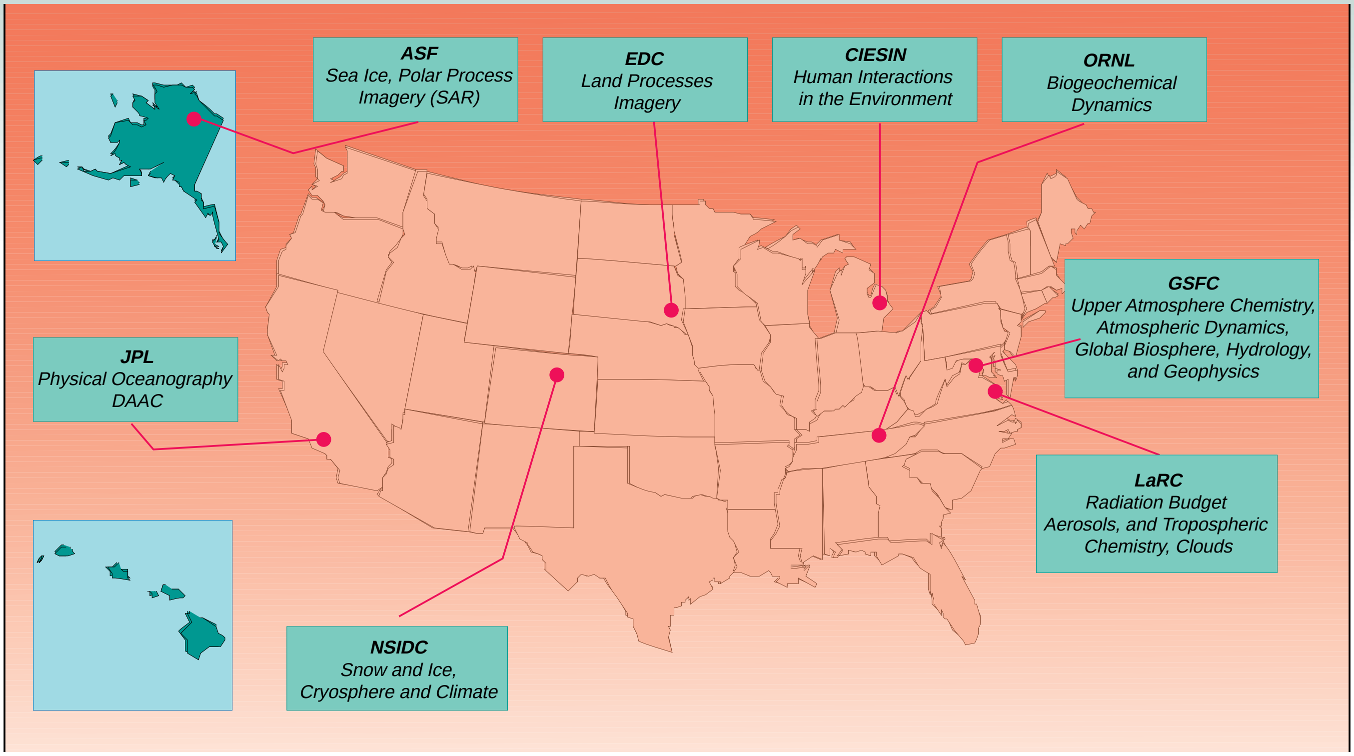
The science data generated by each instrument are sent to the spacecraft over high-bandwidth communication lines. These data are multiplexed and recorded in a solid-state recorder, then sent to the communication subsystem for transmission to the ground. This state-of-art solid-state recorder is designed to hold approximately two orbits of data, up to 140 Gigabytes, using advanced technology solid-state memory devices.

For transmission to the ground, two communications capabilities will be available. First, data can be transmitted via the Tracking and Data Relay Satellite System (TDRSS) on Ku band to the TDRSS Ground Station, White Sands, NM. Second, data can be transmitted directly to the ground on X band. In both cases, transmission is scheduled to occur at specific times based on the availability of TDRSS, or the proximity of a ground station. Continuous direct broadcast of MODIS data will be available on X band and can be received by individual users around the world.

The orientation of the spacecraft is maintained by the guidance, navigation, and control subsystem. This complex and precise subsystem maintains spacecraft pointing accuracy to within 150 arc-seconds of the desired pointing direction, and determines pointing to within 90 arc-seconds using star trackers. Additionally, this subsystem provides safe hold control in the event of a spacecraft operational anomaly.

Electrical power to operate all the instruments and spacecraft subsystems is provided by the electrical subsystem. Power is generated by an advanced, lightweight solar array using gallium arsenide solar cells. This power is then converted into operating voltages, regulated, and distributed to all subsystems and instruments. Electrical energy is stored in nickel hydrogen batteries to enable the spacecraft to operate on the dark portion of the orbit.

The EOS Data and Information System (EOSDIS)



The EOSDIS provides the total ground system for processing, archiving, and distributing science and engineering data from all the EOS spacecraft. EOSDIS also provides the mission operations systems that perform the functions of command and control of the spacecraft and instruments, health and safety monitoring, mission planning and scheduling, initial data capture, and Level 0 processing. Command of all the EOS spacecraft and instruments is done at the EOS Operations Center located at NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland.

Data from the EOS AM-1 spacecraft will flow via the Tracking and Data Relay Satellite System (TDRSS) to the TDRSS ground terminals in White Sands, New Mexico, where the data will be captured and recorded at 150 Mbps. The data will be forwarded via a 45-Mbps communications link to the EOS Data and Operations System (EDOS) at GSFC where they will undergo Level 0 processing, which includes elimination of transmission errors and artifacts, separation of the raw data by instrument packet identification, removal of duplicate packets, and generation of Level 0 production data sets (period covered is specified by the customer). Level 0 data sets for four of the five instruments (MODIS, CERES, MISR, and MOPITT) will then be transferred (over the EOS networks) to the appropriate Distributed Active Archive Center (DAAC) for further processing, utilizing algorithms provided by the Instrument Science Teams. Level 0 data for the ASTER instrument will be sent via physical media to the ASTER Ground Data System (GDS) in Tokyo, Japan, for further processing. A set of ASTER Level 1 data products will be sent via physical media from the ASTER GDS to the EROS Data Center (EDC), where it will be processed to produce higher level data products.

Eight DAACs representing a wide range of Earth science disciplines have been selected by NASA to carry out the responsibilities for processing, archiving, and distributing EOS and related data, and for providing a full range of user support. The EOSDIS utilizes a system-wide EOSDIS Core System (ECS) that provides uniform support across all DAACs for these activities.

The DAACs shown in the following table will process and archive the data from the EOS AM-1 mission.

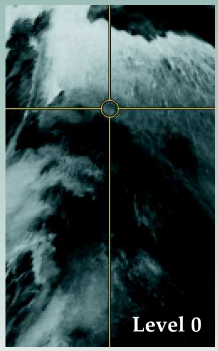
Distributed Active Archive Centers			
DAAC	**Location**	**Discipline**	**Instrument**
EROS Data Center (US Geological Survey)	Sioux Falls, South Dakota	Land processes data	ASTER, MODIS
Goddard Space Flight Center (NASA)	Greenbelt, Maryland	Upper atmosphere chemistry, atmospheric dynamics, global biosphere, hydrology, and geophysics	MODIS
Langley Research Center (NASA)	Hampton, Virginia	Radiation budget, clouds, aerosols, surface radiation, land processes, and tropospheric chemistry	CERES, MISR, MOPITT
National Snow and Ice Data Center (University of Colorado)	Boulder, Colorado	Snow and ice, cryosphere, and climate	MODIS

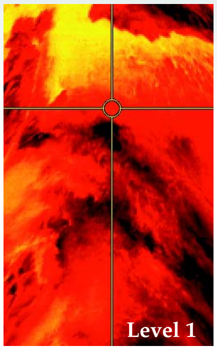
Computing facilities used by the EOS investigators are called Science Computing Facilities (SCF). These facilities range from individual workstations to supercomputers. They are used to develop algorithms and models for the generation of data products, to access services in EOSDIS, to conduct scientific research, and to perform scientific quality control of the data products. Some SCFs support the planning, scheduling, command and control, and analysis of instrument engineering data. Additionally, each EOS instrument team has its own SCF. The main SCFs for EOS AM-1 data are shown in the table at the right.

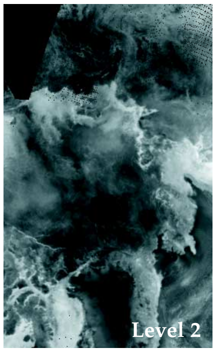
Science Computing Facilities		
ASTER	Jet Propulsion Laboratory (NASA)	Pasadena, California
CERES	Langley Research Center (NASA)	Hampton, Virginia
MISR	Jet Propulsion Laboratory (NASA)	Pasadena, California
MODIS	Goddard Space Flight Center (NASA)	Greenbelt, Maryland
MOPITT	National Center for Atmospheric Research	Boulder, Colorado

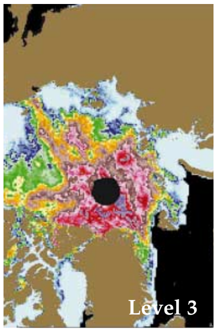
Teams of scientists worldwide have already been selected to receive the data to perform research in areas of international concern. Additionally, EOS data and products will be available to all users, without restriction, at no more than the cost of dissemination, regardless of the intended use.

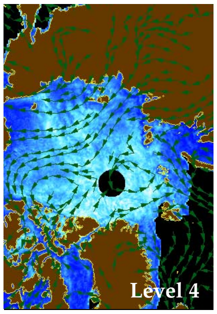
Processing Levels	
Level 0	Reconstructed, unprocessed data at full resolution; all communications artifacts have been removed
Level 1	Level 0 data that has been time-referenced and annotated with ancillary information, including radiometric and geometric calibration coefficients, and geolocation information
Level 2	Derived geophysical variables at the same resolution and location as the Level 1 data
Level 3	Variables mapped on uniform space-time grids, usually with some completeness and consistency
Level 4	Model output or results from analyses of lower level data











The EOS Data Calibration Strategy

Because outer space is such a harsh environment, the performance of all satellite sensors degrades over time. Historically, once an instrument was launched into space, it was eroded by the elements in ways that could not be accurately predicted so that, over time, errors and uncertainties were introduced into the collected data. There is additional concern that jostling an instrument during launch and deployment can affect performance. In anticipation of these problems, EOS sensors will have unprecedented onboard calibration systems enabling engineers on the ground to characterize their performance throughout the lifetime of each satellite's mission and correct for errors introduced into the data by system degradation.

To achieve consistent and accurate measurements that can be used to detect climatic and environmental change, the signals recorded by the detectors in each instrument must be translated into Earth spectral reflectance and temperature units, or the units of reflected and emitted radiance by the Earth and its atmosphere. This translation—or calibration of the instruments—must not only be accurate and consistent among all of the EOS AM-1 instruments' detectors, but it must also be consistent with the detectors of all of the EOS instruments that will follow over the next 18 years.

Hence, for EOS, calibration is the set of operations or processes that are used to determine the relationship between satellite instrument output values (i.e., digital counts) and corresponding known values of a standard, which are expressed in Systeme Internationale (SI) units. Calibration of the EOS instruments requires that the ongoing performance of each be carefully characterized. Characterization is the set of operations or processes used to quantitatively understand the operation of an instrument and its response as a function of the gamut of operating and viewing conditions experienced by the instrument on orbit. In summary, this effort—unparalleled in other space missions—consists of the following elements:

- pre-flight instrument calibration and characterization;
- pre-flight intercomparison of the performance of the instruments;
- installation of calibration devices on the instruments for on-orbit calibration and characterization;
- on-orbit maneuvers of the EOS AM-1 platform for additional calibration and characterization;
- validation of the calibration by comparing satellite observations to simultaneous aircraft observations, and to targets on the Earth's surface and in the atmosphere that have known, stable, or measured physical properties;
- analysis of the multiple calibration information, resolution of conflicting information, and formulation of the calibration used in the data analysis; and
- intercomparison with future EOS platforms.

Pre-flight EOS AM-1 instrument calibration and characterization

Pre-flight instrument calibration and characterization are performed at the instrument builders' facilities. They include radiometric and geometric calibration. Radiometric calibration involves determining the relationship between instrument output and radiant input while the instrument views a calibrated radiant source. For the solar spectrum (400 to 2500 nm), the calibrated radiant source is an integrating sphere which has been calibrated using national standards. For thermal infrared (above 2500 nm), the calibrated source is a variable temperature blackbody.

Pre-flight geometric calibration involves the determination of the detailed spatial response of each instrument band with respect to the nominal instrument telescope pointing direction. Geometric calibration is necessary for converting the instrument radiometric data into images with known relationships to observed Earth targets. Pre-flight geometric calibration is performed by the instrument builders and includes determining the geometrical relationship between the instrument optical axis and the instrument alignment cube (i.e., pointing knowledge), instrument fields-of-view, and band-to-band registration.

Pre-flight instrument characterization is performed by the instrument builder and involves an extensive series of well-designed tests. Characterization includes the quantification of instrument stray light, quantification of ghosting due to internal reflections by the instrument optical elements, measurement of polarization response, assessment of bandpass and center wavelength stability, measurements of temperature and pressure response, measurement of modulation transfer function (MTF), and determination of scattered light sensitivity.

Pre-flight intercomparison between the performance of the instruments

Validation of the radiance calibration scales assigned to the integrating sphere sources by the instrument builders is accomplished through a set of traveling, ultra-stable transfer radiometers used in a series of radiometric measurement comparisons. The EOS AM-1 radiometric measurement comparisons included radiometers from the National Institute of Standards and Technology (NIST), the University of Arizona, the National Research Laboratory of Metrology (NRLM/Japan), and NASA's GSFC. Because the radiometric measurement comparisons are performed on the actual radiant sources used to calibrate EOS AM-1 satellite instruments, the comparisons provide a pre-flight cross calibration of the participating EOS AM-1 instruments. Validation and cross calibration of the radiometric scales assigned to the blackbody sources by instrument builders are accomplished using an ultra-stable, thermal infrared transfer radiometer built by NIST.

On-orbit instrument calibration and characterization

The EOS AM-1 instruments will be radiometrically and geometrically calibrated on orbit using onboard calibrators (OBCs). These OBCs include solar diffusers, blackbodies, space viewports and, in the case of MODIS, a monochromator source known as the SpectroRadiometric Calibration Assembly (SRCA). OBCs are used to transfer the pre-flight instrument calibration to on-orbit operation and to monitor the long-term, on-orbit instrument operation. The majority of OBCs are calibrated pre-flight using reflectance, temperature, radiance, irradiance, or detector standards, and carry the pre-flight calibration scale into orbit. On orbit, OBCs are used to monitor the EOS AM-1 instrument calibration and operation.

Validation of the calibration of OBCs at the subsystem level is accomplished through EOS artifact round-robins. For example, a NASA/NIST-sponsored EOS AM-1 pre-flight round-robin on the measurement of the bidirectional reflectance distribution function (BRDF) of on-board diffuser material was conducted. Participating laboratories include NIST, University of Arizona, JPL, Hughes SBRS, and NASA's GSFC.

On-orbit geometric calibration quantitatively determines the spatial response of an instrument's bands to the instrument optical pointing direction. On-orbit, the EOS AM-1 platform geometric calibration will be performed by the individual instruments through the use of ground control points (GCPs), digital elevation models (DEMs), geometric test sites on the Earth and, possibly, the Moon.

On-orbit maneuvers of the EOS AM-1 satellite for additional calibration and characterization

The Moon will be used by EOS and other remote sensing instruments as a common, stable, on-orbit radiance reference target. The United States Geological Survey (USGS) and Northern Arizona University (NAU) are making radiometric measurements of the Moon with the goal of producing a lunar radiance model that will draw upon lunar radiance measurements over a period of 4.5 years. Consequently, on-orbit measurements of the Moon by EOS AM-1 and other remote sensing instruments can be directly compared to the output of the lunar radiance model. In order for EOS AM-1 instruments to view the Moon at optimum lunar phase and geometry, a calibration attitude maneuver (CAM) of the EOS AM-1 satellite is planned.

The accuracy and precision of Earth remote sensing data sets produced by different instruments are only achieved by the consistent use of common on-orbit calibration sources and measurement methodologies. EOS AM-1 will perform an on-orbit, pitch-based CAM to enable the instruments to view deep space and the Moon. The deep space view provides CERES and ASTER an accurate determination of the DC offsets in their thermal bands; and it provides MODIS the opportunity to characterize the dependence of thermal infrared reflectance on the angle of incidence (AOI) of the scan mirror. Determination of the dependence of thermal infrared reflectance versus AOI is necessary to ensure that all of the MODIS thermal bands are within or near specification. These on-orbit characterizations result in significant improvements in the accuracy of the radiometric data products from these instruments.

The same pitch-based CAM also provides the EOS AM-1 instruments the opportunity to view the Moon at a lunar phase of 22°. The Moon affords the ability to monitor radiometric responsivity and stability in the visible, near-infrared, and shortwave infrared wavelength regions. The appearance of the Moon as a bright target in a dark surround provides EOS instruments an on-orbit target for the determination of scattered light sensitivity, size of source effect, and Modulation Transfer Function (MTF).

Above: NASA's Lockheed ER-2 formation flight of three high-altitude research aircraft over San Francisco, CA.

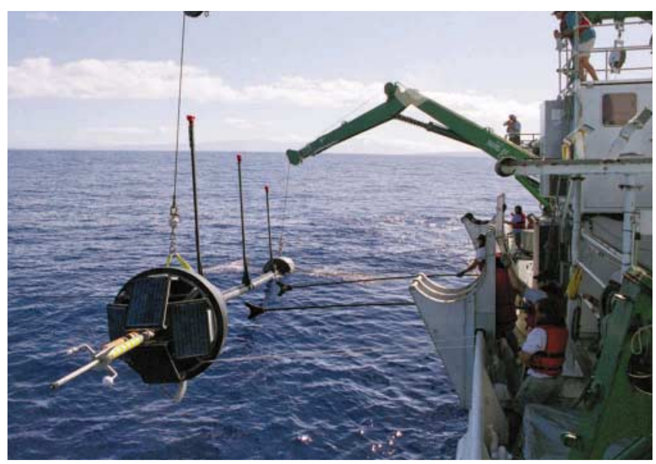
Bottom left: Wallops Flight Facility's Bell Huey helicopter, carrying two side platforms with a POLDER instrument, a modular multi-band radiometer (MMR), an SE-90 spectrometer, infrared thermal (IRT) sensors, and video recording equipment. Pictured here, the helicopter is participating in the BOREAS campaign, near Prince Albert, Saskatchewan, Canada (NASA Ames Research Center).

Validating the calibration

The on-orbit calibration will be validated occasionally by cross-comparing aircraft observations with those of the EOS satellites. Additionally, targets on the Earth's surface and in the atmosphere that have known, stable, or measured physical properties will be remotely sensed by EOS AM-1 sensors. Discrepancies between actual and expected measurements may suggest that the calibration has drifted. Known as vicarious calibration, these on-orbit techniques typically involve deployment of calibrated ground-based or airborne radiometers on or above a spectrally and spatially homogeneous target to make simultaneous measurements during periods of satellite instrument overpasses. The ground-based and airborne radiometric measurements are corrected for atmospheric effects to produce a top-of-the-atmosphere radiance that can be registered and compared to the measured satellite radiance. Participating vicarious calibration instruments are absolutely and relatively calibrated before, during, and after field campaigns using integrating spheres, diffuse reflectors with irradiance standards, and diffuse reflectors with solar illumination. Alternative techniques for vicarious calibration include the use of known and stable reflectance characteristics of molecular scattering in the atmosphere, and stable spectral properties of ocean glint and clouds in the visible-to-near-infrared parts of the spectrum.

Intercomparison with future EOS sensors

Cross-calibration of the EOS AM-1 instruments with each other and with instruments on future EOS satellites is necessary for the production of a continuous 18-year Earth remote sensing data set. One method of cross-calibrating EOS instruments is to have the instruments view identical Earth targets at the same time to compare the resulting measured radiances to some agreed-upon reference radiance. This type of cross-calibration activity is planned for MODIS, MISR, and ASTER. Follow-on EOS missions will also use lunar observations, enabling EOS AM-1 to be cross-calibrated with them as well.



The Marine Optical Buoy (MOBY) being deployed off the southwest coast of Lanai, HI. The primary purpose of the buoy is to measure visible and infrared solar radiation entering and emanating from the ocean. By monitoring variations in the reflected radiation, other quantities can be derived, such as the abundance of microscopic marine plants (phytoplankton). Under the direction of Dennis Clark of NOAA, MOBY data will be used to validate both MODIS and SeaWiFS ocean color products (Ed King, NOAA).

Validation

In both the pre- and post-launch periods of EOS AM-1, EOS instrument team members and interdisciplinary investigators will conduct scientific field campaigns to verify the quality and long-term stability of the EOS sensors' measurements, as well as the validity of the derived geophysical data products. The magnitudes of any uncertainties and errors in EOS AM-1 data products must be quantified, on both spatial and temporal scales, to ensure that the data are scientifically credible and maximally useful. Understanding the uncertainties and errors is also essential for future improvement of the algorithms and Earth observing systems.

To obtain the necessary correlative observations required for validation, the EOS Program will use a four-pronged approach that incorporates the following:

1. surface-based (*in situ*) radiance observations and measurements at specific test sites obtained as part of the EOS interdisciplinary, instrument, and validation teams' investigations;

2. field experiments conducted by EOS interdisciplinary, instrument, and validation teams, as well as participation in, and support of, nationally and internationally coordinated field programs;

3. coordination with national and international observation sites and networks such as the Department of Energy (DoE) Atmospheric Radiation Measurement (ARM) Program, the National Science Foundation (NSF) Long-Term Ecological Research (LTER) sites, and the WCRP Baseline Surface Radiation Network (BSRN); and

4. airborne remote sensing measurements using specifically designed EOS instrument simulators, such as such as the MODIS Airborne Simulator (MAS), AirMISR, MOPITT Airborne Test Radiometer (MATR), and MODIS/ASTER Airborne Simulator (MASTER), as well as community airborne instruments, such as the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS).

These highly-focused validation activities will range from vicarious calibration of the basic radiance measurements to validation of the higher-order biogeophysical products such as land cover, ocean chlorophyll content, net primary productivity, and the planetary energy budget—including components of the atmosphere and surface energy budgets. Validation of the EOS AM-1 Science Data Products encompasses measurements and comparisons made on local-to-regional-to-global scales, including intercomparison of various satellite-derived parameters and the incorporation of satellite-derived information into models of the Earth system and its components.

EOSDIS will serve as the primary data system for archiving of Science Working Group for the AM Platform (SWAMP) validation data. The EOS Project Science Office Validation Home Page (http://eospso.gsfc.nasa.gov/validation/) includes the EOS AM-1 Instrument Science Team Validation Plans and a wealth of information on the EOS Validation Program.

Pictured at right, these graduate students are making measurements of plant productivity in the Canadian boreal forest during the 1994 BOREAS campaign. Below, sun photometers like these were deployed throughout Brazil—in the cerrado and rain-forest regions—to measure optical thickness during the 1995 SCAR-B campaign (David Herring, Goddard Space Flight Center).

MISR Validation Field Measurements

These members of the MISR Team are preparing to make field measurements at Lunar Lake, Nevada, early on the morning of June 5, 1996. Here they are working on a portable instrument that can measure light reflected by the surface in many color bands and at multiple view angles. In the course of the day, they carried this instrument around the test site in a backpack, taking hundreds of images of the surface. During this experiment, they also used instruments that measure sunlight and skylight (Barbara Gaitley, Jet Propulsion Laboratory).

Education and Outreach

While the major goal of NASA's Earth Science Enterprise is to increase scientific understanding of our planet, ESE is not limited to serving the needs of the scientific community. Rather, the ultimate product of the program is education in its broadest forms. According to the Earth Science Strategic Plan, one of the four goals of the program is to "foster the development of an informed and environmentally aware public." Within this context, contributions to the advancement of public knowledge about the Earth are key to measuring the success of the program. These contributions are being accomplished through numerous educational programs, both formal and informal.

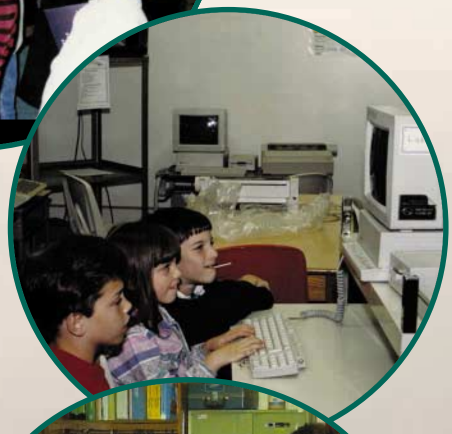
Formal educational initiatives are designed for kindergarten through graduate levels, and include programs designed to enhance teacher/faculty knowledge and research skills; provide curriculum support in the form of instructional products; provide research experiences for students at NASA and related sites; create programs and products that use advanced technologies for education; and promote activities involving collaborative efforts with a range of partners in the public and private sectors that work to enhance education.

Informal education initiatives are directed toward educating the scientific community and the general public concerning Earth Science. Literature is being produced that answers the basic questions of why NASA embarked on the Earth Science Enterprise and what the agency hopes to accomplish concerning the environmental issues that are of primary concern to everyone. Among this literature are numerous brochures, NASA Fact Sheets, fact books, handbooks, newsletters, and World Wide Web sites—all comprising a wealth of information and images.

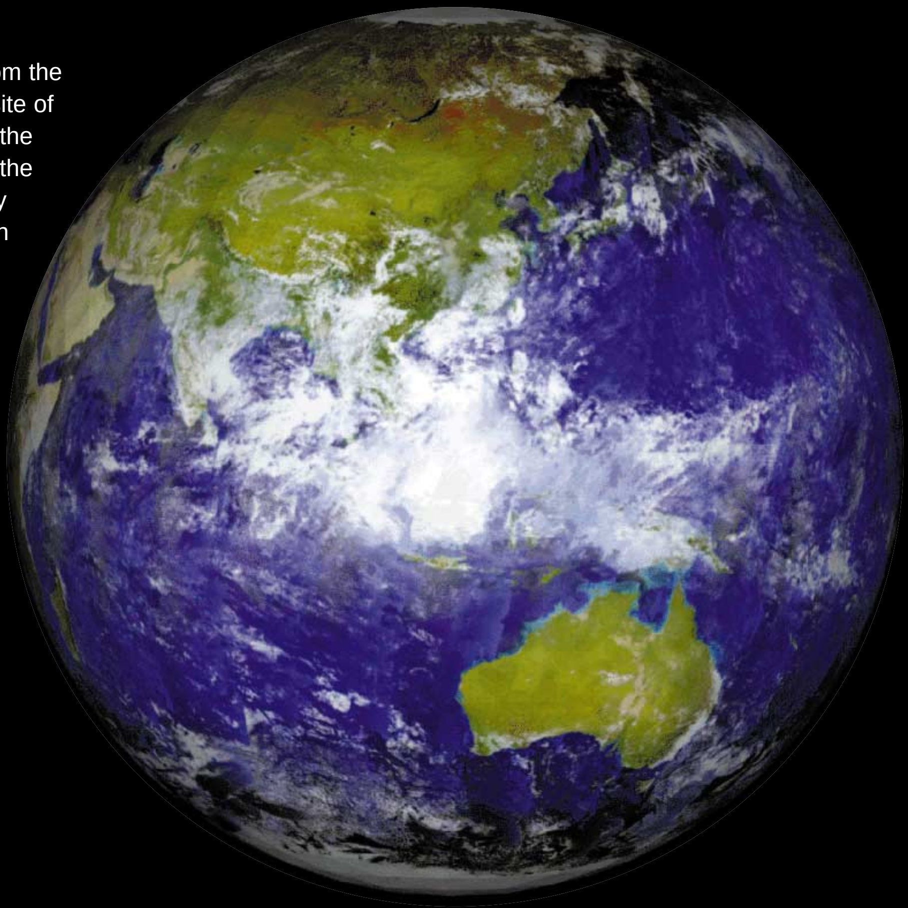
A museum exhibit was opened at GSFC's Visitors Center in February 1998. Additional exhibits are being planned for the Smithsonian National Air and Space Museum, Smithsonian Museum of Natural History, and the American Museum of Natural History's Center for Science Literacy.

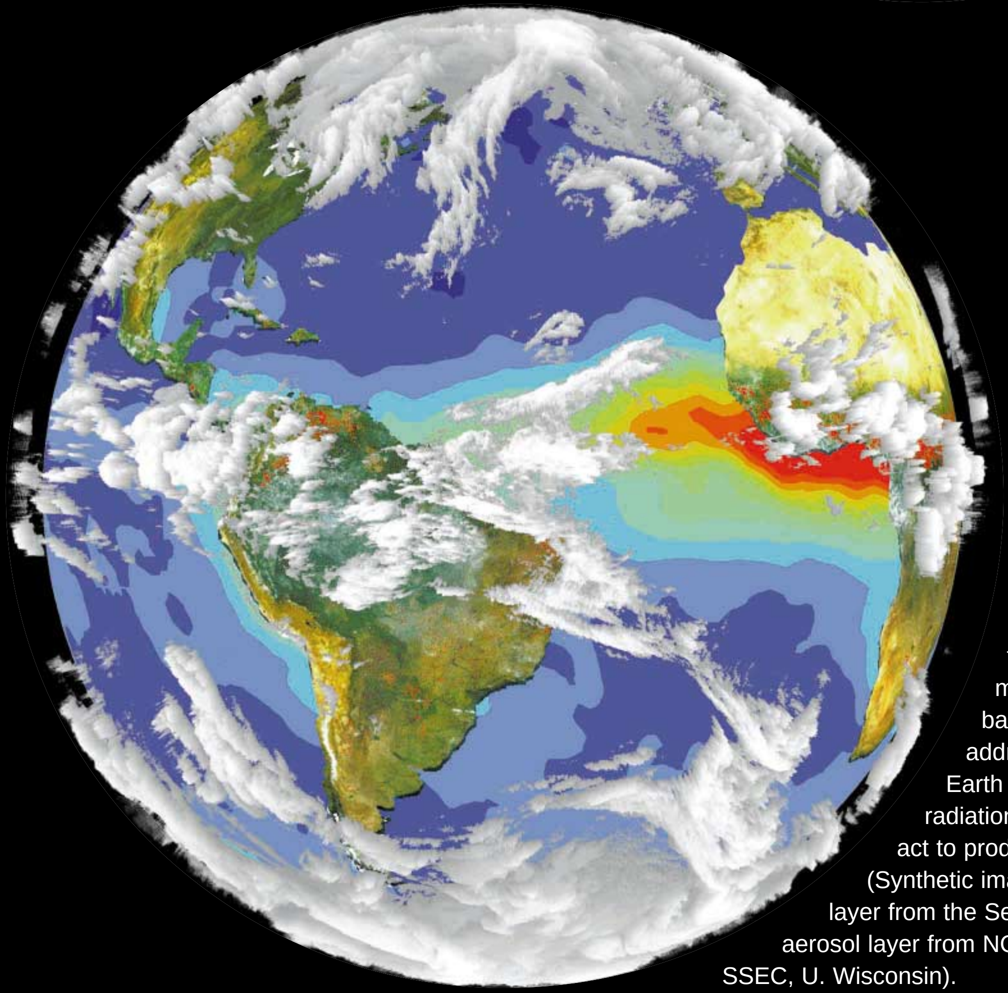
Where possible, the latest multimedia technologies for interactivity and data visualization are being leveraged to couple learning about our home planet with an overview of Earth Science. The idea is to encourage a "hands on" approach that is both entertaining and inspiring.

For more details on how to obtain some of these educational materials, visit the EOS Project Science Office Web site at http://eospso.gsfc.nasa.gov/eos_homepage/ education.html; or the Earth Science site at http: //www.hq. nasa.gov/office/mtpe/education.html.



The Earth as seen in the visible spectrum from the SeaWiFS. This picture represents a composite of data taken between Sept. 18-25, 1997, over the Southeast Asia region. Smoke plumes from the extensive biomass burning almost completely blot out the Asian-Pacific islands in the region surrounding Indonesia (SeaWiFS Project, NASA's Goddard Space Flight Center).





This Earth image is synthesized from four remotely sensed data layers: visible light reflection over land (SeaWiFS), fires over land (AVHRR), aerosols over the oceans (AVHRR) and IR cloud images from four geostationary satellites. The large aerosol plume over the Atlantic is from biomass burning and windblown dust emitted over Africa. Such data fusion from multiple sensors, along with surface-based observations and modeling studies, address the key scientific challenge of the Earth Science Enterprise: how do the Earth's radiation budget, land, water, air, and life interact to produce the environment in which we live? (Synthetic image by R.B. Husar, Washington U.; land layer from the SeaWiFS Project, fire maps from ESA, aerosol layer from NOAA-NESDIS, and cloud layer from SSEC, U. Wisconsin).

Glossary of Terms & References

AERONET	Aerosol Robotic Network
AirMISR	Airborne Multi-angle Imaging SpectroRadiometer
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AOI	angle of incidence
ARM	Atmospheric Radiation Measurement program
ASF	Alaska SAR Facility
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible and Infrared Imaging Spectrometer
BOREAS	Boreal Ecosystem - Atmosphere Study
BRDF	bidirectional reflectance distribution function
BSRN	Baseline Surface Radiation Network
CAM	calibration attitude maneuver
CERES	Clouds and the Earth's Radiant Energy System Network
CIESIN	Consortium for International Earth Science Information Network
CZCS	Coastal Zone Color Scanner
DAAC	Distributed Active Archive Center
DAO	Data Assimilation Office
DEM	digital elevation model
DoE	Department of Energy
ECS	EOSDIS Core System
EDC	EROS Data Center
EDOS	EOS Data and Operations System
El Niño	Spanish for the "Christ Child"; refers to the warm Pacific Ocean currents that periodically appear around Christmas time and can last for months.
ENSO	El Niño Southern Oscillation
ERBE	Earth Radiation Budget Experiment
EOS	Earth Observing System
EOS AM-1	the first EOS platform (launches in 1998); crosses the equator at 10:30 a.m. in a descending polar orbit
EOS CHEM	EOS Chemistry Mission
EOS PM-1	the second EOS platform (launches December 2000); crosses the equator at 1:30 p.m. in an ascending polar orbit
EOSDIS	EOS Data and Information System
EPA	Environmental Protection Agency
EROS	Earth Resources Observation System
ESE	Earth Science Enterprise
FEWS	Famine Early Warning System
GCM	General Circulation Model
GCP	ground control point
GDS	Ground Data System
GSFC	Goddard Space Flight Center
ICESat-1	Ice Cloud & land Elevation Satellite
IDS	Interdisciplinary Science
IRT	Infrared thermal
JAROS	Japan Resources Observation System Organization
Jason-1	EOS Radar Altimeter
JPL	Jet Propulsion Laboratory
Landsat	Land Remote-sensing Satellite
LaRC	Langley Research Center
LTER	Long-Term Ecological Research
MAS	MODIS Airborne Simulator
MASTER	MODIS/ASTER Airborne Simulator
MATR	MOPITT Airborne Test Radiometer
MELCO	Mitsubishi Electric Company
Meteor-3M	Russian Operational Weather Satellite
MISR	Multi-angle Imaging SpectroRadiometer
MITI	Japan's Ministry of International Trade and Industry
MMR	Modular Multi-band Radiometer
MOBY	Marine Optical Buoy
MODIS	Moderate-resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
MTF	modulation transfer function
MWIR	Mid-wave Infrared
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NAU	Northern Arizona University
NCAR	National Center for Atmospheric Research
NDVI	Normalized Difference Vegetation Index
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRLM	National Research Laboratory of Metrology (Japan)
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
OBC	onboard calibrator
ORNL	Oak Ridge National Laboratory
PARABOLA III	Portable Apparatus for Rapid Acquisition of Bidirectional Observations of the Land and Atmosphere

POLDER	Polarization and Directionality of Earth's Reflectances
RGB	Red/Green/Blue color
SAGE III	Stratospheric Aerosol and Gas Experiment III
SAR	Synthetic Aperture Radar
SBRS	Hughes Corporation's Santa Barbara Remote Sensing
SCF	Science Computing Facility
SCAR-B	Smoke, Clouds, and Radiation-Brazil
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SI	Systeme Internationale
SRCA	Spectroradiometric Calibration Assembly
SST	Sea Surface Temperature
SWAMP	Science Working Group for the EOS AM-1 Platform
SWIR	Short-Wavelength Infrared
TDRSS	Tracking and Data Relay Satellite System
TIR	Thermal Infrared
TIROS	Television and Infrared Observation Satellite
TLCF	Team Leader Computing Facility
TM	Thematic Mapper
TOMS	Total Ozone Mapping Spectrometer
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measuring Mission
USGS	United States Geological Survey
VNIR	Visible and Near-Infrared
WCRP	World Climate Research Program

References

(1) Arrhenius, S., 1896: On the influence of carbonic acid in the air upon the temperature of the ground. *Phil. Mag.*, **41**, 237-276.

(2) Vitousek, P.M., H.A. Mooney, J. Lubchenco, and J.M. Melillo, 1997: Human Domination of Earth's Ecosystems, *Science*, **277**, 494-500.

(3) Groisman, P., T. R. Karl, and R. W. Knight, 1994: Observed impact of snow cover on the heat balance and the rise of continental spring temperatures, *Science*, **263**, 198-200.

(4) Doake, C. S. M., and D. G. Vaughan, 1991: Rapid disintegration of the Wordie Ice Shelf in response to atmospheric warming. *Nature*, **350**, 328-330.

(5) Rosenzweig, C., and M. L. Parry, 1994: Implications of climate change for international agriculture. U.S. Environmental Protection Agency, EPA 230-B-94-003, Washington, DC.

(6) Wallace, J. M., and S. Vogel, 1994: Reports to the Nation On Our Changing Planet: El Niño and Climate Prediction. National Oceanic and Atmospheric Administration, NA27GPO232-01, Boulder, CO.

(7) Bell, G. D., and J. E. Janowiak, 1993: Atmospheric circulation associated with the midwest floods of 1993. *Bull. Amer. Meteor. Soc.*, **76**, 681-695.

(8) Climate Analysis Center, 1995 ENSO winter impacts, California flooding, mild to the East. NOAA Special Climate Summary - 95/1.

(9) Hansen, J. A., Lacis, R. Ruedy, and M. Sato, 1992: Potential climate impact of Mount Pinatubo eruption, *Geophys. Res. Lett.,* **19**, 215-218,

(10) Myneni, R. B., C. D. Keeling, C. J. Tucker, G. Asrar, and R. R. Nemani, 1997: Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature*, **386**, 698-702.

(11) Gumley, L. E., and M. D. King, 1995: Remote sensing of flooding in the US upper midwest during summer of 1993. *Bull. Amer. Meteor. Soc.*, **76**, 933-943.

Acknowledgments

Writer

David Herring, EOS AM-1 Science Outreach Coordinator, Science Systems and Applications, Inc.

Main Contributors

Yoram Kaufman, EOS AM-1 Project Scientist
Jim Collatz, EOS AM-1 Deputy Project Scientist
Francesco Bordi, EOS AM-1 Project Office Liaison, Computer Sciences Corp.
Jon Ranson, EOS AM-1 Deputy Project Scientist

Layout and Design

Winnie Humberson, Raytheon STX Corp.

Editorial Board

John Hraster, Earth System Sciences Program Office Director
Michael King, EOS Senior Project Scientist
Vince Salomonson, Earth Sciences Directorate Chief
Yoram Kaufman, EOS AM-1 Project Scientist
Chris Scolese, EOS AM-1 Project Manager
Charlotte Griner, EOS Senior Editor, Raytheon STX Corp.
Blanche Meeson, Assistant Director for Earth Sciences Education and Outreach

Additional Manuscript Reviewers and Contributors

Bill Bandeen, Raytheon STX Corp.
Bruce Barkstrom, CERES Team Leader
Dave Diner, MISR Team Leader, Jet Propulsion Lab.
Jim Drummond, MOPITT Team Leader, U. of Toronto
Renny Greenstone, Raytheon STX Corp.
Anne Kahle, ASTER Team Co-Leader, Jet Propulsion Lab.
Ralph Kahn, MISR Team Member, Jet Propulsion Lab.
Tim Suttles, Raytheon STX Corp.

For additional copies, contact Charlotte Griner at cgriner@pop900.gsfc.nasa.gov.

For more information on EOS AM-1, access the Web page at http://modarch.gsfc.nasa.gov/EOS-AM.

MODIS Technical Specifications

Orbit:	705 km, 10:30 a.m. descending node (AM-1) or 1:30 p.m. ascending node (PM-1), sun-synchronous, near-polar
Scan Rate:	20.3 rpm, cross track
Swath Dimensions:	2330 km (across track) by 10 km (along track at nadir)
Telescope:	17.78 cm diam. off-axis, afocal (collimated), with intermediate field stop
Size:	1.0 × 1.6 × 1.0 m
Mass:	250 kg
Power:	162.5 W (orbital average)
Data Rate:	10.8 Mbps (peak daytime); 6.2 Mbps (orbital average)
Quantization:	12 bits
Spatial Resolution:	250 m (bands 1-2)
(at nadir):	500 m (bands 3-7)
	1000 m (bands 8-36)
Design Life:	6 years

Primary Use	Band	Bandwidth[1]	Saturation*	Required SNR[2]
Land/Cloud	1	620-670	1.5555	128
Boundaries	2	841-876	1.0490	201
Land/Cloud/Aerosol	3	459-479	1.0696	243
Properties	4	545-565	1.0130	228
	5	1230-1250	0.8420	74
	6	1628-1652	1.0338	275
	7	2105-2155	0.3249	110
Ocean Color/	8	405-420	0.3728	880
Phytoplankton/	9	438-448	0.2593	838
Biogeochemistry	10	483-493	0.1913	802
	11	526-536	0.1580	754
	12	546-556	0.1243	750
	13	662-672	0.0750	910
	14	673-683	0.0748	1087
	15	743-753	0.0741	586
	16	862-877	0.0599	516
Atmospheric	17	890-920	0.7490	167
Water Vapor	18	931-941	1.1422	57
	19	915-965	0.8447	250
Cirrus Clouds	26	1.360-1.390	0.8944	1504

Primary Use	Band	Bandwidth[1]	Saturation*	Required NEΔT(K)[3]
Surface/Cloud	20	3.660-3.840	333	0.05
Temperature	21	3.929-3.989	429	2.00
	22	3.929-3.989	329	0.07
	23	4.020-4.080	329	0.07
Atmospheric	24	4.433-4.498	318	0.25
Temperature	25	4.482-4.549	314	0.25
Water Vapor	27	6.535-6.895	323	0.25
	28	7.175-7.475	320	0.25
	29	8.400-8.700	330	0.05
Ozone	30	9.580-9.880	364	0.25
Surface/Cloud	31	10.780-11.280	399	0.05
Temperature	32	11.770-12.270	391	0.05
Cloud Top	33	13.185-13.485	335	0.25
Altitude	34	13.485-13.785	341	0.25
	35	13.785-14.085	339	0.25
	36	14.085-14.385	371	0.35

* Saturation for bands 1-19 & 26 are given in reflectance values; bands 20-25 & 27-36 are given in kelvins.

[1] Bands 1 to 19, nm; Bands 20-36, µm

[2] SNR = Signal-to-noise ratio

[3] NEΔT = Noise-equivalent temperature difference

} Performance goal is 30-40% better than required

MISR Technical Specifications

Orbit:	705 km, 10:30 a.m. descending node, sun-synchronous, near-polar
Swath Dimensions:	360 km (cross-track overlap at all nine view angles)
Cameras:	Nine CCD-based pushbroom imagers with refractive superachromatic f/5.5 telecentric lenses
Camera Names/: View/Angles	An 0.0° (nadir)
	Af 26.1° (afward of nadir)
	Aa 26.1° (afward of nadir)
	Bf 45.6° (forward of nadir)
	Ba 45.6° (afward of nadir)
	Cf 60.0° (forward of nadir)
	Ca 60.0° (afward of nadir)
	Df 70.5° (forward of nadir)
	Da 70.5° (afward of nadir)
Spectral Bands:	Blue 425.4-467.3 nm
	Green 543.2-571.8 nm
	Red 660.7-682.6 nm
	Near IR 846.5-886.2 nm
	(Solar weighted, measured in-band response)
Polarization Sensitivity:	<1%
Radiometric Uncertainty:	3% of absolute radiance at full signal
Signal-to-Noise Ratio:	>700 at full signal at highest spatial resolution
Size:	90 × 90 × 130 cm
Mass:	149 kg
Power:	72 W (typical orbital average) 83 W (worst case orbital average)
Data Rate:	3.3 Mbps (orbital average)
Quantization:	14 bits linear, compressed by square-root encoding to12 bits
Spatial Sampling:	275 m, 550 m, or 1.1 km (individually commandable for each channel)
Design Life:	6 years

Application	**Primary Bands**	**Primary Cameras**
Radiometric Cloud Detection	Red, Near IR	All
Stereoscopic Cloud Detection and Classification	Red	Af, An, Aa
Cirrus Cloud Detection	Blue, Red, Near IR	Df, Cf, Ca, Da
Marine Aerosols	Red, Near IR	All
Land Aerosols	All	All
Surface/Cloud Bidirectional Reflectance Factors and Albedos	All	All
Land Cover Classification	All	All
Marine Phytoplankton	Blue, Green	Bf, Ba

MOPITT Technical Specifications

Orbit:	705 km, 10:30 a.m. descending node (AM-1), sun-synchronous, near-polar
Scan Rate:	12 sec per swath
Swath Dimensions:	640 km
Telescope:	N/A
Size:	102.9 × 75.1 × 43.6 cm
Mass:	192 kg
Power:	260 W
Data Rate:	27 kbps
Quantization:	N/A
Sensitivity:	10 ppbv for CO, 12 ppbv at 1200 ppbv for CH_4
Spatial Resolution:	22 km at nadir
Design Life:	6 years
Heritage Instruments:	Pressure-modulated cell elements used in the Pressure-Modulated Radiometer (PMR), Stratospheric and Mesospheric Sounder (SAMS), and Improved Stratospheric and Mesospheric Sounder (ISAMS) instruments, using similar correlation spectroscopy techniques.

Primary Use	Channel	Bandwidth (µm)	Modulator Type	Cell Pressure (mb)	Cell Temperature (K)	Cell Length (mm)
CO Profiles	1	4.562-4.673	LMC1	200	300	2-10
CO Column (Total Burden)	2	2.323-2.345	LMC1	200	300	2-10
CO Profiles	3	4.562-4.673	PMC1	50-100	300	10
CH_4 Column (Total Burden)	4	2.223-2.294	LMC2	800	300	2-10
CO Profiles	5	4.562-4.673	LMC3	800	300	2-10
CO Column (Total Burden)	6	2.323-2.345	LMC3	800	300	2-10
CO Profiles	7	4.562-4.673	PMC2	25-50	300	10
CH_4 Column (Total Burden)	8	2.223-2.294	LMC4	800	300	2-10

LMC = Length modulated cell
PMC = Pressure modulated cell

CERES Technical Specifications

Orbit:	705 km altitude, 10:30 a.m. descending node (AM-1) or 1:30 p.m. ascending node (PM-1), sun-synchronous, near-polar; 350 km altitude, 35° inclination (aboard TRMM)
Spectral Bands:	Shortwave: 0.3-5.0 μm Window: 8-12 μm Total: 0.3 to >200 μm
Swath Dimensions:	Limb to limb
Field of View (FOV):	± 78° cross-track scan and 360° azimuth biaxial scan
Instrument IFOV:	14 mrad
Spatial Resolution:	20 km at nadir
Mass:	45 kg (per instrument)
Duty Cycle:	100%
Power:	45 W (average power per instrument)
Data Rate:	20 kbps (both instruments)
Size:	60 × 60 × 70 cm (deployed)
Design Life:	6 years

Spectral Region	**Primary CERES Data Products (most require cloud imager and 4-D assimilation data)**
0.3-5.0 μm	Top-of-the-Atmosphere reflected solar fluxes Clear sky and cloud-reflected fluxes Shortwave Cloud Radiative Forcing Clear-Sky and Cloudy-Sky Albedo Shortwave surface energy budget Solar radiative heating within the atmosphere column Shortwave Aerosol Radiative Forcing
8-12 μm	Atmospheric window radiative fluxes Longwave window cloud radiative forcing Atmospheric Greenhouse effect
0.3 to >200 μm	Top-of-the-Atmosphere thermal emitted longwave fluxes Clear sky and cloud longwave fluxes Longwave Cloud Radiative Forcing Longwave surface energy budget Longwave radiative heating within the atmosphere column Longwave aerosol radiative forcing

ASTER Technical Specifications

Orbit:	705 km, 10:30 a.m. descending node, sun-synchronous, near-polar		
Mass:	405 kg		
Power:	463 W (average), 570 W (peak)		
	VNIR	**SWIR**	**TIR**
Spectral Resolution:	15 m	30 m	90 m
Data Rate:	62 Mbps	23 Mbps	4 Mbps
Cross-track Pointing:	±24°	±8.55°	±8.55°
Cross-track Pointing (km):	±318 km	±116 km	±116 km
Swath Width:	60 km	60 km	60 km
Quantization:	8 bits	8 bits	12 bits
Size:	58 × 65 × 83 cm	72 × 134 × 90 cm	73 × 183 × 110 cm
Design LIfe:	6 years	6 years	6 years
Stereo:	Yes	No	No

Wavelength Region	**Band**	**Bandwidth (µm)**	**Primary Purpose**	**Saturation (W/m2/sr/µm)**
VNIR	1	0.52-0.60	Land/Cloud Properties	427
	2	0.63-0.69	Land/Cloud Properties	358
	3	0.76-0.86	Land/Cloud Properties	218
SWIR	4	1.60-1.70	Clouds, Surface Composition	55
	5	2.145-2.185	Surface Composition	17.6
	6	2.185-2.225	Surface Composition	15.8
	7	2.235-2.285	Surface Composition	15.1
	8	2.295-2.365	Surface Composition	10.6
	9	2.360-2.430	Surface Composition	8
TIR	10	8.125-8.475	Surface Temperature/Composition	Radiance of 370 k blackbody
	11	8.475-8.825	Surface Temperature/Composition	Radiance of 370 k blackbody
	12	8.925-9.275	Surface Temperature/Composition	Radiance of 370 k blackbody
	13	10.25-10.95	Surface Temperature/Composition	Radiance of 370 k blackbody
	14	10.95-11.65	Surface Temperature/Composition	Radiance of 370 k blackbody

Inside pocket for the backcover

4” h x 7.5” top w x 8.5” bottom W