MONITORING EARTH'S VITAL SIGNS

A new NASA satellite—one of a fleet called the Earth Observing System—is using five state-of-the-art sensors to diagnose the planet's health like never before

by Michael D. King and David D. Herring

Flying 705 kilometers above the earth's surface, a satellite called Terra is conducting a comprehensive health examination of our world. Everything from clouds and plants to sunlight and temperature and fire and ice influences climate, and Terra is just beginning to collect this information every day over the entire earth. As the bus-size satellite circles the globe from pole to pole, its sensitive instruments track the planet's vital signs as each region comes into view.

Certain environmental changes are occurring today at rates never seen in our planet's recent history. Imagine, for instance, the hundreds of fires set deliberately every year to clear land for agriculture, a practice that has quadrupled during the past century. Humans today burn an average of 142,000 square kilometers of tropical forests—an area roughly the size of Arkansas—every year. Some of Terra's sensors can track the flames and gauge their intensity, whereas others measure the extent of burn scars and observe how smoke particles and gases move through the atmosphere. One of these sensors can even distinguish changes at a resolution of 15 meters—a view close enough to pick out spots where smoldering embers may again burst into flame.

Terra is the flagship of the Earth Observing System (EOS), a National Aeronautics and Space Administration satellite program that will bring scientists closer to deciphering the earth's climate well enough to predict future changes—a charge that requires an unprecedented ability to differentiate natural cycles from changes that people create. Natural geologic forces, such as volcanic eruptions, variations in ocean currents and cycles of ice ages, have been rearranging the surface and climate of our planet since its formation 4.5 billion years ago. But today compelling scientific evidence illustrates that human activities are speeding up the rate of global change and have even attained the magnitude of a geologic force [see "The Human Impact on Climate," by Thomas R. Karl and Kevin E. Trenberth; SCIENTIFIC AMERICAN, December 1999].

We need to make many measurements all over the world, over a long period, in order to supply computer simulations with the right information to enable us to forecast climate change. To that end, we and our EOS colleagues identified 24 factors that together play a major role in determining climate. These factors include the flux of sunlight and other radiant energy, concentrations of greenhouse gases, snow and ice cover, clouds and aerosols, and changes in vegetation and other land-surface features. The Terra mission is designed to measure 16 of those 24 characteristics [*see list on page 74*].

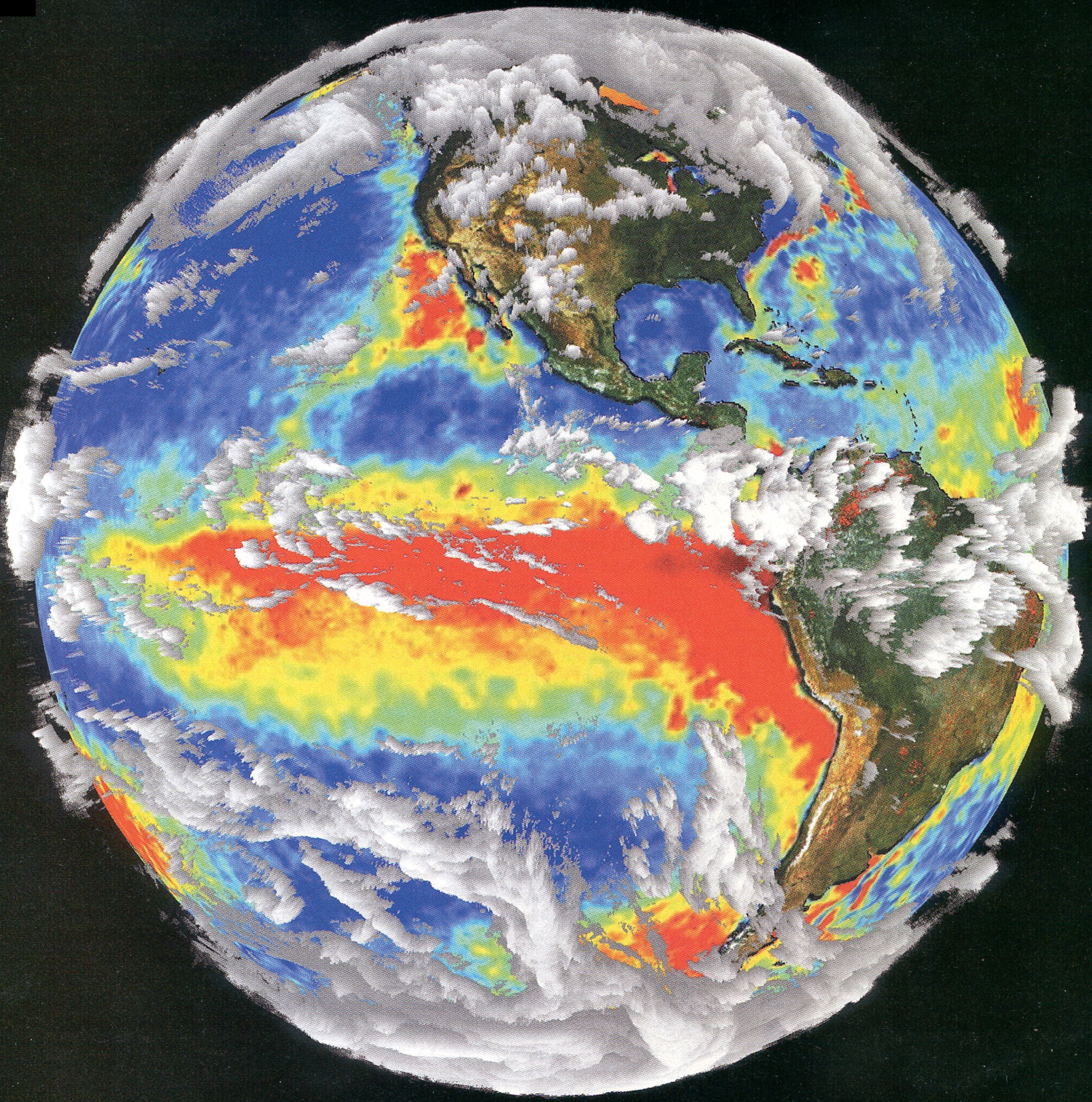
In 1988 NASA's Earth System Sciences Committee issued a report calling for a long-term strategy for measuring the earth's vital signs. This committee emphasized that the only feasible way to monitor these signs consistently for a long time is by using satellite-borne sensors that can "see" the earth from space [see "Earth from Sky," by Diane L. Evans, Ellen R. Stofan, Thomas D. Jones and Linda M. Godwin; SCIENTIFIC AMERICAN, December 1994]. Consequently, in 1991, NASA initiated the Earth Observing System, and the U.S. Congress has since earmarked $7.4 billion to design and implement the program through October 2001. Our team devoted $1.3 billion to building and launching Terra, the newest member of the EOS fleet.

A New Generation of Remote Sensors

Terra rocketed into orbit on December 18, 1999, and specialists now guide its flight and control its sensors from a command center at the NASA Goddard Space Flight Center in Greenbelt, Md. Terra's sensors are not actively scanning the surface as do instruments that transmit laser or radar beams and track the way they bounce off the planet's surface. Terra's sensors are passive, much like a digital camera.

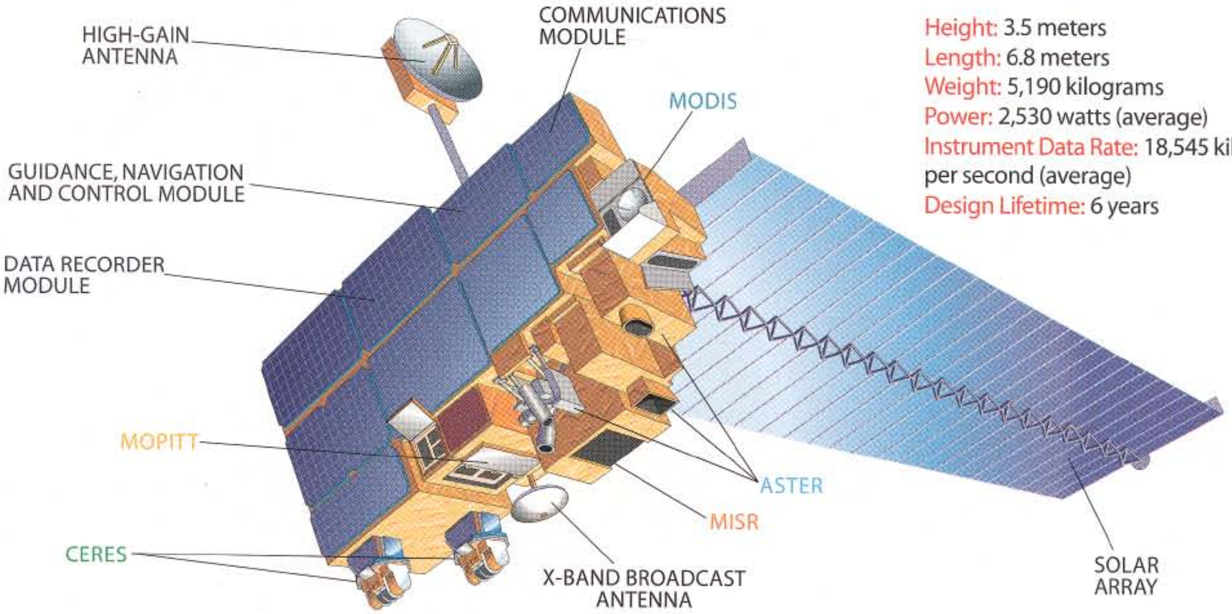
Packets of energy—sunlight and infrared light—escape the earth's atmosphere and pass through the sensors' apertures. Those energy packets then strike specially designed detectors that are sensitive to discrete wavelengths of electromagnetic energy. Similar to the way we can tune into different stations on a car radio, Terra's spectroradiometers enable researchers to detect different wavelengths of radiant energy. If those wavelengths are red, green and

IMAGE SYNTHESIZED BY R.B. HUSAR *Washington University*



LAYERS OF CLIMATE CHARACTERISTICS are just beginning to be collected by the Terra satellite every day over the entire planet. Previous satellite sensors tracked the vital signs that form this synthesized image of vegetation (*green on continents*), forest fires (*red dots on continents*), ocean temperature (*colors over oceans*) and cloud cover. The warm waters of the Pacific Ocean (*red*), off the western coast of South America, are a telltale sign of an El Niño event.

Terra and Its Five Climate-Monitoring Sensors



Height: 3.5 meters
Length: 6.8 meters
Weight: 5,190 kilograms
Power: 2,530 watts (average)
Instrument Data Rate: 18,545 kilobytes per second (average)
Design Lifetime: 6 years

ALL TERRA SENSOR ILLUSTRATIONS BY GEORGE RETSECK

Vital Signs That Terra Will Measure

AEROSOLS
AIR TEMPERATURE
CLOUDS
FIRES
GLACIERS
LAND TEMPERATURE
LAND USE
NATURAL DISASTERS
OCEAN PRODUCTIVITY
OCEAN TEMPERATURE
POLLUTION
RADIATION
SEA ICE
SNOW COVER
VEGETATION
WATER VAPOR

ICONS BY LAURIE GRACE

blue, they can easily make a color image that our eyes can see. If the measured wavelengths are invisible, such as those in the infrared or ultraviolet portions of the spectrum, scientists must assign them a visible color to make a "false-color" image that our eyes can interpret.

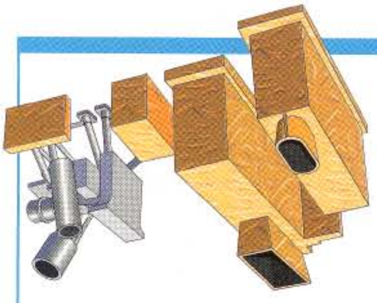
The EOS missions rely on two integral components in addition to the satellites: a system for storing the information and people to interpret it. Already the project supports some 850 scientists at government agencies and academic institutions around the world. What the satellites beam back to the earth is a voluminous stream of numbers—tens of trillions of bytes of information each week—that must be processed to become meaningful. An advanced computer network, called the EOS Data and Information System (EOSDIS), receives and processes the numbers. Four centers across the U.S. then archive the measurements from Terra and distribute them to scientists and civilians alike.

This free sharing of data contrasts sharply with many past satellite missions, for which public access was largely inaccessible to all but the highest-funded research organizations. A single image from the Landsat satellites, the first of which was launched in 1972, can cost hundreds or even thousands of dollars. Some of Terra's data, on the other hand, will be broadcast on X-band directly to anyone who has a compatible receiving station and the capacity to process and store such a huge flow of information. A variety of commercial markets can benefit from EOS data. Satellite maps of high productivity in the ocean, for instance, can guide commercial fishing outfits to likely concentrations of fish. In a similar fashion, images of agricultural fields will help farmers judge where crops are thriving and where they may be under stress. Such images can help farmers visualize patterns of runoff for particular fields and, in turn, refine their strategies for where, when and how much to irrigate and fertilize.

More Eyes in the Sky

In addition to Terra, three other EOS satellites are already orbiting the globe and measuring other vital signs of the climate, such as changes in the sun's energy output and winds blowing over the oceans. If these instruments survive their predicted lifetimes, and if Congress continues to fund the EOS effort, these satellites will be followed by 15 or more others, and together they will generate a 15-year global data set. To make accurate climate predictions, we will need such measurements spanning several decades.

Integrating observations from the sensors on board Terra and the other EOS satellites will make it possible to disentangle the myriad causes and effects that determine climate. Monitoring how patterns of deforestation correlate with rainfall and cloud cover, for example, will help researchers assess how the loss of trees affects regional water cycles. Com-



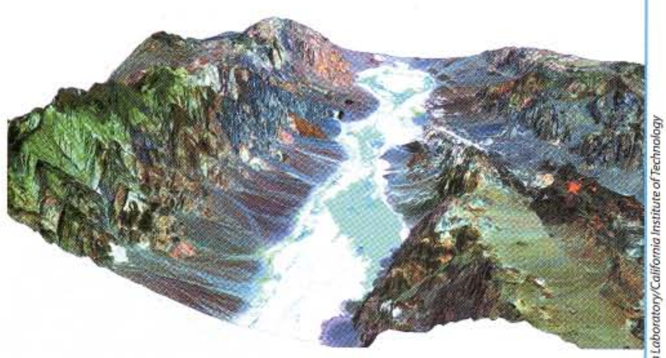
ASTER

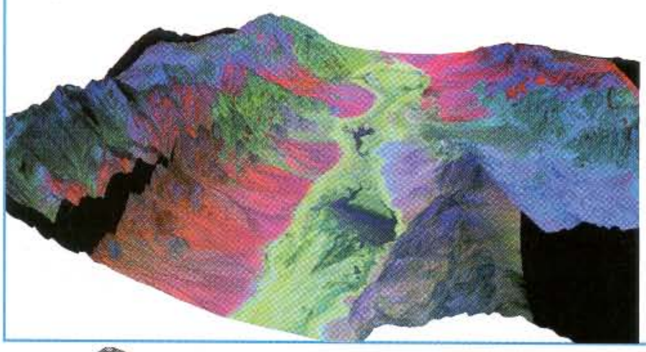
Advanced Spaceborne Thermal Emission and reflection Radiometer

Vital Signs Measured:

Unique Characteristics: Highest spatial resolution of all Terra sensors and the unique ability to point toward special targets
Sensors: Three distinct telescope subsystems that monitor wavelengths in the visible and near infrared, shortwave infrared, and thermal infrared portions of the spectrum
Sponsor: Japanese Ministry of International Trade and Industry
Spatial Resolution: Ranging from 90 to 15 meters

The earth's land surfaces emit energy and temperatures that ASTER measures at ultrahigh resolution. These vital signs are key to estimating the planet's radiation budget and will be particularly useful for identifying rocks, soils and vegetation. Farmers can use such high-resolution, multispectral images to assess the way changes in surface temperature, ground slope and soil type impact the health of their crops. ASTER can also monitor ongoing changes in other surface features—such as receding glaciers and ice sheets, expanding desert boundaries, deforestation, floods and wildfires—which will help researchers distinguish between natural changes and those that humans cause. Because ASTER's telescopes can be tilted toward erupting volcanoes and other special targets, they can generate detailed stereoscopic images that will greatly refine digital topographic maps of the planet. These images will extend the collection that the Landsat satellites have been gathering since 1972.





ROCKS AND VEGETATION come to false-color life in this simulated ASTER image of a 60-kilometer-wide swath of Death Valley, Calif. One sensor detects thermal infrared light (*left*), which highlights the composition of the land surface: rocks rich in quartz are red, salt deposits are light green, and so on. Shorter-wavelength infrared light and visible light recorded over the same scene (*above*) show vegetation as green, water as blue and iron-rich volcanic rocks as orange smudges.

COURTESY OF MICHAEL ABRAMS *Jet Propulsion Laboratory/California Institute of Technology*

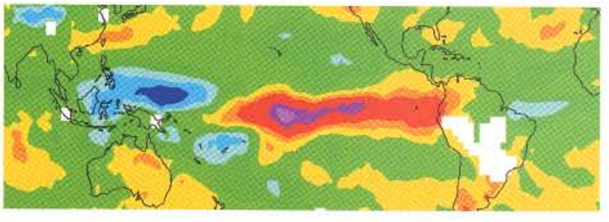
CERES

Clouds and the Earth's Radiant Energy System

Vital Signs Measured:

Unique Characteristic: First satellite sensor to record radiation fluxes throughout the atmosphere
Sensors: Two broadband scanning radiometers
Sponsor: NASA Langley Research Center
Spatial Resolution: 20 kilometers

Predicting global temperature change requires a keen understanding of how much radiation, in the form of heat and sunlight, enters and leaves the earth's atmosphere. Yet to date, researchers cannot account for about 8 percent of incoming solar radiation once it enters the atmosphere. One explanation for the missing energy is that clouds and aerosols—tiny particles of smoke and dust—absorb energy and scatter it in the lower atmosphere, where satellites that track the energy fluxes have never looked. To better quantify the roles that clouds play in the earth's energy system, CERES (with input from MODIS) will measure the flux of radiation twice as accurately as previous sensors, both at the top of the atmosphere and at the planet's surface. The CERES instruments extend the heritage begun by NASA's Earth Radiation Budget Experiment (ERBE) satellite sensors, which flew in the 1980s.



EARLY CERES sensors recorded the largest changes yet observed in radiation emitted to space from the eastern Pacific Ocean in February 1998. Warmer waters, generated at the peak of an El Niño event, increased the occurrence of cumulonimbus clouds, which in turn trapped more of the heat radiating from the ocean and the lower atmosphere (*red*).

TAKMENG WONG *NASA Langley Research Center* paring similar measurements from more than one sensor will help ensure that all instruments are seeing the same signals and that onboard calibration devices are working properly. Researchers will also compare the satellite measurements with those gleaned from dozens of other instruments based in aircraft, on ships and buoys, and on the ground.

The process of diagnosing climate takes hundreds of hours of computer time. The first four-dimensional "snapshot" of our planet will probably not be ready until next winter, and scientists may need many years after that to complete the first thorough statistical evaluation. The earth's climate system is intricately interconnected. What we have described here only scratches the surface of what the Terra mission can accomplish. Many of its contributions will undoubtedly prove to be serendipitous as innovative studies and new applications emerge in the years ahead. SA

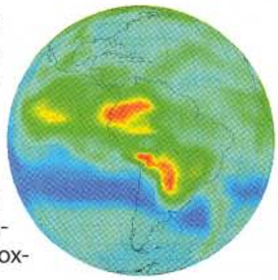
MOPITT

Measurements Of Pollution In The Troposphere

Vital Sign Measured:

Unique Characteristic: First satellite sensor to trace pollutants to their source
Sensor: Scanning radiometer that uses gas correlation spectroscopy
Sponsor: Canadian Space Agency
Spatial Resolution: 22 kilometers

Two trace gases won't escape MOPITT, which measures the global distribution and concentration of methane and carbon monoxide in the lower atmosphere. Methane—a greenhouse gas with nearly 30 times the heat-trapping capacity of carbon dioxide—is known to leak from swamps, livestock herds and icy deposits under the seafloor, but the output of these individual sources is not known. One way or another, methane is gathering in the lower atmosphere at a rate of about 1 percent a year. Carbon monoxide, which is expelled from factories, automobiles and forest fires, hinders the atmosphere's natural ability to rid itself of other harmful chemicals. The first satellite sensor to use gas correlation spectroscopy, MOPITT can distinguish these two gases from others, such as carbon dioxide and water vapor. As emitted heat or reflected sunlight enters the sensor, it passes through onboard containers of carbon monoxide and methane, producing a signal that correlates with the presence of these gases in the atmosphere.



CARBON MONOXIDE gathers over South America in this computer simulation. High concentrations of the gas (*red* and *yellow*) originate from fires set to clear forests, and easterly winds at the equator transport it over the Pacific Ocean.

NCAR/MOPITT TEAM, CANADIAN SPACE AGENCY

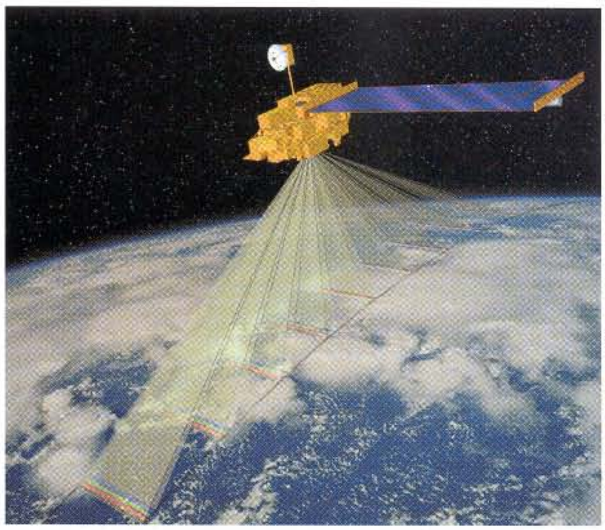
MISR

Multiangle Imaging SpectroRadiometer

Vital Signs Measured:

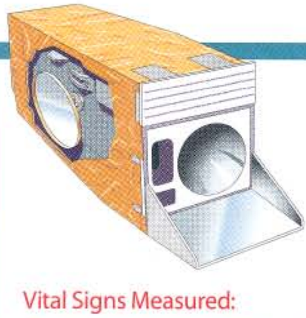
Unique Characteristic: Produces stereoscopic images of clouds and smoke plumes
Sensors: Nine charge-coupled device (CCD) cameras
Sponsor: Jet Propulsion Laboratory
Spatial Resolution: Ranging from 1.1 kilometers to 275 meters

No instrument like MISR has ever flown in space. Viewing the sunlit earth simultaneously at nine widely spaced angles, MISR collects global images of reflected sunlight in four colors (blue, green, red and near-infrared). The way the reflections change from one view angle to another will make it possible to distinguish different types of clouds, aerosols and land surfaces. Researchers can combine MISR images with stereoscopic techniques to design three-dimensional models that will help them trace aerosols and smoke plumes back to their sources. And as MISR covers the globe at the equator once every nine days, its multiangle measurements will enable researchers to better interpret the roles that clouds and aerosols play in the planet's energy budget.



NINE SIMULTANEOUS VIEWING ANGLES make it possible for MISR to measure stereoscopically the interactions among aerosols, clouds and radiation.

COURTESY OF SHIGERU SUZUKI AND ERIC M. DE JONG *Solar System Visualization Project, Jet Propulsion Laboratory*



MODIS

MODerate-resolution Imaging Spectroradiometer

Vital Signs Measured:

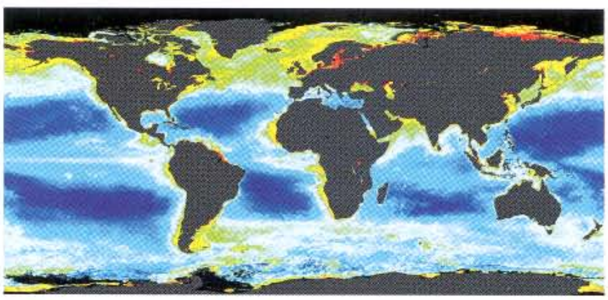
Unique Characteristic: Only Terra sensor to see the entire planet's surface every one to two days

Sensors: Four sets of detectors that are sensitive to visible light and to radiation in the near, shortwave, midwave and thermal portions of the infrared spectrum

Sponsor: NASA Goddard Space Flight Center

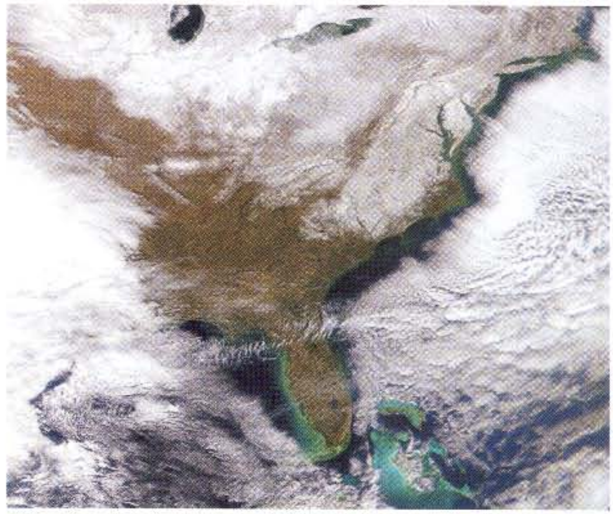
Spatial Resolution: Ranging from 1 kilometer to 250 meters

Seeing the entire globe in 36 discrete spectral bands, MODIS tracks a wider array of the earth's vital signs than any other Terra sensor. For instance, the sensor measures the percentage of the planet's surface that is covered by clouds almost every day with its sweeping 2,330-kilometer-wide viewing swath. This wide spatial coverage will enable MODIS, together with MISR and CERES, to determine the impact of clouds on the planet's energy budget—an important contribution considering that clouds remain the greatest area of uncertainty in global climate models. The sensor has an unprecedented channel (centered at 1.375 microns) for detection of wispy cirrus clouds that are believed to contribute to global warming by trapping heat emitted from the surface. MODIS will also monitor how smoke plumes and other aerosols mingle with clouds and alter their ability to absorb and reflect energy.



CHLOROPHYLL in microscopic ocean plants strongly reflects green light (*shown above as yellow, red and green*), which makes it possible for satellites such as SeaWiFS to track their abundance. MODIS will go a step further by monitoring how intensely the plants fluoresce, a signal of their productivity.

As it monitors global cloud cover, MODIS will also help investigators track changes to the land surface. The sensor is mapping the extent of snow and ice brought by winter storms and frigid temperatures, and it will observe the "green wave" sweep across continents as winter gives way to spring and vegetation blooms in response. It will see where and when disasters strike—such as volcanic eruptions, floods, severe storms, droughts and wildfires—and will help guide people out of harm's way. MODIS's bands are particularly sensitive to fires; they can distinguish flaming from smoldering burns and provide better estimates of the amounts of aerosols and gases they release into the atmosphere.



SNOW COVER, such as this scene imaged by NASA's SeaWiFS satellite after the January 25 blizzard in the eastern U.S., is one of many climate factors that MODIS measures.

The sensor is also ideal for monitoring large-scale changes in the biosphere that will yield new insights into the workings of the global carbon cycle. Although no current satellite sensor can measure directly carbon dioxide concentrations in the atmosphere, MODIS can quantify the photosynthetic activity of plants to estimate how much of the greenhouse gas they are absorbing. In addition, the sensor will take a sophisticated look at the marine biosphere by measuring the fluorescent glow of chlorophyll in the ocean [*see image at left*].

SeaWiFS PROJECT, NASA GODDARD SPACE FLIGHT CENTER

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Further Information

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Visit NASA's Earth Observatory Web site at http://earthobservatory.nasa.gov