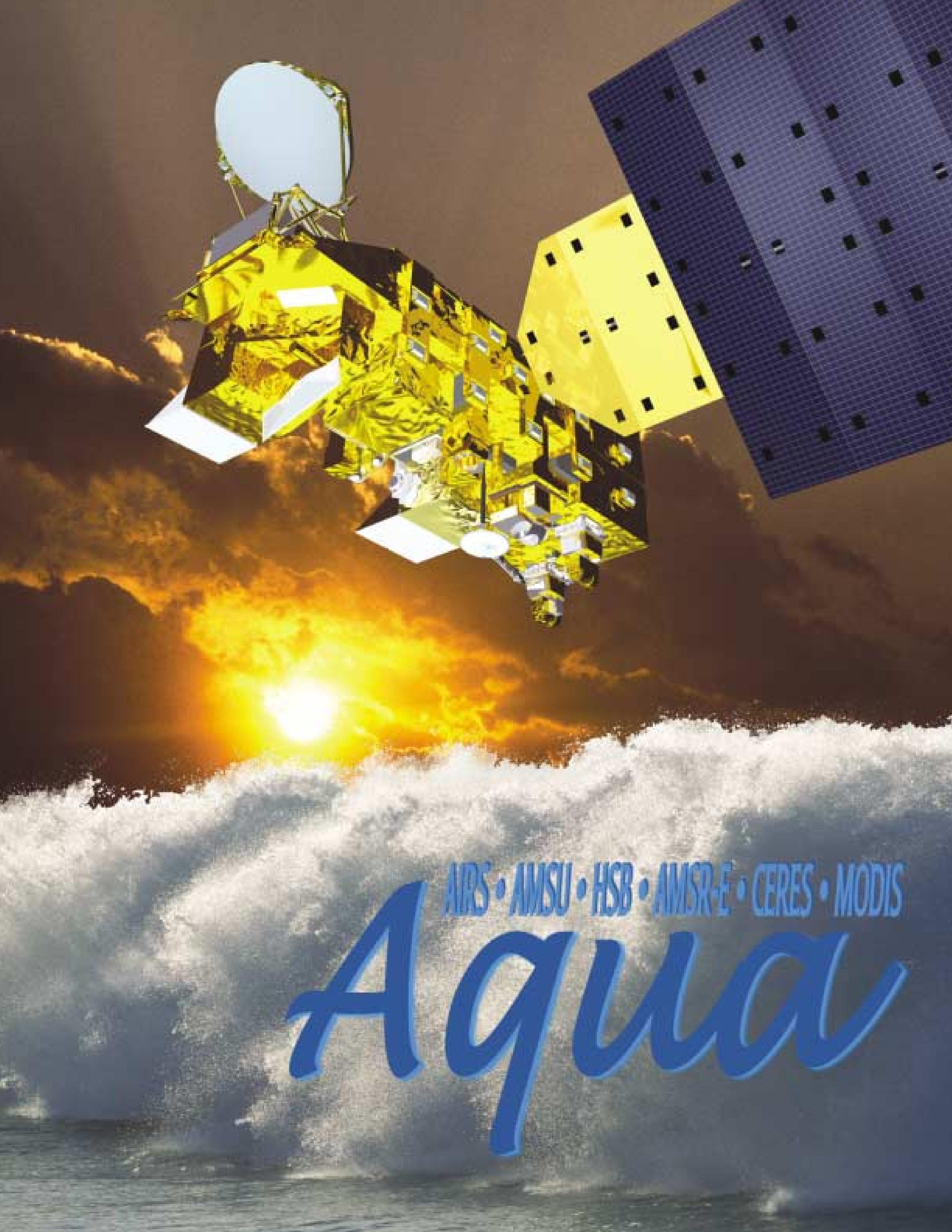

AIRS • AMSU • HSB • AMSR-E • CERES • MODIS
Aqua

Aqua at TRW, August 2001, being positioned for lowering into the thermal vacuum chamber. (Photo by Sally Aristei.)

Front cover: The computer rendering of the Aqua spacecraft was done by Reto Stöckli, based on earlier versions by TRW.

Aqua

MONITORING THE EARTH'S WATER CYCLE AND ASSOCIATED VARIABLES FROM THE VANTAGE OF SPACE

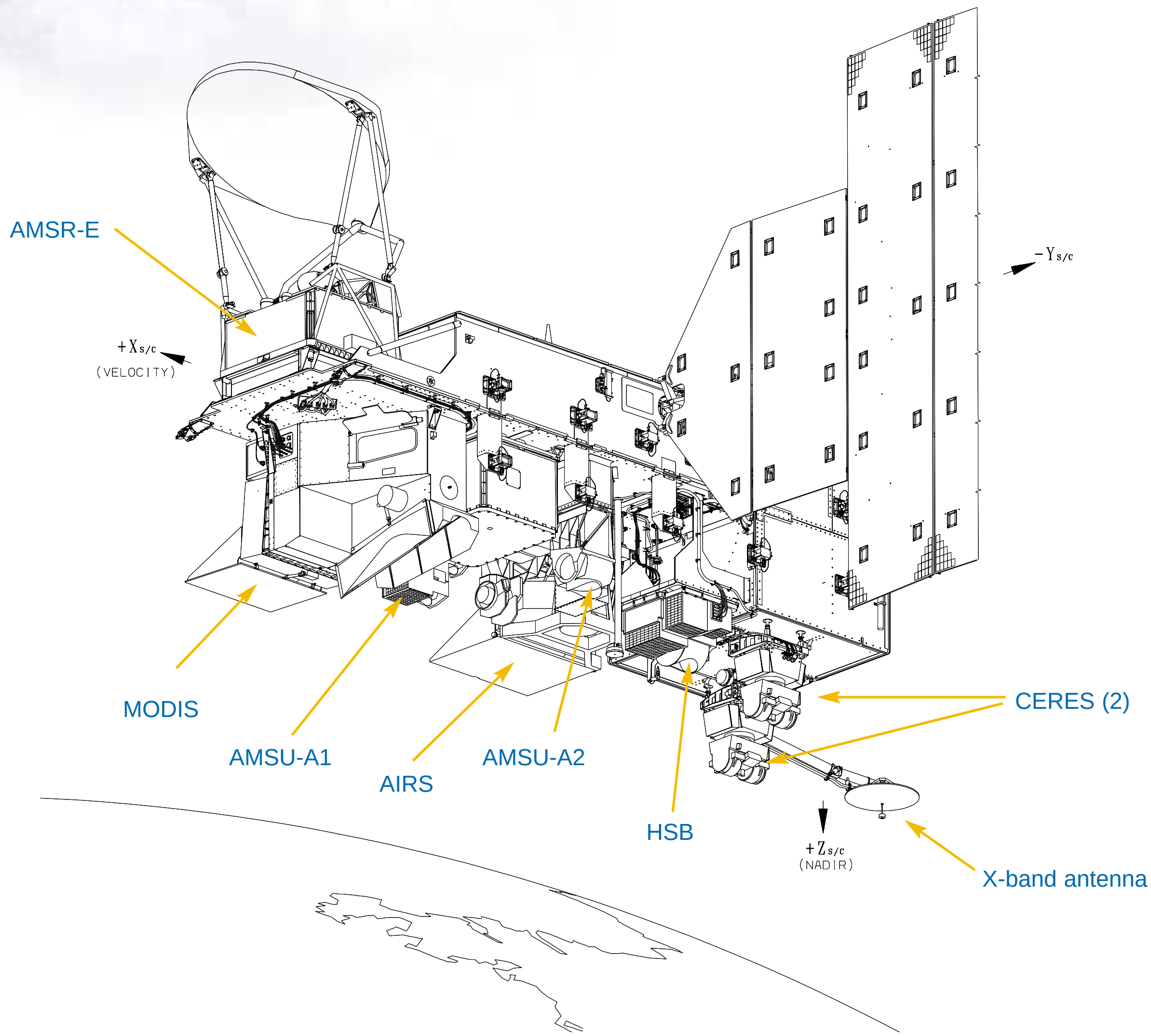
Photos of the Aqua spacecraft at TRW in Redondo Beach, California, with all instruments on board. After launch, the solar array will be unfurled, instrument doors will be opened, and antennas will be deployed, with the resulting configuration indicated in the line drawing on p. 2. (Photos courtesy of TRW.)

Aqua Overview

Issues of climate and climate change have considerable relevance to all species of life on Earth. Furthermore, they have received much publicity over the past many years, particularly because of the realization that humans could be having unintended and perhaps detrimental impacts. Nonetheless, the understanding of the Earth / atmosphere system remains inadequate to sort out with certainty human from non-human impacts on long-term climate or to predict with high confidence the likely course of climate changes over the next several decades.

Aqua is a satellite mission aimed at improving our understanding of the Earth / atmosphere system, along with changes occurring within it, through the monitoring and analysis of dozens of Earth variables from a space-based platform orbiting the Earth. Aqua is part of the Earth Observing System (EOS), an international Earth-focused satellite program centered at the United States (U.S.) National Aeronautics and Space Administration (NASA).

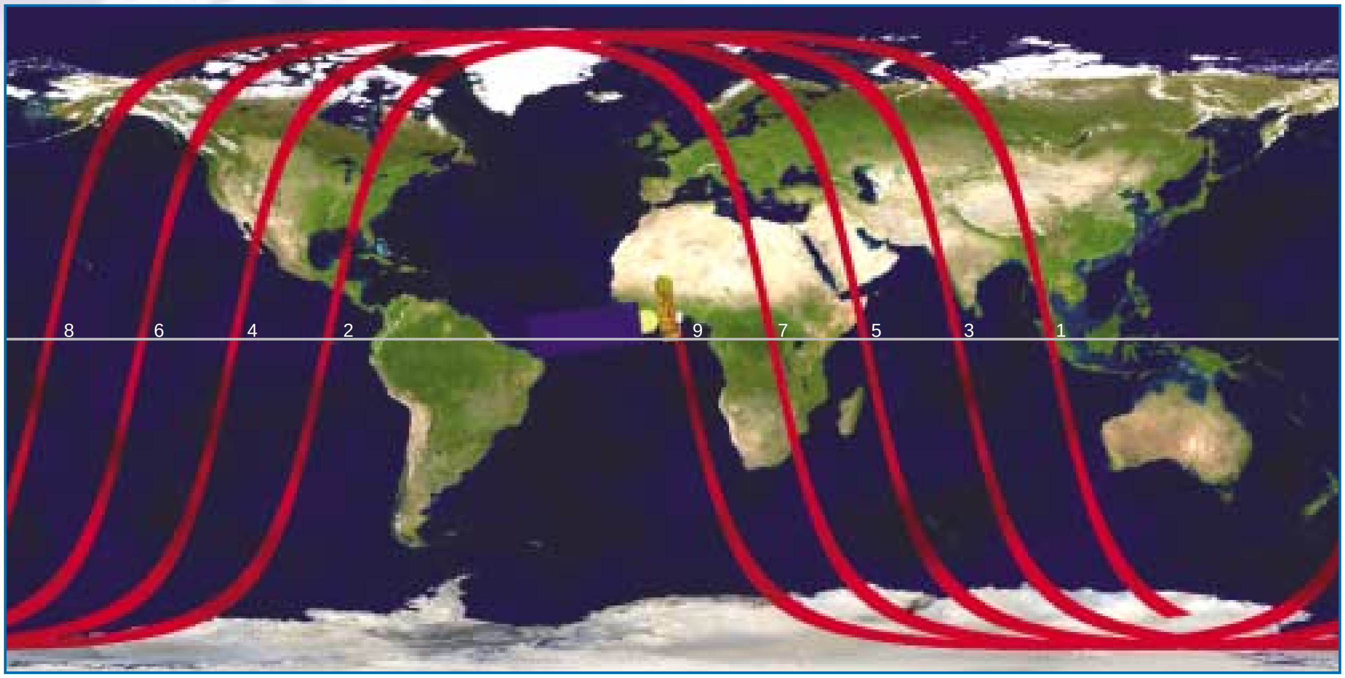
"Aqua" being Latin for "water", the Aqua mission is named for the large amount of information it will collect about the Earth's water cycle, including ocean surface water, evaporation from the oceans, water vapor in the atmosphere, clouds, precipitation, soil moisture, sea ice, land ice, and snow cover on the land and ice. Additional variables also being measured by Aqua include radiative energy fluxes, atmospheric aerosols, vegetation cover on the land, phytoplankton and dissolved organic matter in the oceans, and air, land, and water temperatures. One particularly exciting benefit anticipated from Aqua is an improvement in weather forecasting resulting from the Aqua atmospheric temperature and water vapor profiles.



Line drawing of the deployed Aqua spacecraft, with the six Earth-observing instruments and the X-band antenna labeled. As indicated, the Advanced Microwave Sounding Unit (AMSU) has two physically separated parts, the AMSU-A1 and the AMSU-A2; these work together as a single unit. Also, the solar array in the upper right portion of the drawing extends outward much farther, about 14 m, when fully deployed. (Line drawing courtesy of TRW, with labels added later.)

Schematic of the water cycle.

The importance of water to the Earth's climate and to the millions of species of life living on the Earth is enormous. This importance and the abundance of water at the Earth's surface combine to make appropriate the labeling of the Earth as the "water planet." Liquid water covers approximately 70% of the Earth's surface and is essential to humans and all other known life forms. Gaseous water, in the form of atmospheric water vapor, is the Earth's primary greenhouse gas, helping to maintain the Earth's atmosphere within a temperature range conducive to life as we know it. Solid water, in the form of ice and snow, helps control polar climates, for instance by reflecting back to space much of the solar radiation incident on it and in winter insulating the underlying land and oceans from the cold polar atmosphere. Evaporation of water involves the absorption of energy, which is later released to the atmosphere as the resultant water vapor condenses into liquid or solid form. The energy released helps power the atmospheric circulation. Patterns of sea surface temperature also influence atmospheric temperatures and circulations, with these patterns changing noticeably, especially in the tropical Pacific, between, for instance, El Niño and La Niña conditions. Aqua measurements will provide information on all of these elements of the global water cycle and should contribute toward answering some of the open questions regarding the extent to which snow, ice, clouds, and water vapor enhance or suppress global and regional temperature changes and other aspects of climate change.



The Aqua spacecraft will carry six major Earth-observing instruments and will be launched from Vandenberg Air Force Base in California, on board a Delta II 7920 - 10L launch vehicle. The launch is scheduled for no earlier than April 18, 2002. Once the spacecraft is launched, it will be maneuvered into a near-polar orbit at an altitude of 705 kilometers, with the satellite orbiting the Earth every 98.8 minutes and crossing the equator on its northward journey at 1:30 p.m. local time and on its southward journey at 1:30 a.m. local time. This will allow collection of afternoon data (as well as 1:30 a.m. data), complementary to the collection of morning data (about 10:30 a.m.) by the EOS Terra satellite launched in December 1999. In order to emphasize the afternoon / morning contrast, the Aqua and Terra missions were originally named EOS-PM and EOS-AM, respectively.

The six Earth-observing instruments on Aqua are:

- Atmospheric Infrared Sounder (AIRS)
- Advanced Microwave Scanning Radiometer for EOS (AMSR-E)
- Advanced Microwave Sounding Unit (AMSU)
- Clouds and the Earth’s Radiant Energy System (CERES)
- Humidity Sounder for Brazil (HSB)
- Moderate Resolution Imaging Spectroradiometer (MODIS)

Technically, the spacecraft will be carrying eight Earth-observing instruments, as it has two identical copies of the CERES and the AMSU consists of two physically separate units, the AMSU-A1 and AMSU-A2. Also, Aqua carries several additional instruments, to run the spacecraft, format and store the data, and send the data to the ground. Using standard satellite terminology, however, the

Schematic of the Aqua orbit, with nine consecutive passes over the equator labeled sequentially. Aqua will orbit the Earth at an altitude of 705 km and will approach but not pass directly over the North and South Poles. As the satellite passes northward across the equator, it will do so at 1:30 p.m. local time, then, 49.4 minutes later, as it passes southward across the equator on the opposite side of the Earth, it will do so at 1:30 a.m. local time. (Schematic by Jesse Allen.)

Aqua spacecraft is generally said to have six instruments, as listed above. Of these, the AMSR-E is provided by Japan, the HSB is provided by Brazil, and the other four instruments plus the spacecraft, the launch vehicle, and the launch are provided by the United States.

Five science teams have worked for years developing methods (or "algorithms") to convert the Aqua data into meaningful geophysical parameters. These teams are organized by instrument, with one U.S. team each for the AMSR-E, CERES, and MODIS, and one team for the instrument triplet of AIRS, AMSU, and HSB, three atmospheric sounders whose data will be used in a closely coupled manner to derive final products. There is also a Japanese science team for the AMSR-E and the companion AMSR to be launched on board the Japanese Advanced Earth Observing Satellite II (ADEOS II), scheduled for launch in late 2002. Another critically important component of the Aqua program and the larger EOS program is the EOS Data and Information System (EOSDIS), which will handle much of the Aqua data flow once it arrives, generating, storing, and distributing many of the data products.

Aqua's solar array prior to its final installation on the Aqua spacecraft. After launch, the array will be unfurled, stretching 14 m outward from the spacecraft bus. (Photo by Claire Parkinson.)

The different sides of Aqua, from the TRW cleanroom.

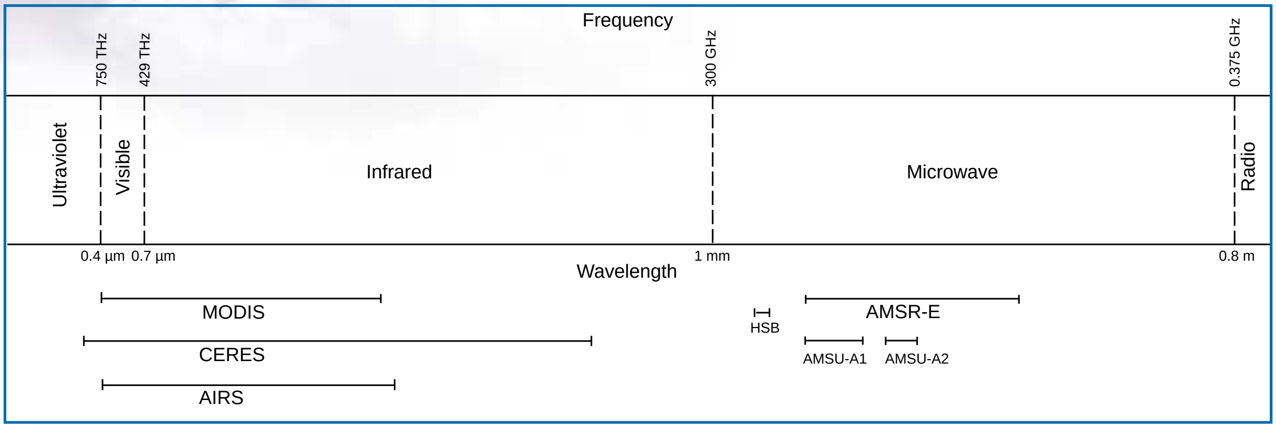
Space-viewing side, with the star trackers prominent in the middle right and the AMSR-E antenna prominent at the top. (Photo by Sally Ariistei.)

Earth-viewing side, with most of the Earth-observing instruments clearly visible. (Photo by Sally Aristei.)

The different sides of Aqua, from the TRW cleanroom.

Solar array side prior to the installation of the solar array panel. (Photo by Claire Parkinson.)

Side opposite the solar array, with, left to right, the AMSR-E, MODIS, AMSU-A1, AIRS (with a white protective covering), and CERES (with purge covers) instruments partially visible. (Photo by Claire Parkinson.)



Schematic of the portion of the electromagnetic spectrum being measured by Aqua, with the measurement ranges for each of the Aqua instruments indicated. Numbers above the band are frequencies, and numbers below the band are wavelengths. (Schematic by Claire Parkinson and Winnie Humberson.)

Radiation, the Electromagnetic Spectrum, and Aqua

Like all Earth-observing satellite instruments, the Aqua instruments directly measure only radiation. Furthermore, the Aqua instruments are all "passive" in that they do not send a signal out and receive it back, as would, for instance, a radar system, but instead simply record and transmit radiation coming to them. It is from these radiation data that researchers attempt to derive information about the Earth and its atmosphere. The six Aqua instruments measure radiation at ultraviolet, visible, infrared, and microwave wavelengths, in some cases at individual wavelengths and in others throughout wavelength bands.

Near-infrared ("near" because of being near the visible wavelengths), visible, and all shorter wavelengths are considered "shortwave," while much longer wavelengths, including all microwave wavelengths, are considered "longwave." Within the Earth system, natural shortwave radiation comes predominantly from the sun, whereas longwave radiation is predominantly from the Earth. Hence satellite instruments measuring longwave radiation can do so irrespective of whether there is sunlight illuminating the scene. In contrast, the amount of solar illumination is a critical factor for visible observations. For most visible observations, solar illumination is essential, although for a few, such as the observation of city lights at night, solar illumination is a hindrance.

By having instruments covering some ultraviolet, visible, infrared, and microwave wavelengths, researchers will be able to use Aqua data to address a much wider range of Earth science topics than if all the data came from a more limited segment of the electromagnetic spectrum. For instance, the visible data will allow determination of cloud coverage in any daylit portion of the globe, but at the same time, the very property of visible data that allows them to depict clouds hinders them from obtaining unobscured surface data from surfaces under the clouds. In contrast, radiation at many microwave frequencies travels through most clouds nearly unhindered, so that the microwave satellite data can reveal information about the Earth's surface even in the presence of a substantial cloud cover. This tremendous advantage of microwave data for surface observations, however, comes with a cost: by being at lower frequencies and longer wavelengths than the visible data, the microwave data generally have much coarser spatial resolutions. This means, for instance, that microwave measurements can be used to monitor snow cover daily, irrespective of cloud cover or the amount of sunlight, but at a coarse spatial detail, while on those days with daylight and minimal cloud coverage, visible measurements can obtain a much more detailed picture of the snow coverage. By having both types of measurements, the Aqua mission increases its potential for leading to improved understandings and more complete monitoring of the Earth / atmosphere system.

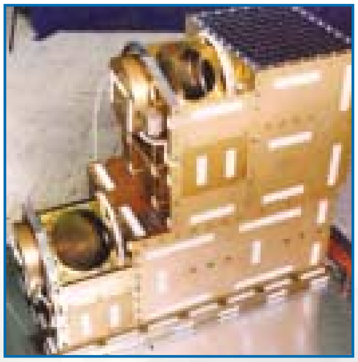
The Aqua Instruments and Their Measurements

Atmospheric Infrared Sounder (AIRS), Advanced Microwave Sounding Unit (AMSU), Humidity Sounder for Brazil (HSB)

AIRS is a high-resolution infrared sounder with its central purpose being to obtain atmospheric temperature and humidity profiles from the surface upward to an altitude of 40 km. The AIRS instrument has 2,382 channels, measuring visible and infrared radiation at wavelengths between 0.4 and 15.4 µm, with 2378 of the channels measuring in the infrared range 3.74-15.4 µm and the remaining four channels measuring in the visible / near-infrared range 0.4-1.1 µm. AIRS will provide infrared information at a 13.5 km horizontal resolution at nadir (directly below the satellite) and visible / near-infrared information at a 2.3 km horizontal resolution at nadir. Data collected for off-nadir locations will have coarser resolutions. The AIRS instrument is expected to provide substantial improvements, especially in the temperature measurements, over any previous sounder flown in space.

AIRS. (Photo courtesy of BAE Systems.)

The AIRS instrument is joined on Aqua by two instruments closely coupled to it. One is the AMSU, also labeled AMSU-A and consisting of two physically separate units, labeled AMSU-A1 and AMSU-A2. The AMSU will aid in the atmospheric temperature profiling, especially for the upper atmosphere. AMSU will provide temperature measurements up to an altitude of 40 km, plus a cloud-filtering capability for observations in the troposphere, the portion of the atmosphere from the surface to an altitude of approximately 12 km, a height varying with location and time. The troposphere contains by far the majority of the Earth's cloud cover. AMSU has 15 channels, measuring radiation in the frequency span of 23-90 GHz. Twelve channels (measuring between 50 and 60 GHz) are predominantly for atmospheric temperature sounding, while the remaining three channels (measuring at 24, 31, and 89 GHz) are predominantly for atmospheric water vapor and precipitation estimates. Horizontal resolutions of the AMSU data are approximately 40.5 km at nadir. Earlier AMSU instruments have flown successfully on satellites of the National Oceanic and Atmospheric Administration (NOAA), beginning with the NOAA-15 satellite launched in May 1998. The precursor Microwave Sounding Unit (MSU), first launched in October 1978, flew on the Television Infrared Observation Satellite-N (TIROS-N) and on NOAA 6 through NOAA 14.



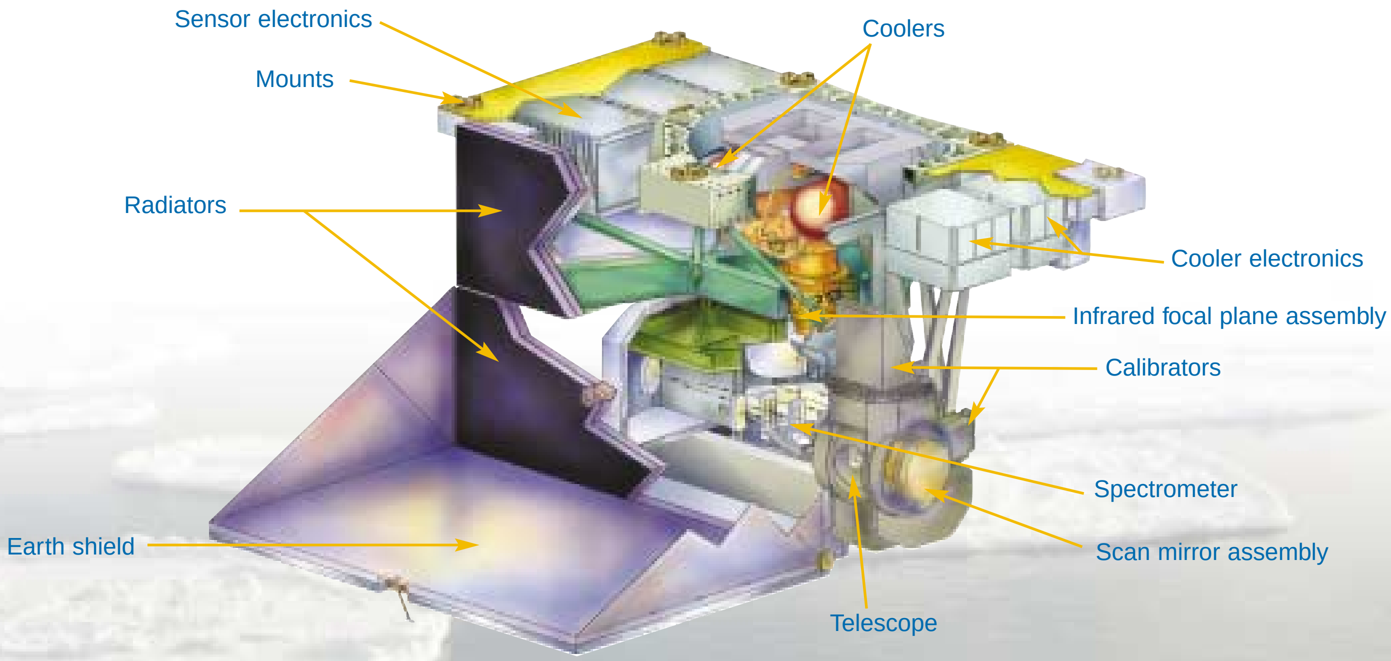
AMSU-A1. (Photo courtesy of Aerojet.)

The other Aqua instrument closely coupled to the AIRS is the HSB. The HSB will obtain humidity soundings through the atmosphere, for determining cloud liquid water, precipitation, and integrated precipitable water. The HSB is particularly important for allowing the AIRS / AMSU / HSB complement to obtain accurate humidity profiles under overcast conditions. HSB is a four-channel radiometer, with one channel measuring radiation at 150 GHz and the other three channels measuring radiation at 183.31 GHz. The horizontal resolution of the HSB data is 13.5 km at nadir. The HSB is a modified version of the AMSU-B flown on NOAA satellites along with the AMSU-A1 and AMSU-A2 beginning with NOAA 15 in May 1998. The AMSU-B will be replaced by a similar instrument, the Microwave Humidity Sounder (MHS), beginning with NOAA 17 in 2002.

The AIRS / AMSU / HSB complement has been constructed to obtain atmospheric temperature profiles to an accuracy of 1 K for every 1 km layer in the troposphere and an accuracy of 1 K for every 4 km layer in the stratosphere (the atmospheric layer immediately above the troposphere) up to an altitude of 40 km. The 1 K accuracy for every 1 km layer in the troposphere will match the temperature accuracy of radiosondes launched upward from the ground for individual profiles, but the AIRS / AMSU / HSB system will have a huge advantage over radiosondes in terms of the frequency and global coverage of the measurements. In conjunction with the temperature profiles, the AIRS / AMSU / HSB system will obtain humidity profiles to an accuracy of 10% in 2 km layers from the surface up through the troposphere.

AMSU-A2, installed on the Aqua spacecraft. (Photo by Dave Stroud.)

HSB. (Photo courtesy of Instituto Nacional de Pesquisas Espaciais.)



Labeled schematic of the AIRS instrument. (Schematic courtesy of BAE Systems, with labels added later.)

Other variables that will also be calculated from the AIRS / AMSU / HSB data are land and sea surface skin temperatures, surface albedo (or reflectance), fractional cloud coverage, cloud-top pressure, cloud-top temperature, cloud spectral properties, cloud liquid water, integrated precipitable water, the trace gases ozone, methane, carbon dioxide, and carbon monoxide, surface net longwave and shortwave fluxes, and top-of-the-atmosphere outgoing longwave and shortwave radiative fluxes. The longwave and shortwave observations are of course limited to the wavelengths that the AIRS, AMSU, and HSB instruments measure.

Data Products from AIRS/AMSU/HSB

Level 1A Radiance Counts (for AIRS, AMSU, and HSB separately)
Level 1B Calibrated, Geolocated Radiances (for AIRS, AMSU, and HSB separately)
Level 2 Cloud-Cleared Radiances

Radiative Flux Product:	Clear-column Radiance Outgoing Longwave Radiation at the Top of the Atmosphere Outgoing Shortwave Radiation at the Top of the Atmosphere Net Longwave Flux at the Surface Net Shortwave Flux at the Surface
Atmospheric Temperature Product:	Temperature Profile through the Atmosphere (30 levels) Tropopause Height Stratopause Height
Humidity Product:	Water Vapor Profile through the Atmosphere Total Precipitable Water Cloud Liquid-Water Content Precipitation Indication Cloud-Ice Indication
Cloud Product:	Cloud-Top Pressure Cloud-Top Temperature Fractional Cloud Cover Cloud Spectral Properties Cloud Type
Ozone Product:	Ozone Profile through the Atmosphere Total Ozone
Trace Constituent Product:	Total Carbon Dioxide Total Carbon Monoxide Total Methane
Surface Analysis Product:	Sea Surface Skin Temperature Land Surface Skin Temperature Infrared Surface Emissivity Microwave Surface Emissivity Surface Albedo

Each of these products is described in the *EOS Data Products Handbook,* Volume 2.

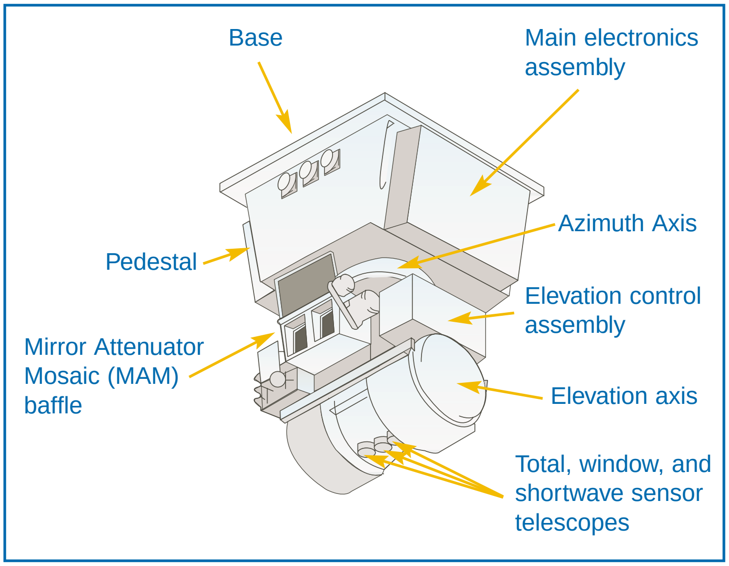
Clouds and the Earth's Radiant Energy System (CERES)

CERES is a broadband, scanning radiometer measuring the shortwave and total radiation outgoing from the Earth system at the top of the atmosphere, plus the radiation outgoing from a prominent atmospheric window (where there is little atmospheric absorption). The aim of the CERES scientists is to determine the fluxes of radiative energy, or radiation, out of the Earth / atmosphere system and within the system and to use those fluxes to examine the radiative forcing of climate and climate change, including the radiative forcing from clouds. The latter presents a major climate measurement challenge, as the effect of clouds on climate is the ensemble of thousands of cloud systems, so that average changes as small as 2 W / m^2 are important at the same time that individual clouds can change local radiation fields by as much as 1000 W / m^2.

The two CERES instruments, being worked on in a cleanroom at TRW. (Photo courtesy of TRW.)

The CERES instrument has the following three channels, each measuring a broad band of radiation:

(1) A 0.3-5 µm channel measuring shortwave, solar radiation reflected from the Earth / atmosphere system back toward outer space. This channel provides a direct measurement of the outgoing shortwave radiation at the location of the satellite (top-of-the-atmosphere flux) and information also on shortwave cloud radiative forcing and shortwave aerosol radiative forcing.



Labeled schematic of the CERES instrument. (Relabeled from a schematic courtesy of Kory Priestley.)

(2) A channel spanning wavelengths from 0.3 µm to greater than 100 µm, measuring top-of-the-atmosphere total reflected and emitted radiative energy in those wavelengths, which cover the majority of the Earth's emitted radiation. The difference between the measurements from this channel and the shortwave radiation channel provides a measure of the broadband thermal emitted radiation and information on longwave cloud forcing.

(3) An 8-12 µm channel measuring top-of-the-atmosphere radiation emitted in the major 8-12 µm atmospheric window. This atmospheric window is dominated by emission from the Earth's surface and lower atmosphere.

The combination of the CERES broadband thermal emitted radiation from 0.3 µm to greater than 100 µm and window thermal emitted radiation from 8 µm to 12 µm allows an improved isolation of the greenhouse effect of gases such as water vapor. CERES data in combination with data from the AIRS will allow the first direct measurement of the far-infrared emission at wavelengths from 15 µm to 100 µm. These wavelengths are dominated by the greenhouse effect of upper tropospheric water vapor.

Several of the CERES data products are highly integrated and are early examples of multi-instrument and multi-spacecraft capabilities. For example, cloud and aerosol properties determined from the MODIS sensor will be carefully matched to each CERES field of view. Four-dimensional fields of temperature and humidity profiles will also be matched to the CERES observations. Finally, 3-hourly geostationary satellite data will be merged with CERES observations on the Terra and Aqua spacecraft to improve the diurnal sampling of radiation fields. All of these data will be merged to produce the most consistent picture yet of surface and atmospheric properties and of radiative fluxes from the surface, through the atmosphere, to the top of the atmosphere, where they are constrained against the direct CERES observations. The CERES data will have a horizontal resolution at nadir of 20 km, and gridded data products will be analyzed at 1° resolution.

Aqua will carry two CERES instruments, the fourth and fifth CERES to fly in space. The first CERES was launched in November 1997 on board the Tropical Rainfall Measuring Mission (TRMM) satellite, and the next two CERES were launched in December 1999 on Terra. The TRMM and Terra CERES have obtained levels of accuracy never before achieved for comprehensive Earth radiation-budget measurements. All the CERES instruments have the capability of operating in either of two scanning modes: fixed azimuth plane scanning, where the scan lines are perpendicular to the path of the satellite, and rotating azimuth plane scanning, where the scan lines are at a wide range of angles with respect to the satellite's path. The paired CERES on Terra and on Aqua provide both of those missions with the possibility of coincident

Schematic of the CERES scan lines as the Aqua satellite passes over South America. The scan lines from the CERES operating in the fixed azimuth plane scanning mode are all perpendicular to the orbital ground track, systematically lined up like a TV raster scan. The scan lines from the CERES operating in the rotating azimuth plane scanning mode appear closer to pinwheels when mapped onto the Earth, sampling a wide range of viewing angles. (Schematic courtesy of TRW.)

fixed azimuth plane scanning from one CERES and rotating azimuth plane scanning from the other CERES, enhancing the quality of the final products.

The main precursor instrument to CERES was the Earth Radiation Budget Experiment (ERBE) in the 1980s and 1990s. The CERES efforts have benefited tremendously from the ERBE experience, and the CERES fixed azimuth plane scanning essentially continues the ERBE measurements at improved spatial resolution. The fixed azimuth plane scanning is designed to optimize spatial sampling, imaging the entire Earth. The CERES rotating azimuth plane scanning, in contrast, is designed to optimize the sampling from various viewing angles, in order to convert the radiances measured from the fixed azimuth plane scanning, at one view angle, into appropriate fluxes integrated over all view angles. The angular flux information provided by the rotating azimuth plane scanning greatly improves the accuracy of the derived radiation balance. Furthermore, the CERES instruments have twice the spatial resolution of the ERBE instruments, plus improved instrument calibration.

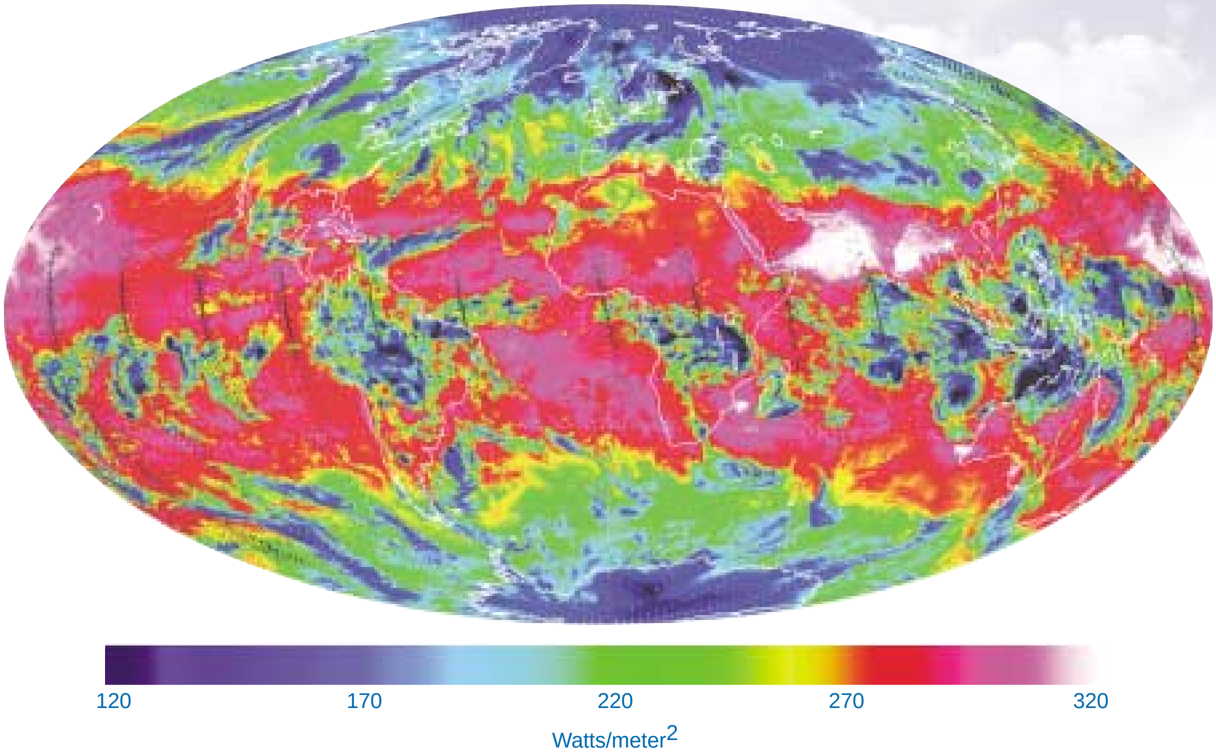
The CERES Science Team has processed and analyzed data from the TRMM and Terra CERES and intercompared the results with results from ERBE. In fact, amongst the CERES data products are “ERBE-like” results that are calculated in the same manner as the ERBE products, specifically to allow well-defined intercomparisons, even though the “ERBE-like” results cannot take full advantage of the CERES advances. Once Aqua is launched, the data from the Aqua CERES will extend the record begun with the TRMM and Terra CERES and, in conjunction with the Terra data, will improve the diurnal sampling of the Earth’s radiation fields. ERBE-like products will continue to be produced, for long-term climate monitoring and climate change studies, while the record of the more advanced CERES products will also lengthen. CERES is a prototype for the operational U.S. National Polar-orbiting Operational Environmental Satellite System (NPOESS), which will continue this climate time series starting in 2009.

Data Products from CERES

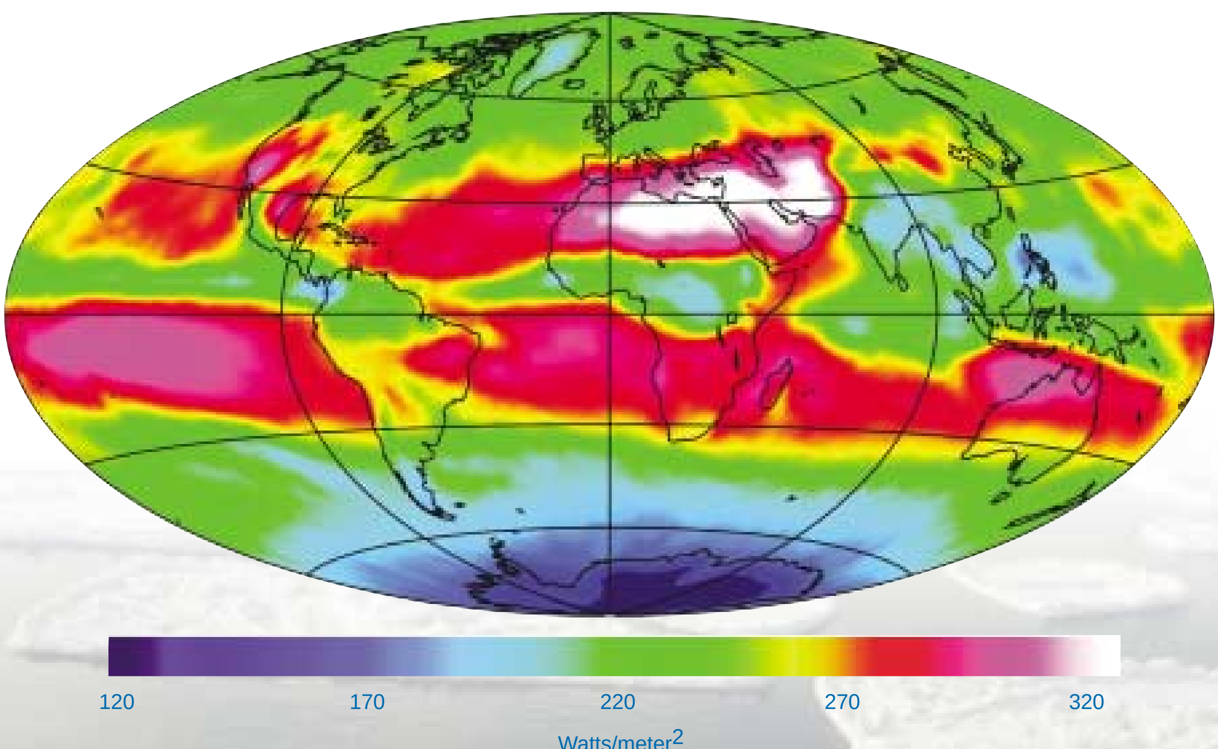
Fluxes of outgoing radiation at the top of the atmosphere
- Shortwave radiation (solar radiation reflected from the Earth / atmosphere system)
- Total radiation (reflected and emitted)
- Longwave radiation (emitted from the Earth / atmosphere system)
- Radiation in the 8-12 micrometer atmospheric window

Fluxes of shortwave and longwave radiation at the Earth’s surface
Fluxes of shortwave and longwave radiation at multiple levels in the atmosphere
Cloud properties (cloud fraction, height, optical depth, particle size, water / ice phase)
Aerosol optical depth

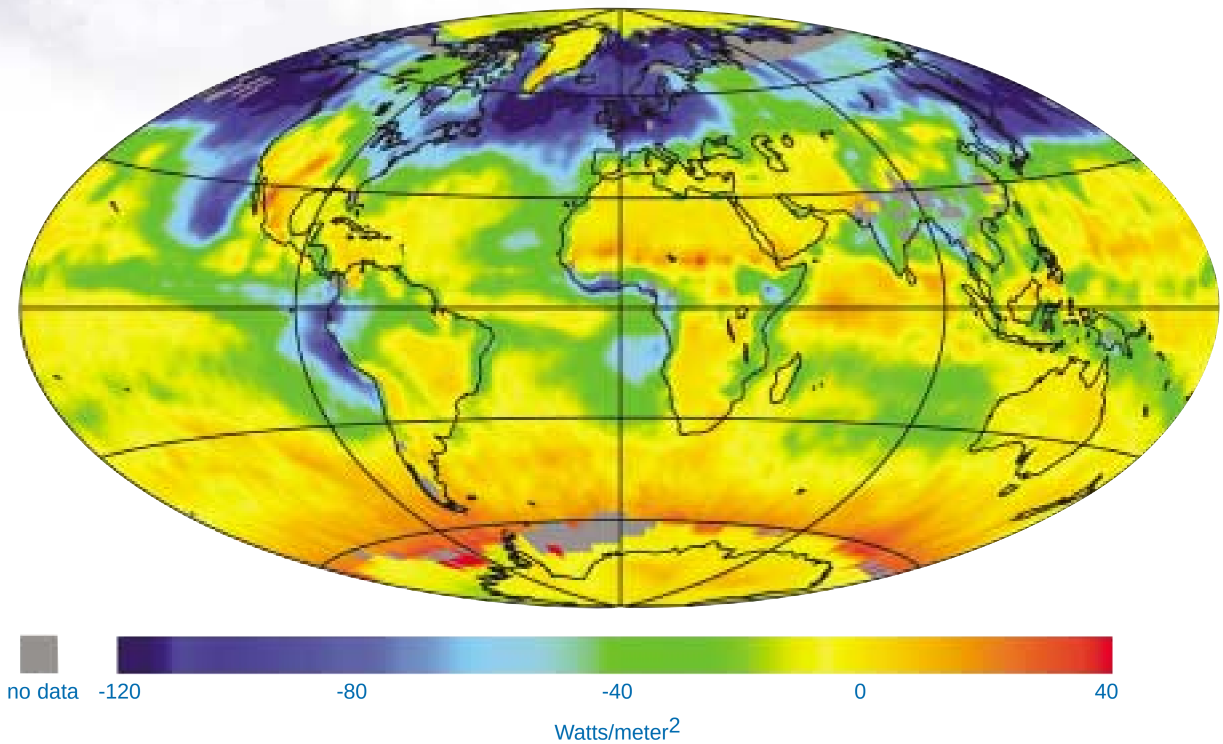
Each of these products is described in the *EOS Data Products Handbook*, Volume 2.



Night-time emitted thermal flux derived from Terra CERES data for March 3, 2000, shortly after the CERES instrument covers were opened. Thermal infrared emission to space increases with increasing emitting temperature of the surface, atmosphere, or cloud and shows large spatial variability. On this day, some of the largest (clear tropical ocean; white) and smallest (thunderstorm; deep blue) thermal fluxes on the Earth are near India and are separated by only a few hundred km. In fact, the lowest thermal flux is not from the polar regions but is from the tops of deep cold thunderstorm clouds in the tropics. (Image courtesy of the CERES Science Team.)



Monthly average longwave flux derived from Terra CERES data for July 2000. Monthly averages smooth out storm systems that are prominent on the CERES images for individual days, highlighting instead major climate features including tropical clouds and equator-to-pole gradients. (Image courtesy of the CERES Science Team.)



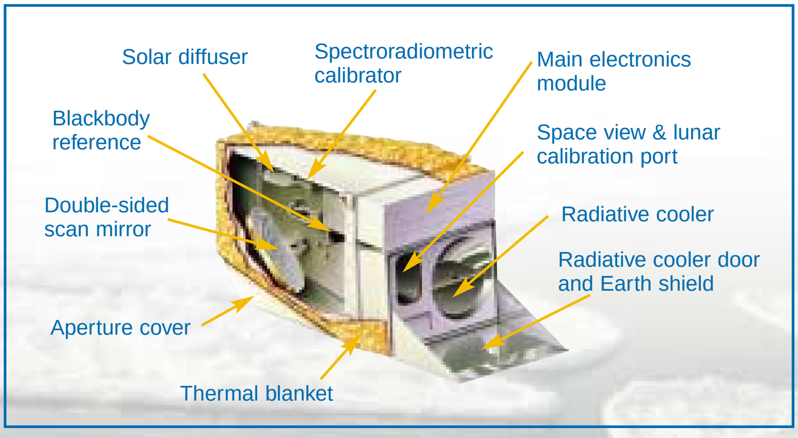
Net cloud radiative forcing for July 2000, as derived from data of the Terra CERES, using ERBE-like fluxes. Clouds cool the Earth by reflecting solar radiation back to space, but warm the Earth by trapping thermal infrared radiation, some of which would otherwise be lost to space. The net of these two effects of clouds on the radiation balance is called the Net Cloud Radiative Forcing. Note the strong cooling effect (negative values) clouds have on the middle and high Northern Hemisphere latitudes during summer. Low level marine boundary layer clouds west of California, Peru, and southern Africa also strongly cool, because of their low altitudes. Net heating by clouds (positive values) occurs for thin high cirrus clouds and can be seen over the African Sahel and some of the southwestern U.S. The positive values seen near Antarctica are highly uncertain, and values in that vicinity will eventually be determined much more accurately with the more advanced Terra CERES and Aqua CERES data products that merge MODIS snow/ice detection and CERES radiative fluxes. (Image courtesy of the CERES Science Team.)

The Moderate Resolution Imaging Spectroradiometer (MODIS)

MODIS is a cross-track scanning radiometer constructed to obtain information about many different biological and physical processes within the Earth / atmosphere system through visible and infrared measurements. In contrast to the focused radiation-budget measurements of CERES, the MODIS measurements are far more wide-ranging and multipurpose. For a sampling, the MODIS data will be used to obtain information on atmospheric temperatures and humidities, cloud coverage, cloud properties, aerosol properties, land and sea surface temperatures, ocean color, ocean sediments, chlorophyll fluorescence, net primary productivity, vegetation indices, land cover and land cover change, natural and human-caused fires, continental snow distribution and depth, and sea ice distribution and surface temperature. MODIS will enable variability in land cover and condition to be monitored daily, at 250 m and 500 m spatial resolutions, thereby allowing improved information to be available about the location and magnitude of deforestation and other alterations in land cover. Land and ocean productivity measures will be produced and combined to give an indication of global primary productivity. Aerosols, which scatter and absorb solar radiation and modify cloud microphysics, will be obtained globally at 10 km resolution, composited from the higher resolution MODIS radiative data. Cirrus clouds will be examined not only to determine their properties, including the extent of thin cirrus cloud coverage, but also to remove these clouds from selected MODIS images in order to provide an unobscured view of the underlying surface.

The MODIS instrument with the radiative cooler door closed. (Photo courtesy of Raytheon.)

The MODIS instrument with the radiative cooler door open. (Photo courtesy of Raytheon.)



Labeled schematic of the MODIS instrument. (Schematic courtesy of Raytheon.)

Data Products from MODIS

Level 1A Radiance Counts
Level 1B Calibrated, Geolocated Radiances
Geolocation Data Set
Processing Framework and Match-Up Database

Atmosphere Products:

- Atmospheric Profiles (including temperature and water vapor)
- Total Ozone
- Total Precipitable Water
- Cloud Microphysical Properties (optical depth, effective particle / drop size, thermodynamic phase)
- Cloud Top Properties (temperature, emissivity, pressure)
- Cloud Mask
- Aerosol Optical Depth
- Aerosol Size Distribution

Ocean Products:

- Normalized Water-Leaving Radiance
- Clear-Water Epsilon
- Ocean Water Attenuation Coefficient
- Absorption Coefficients in the Oceans
- Sea Surface Temperature
- Ocean Primary Productivity
- Coccolith Concentration in the Oceans
- Chlorophyll Fluorescence in the Oceans
- Chlorophyll *a* Pigment Concentration in the Oceans
- Pigment Concentration in the Oceans
- Phycoerythrin Concentration in the Oceans
- Photosynthetically Active Radiation
- Suspended Solids Concentration in the Oceans
- Organic Matter Concentration in the Oceans

Land and Ice Products:

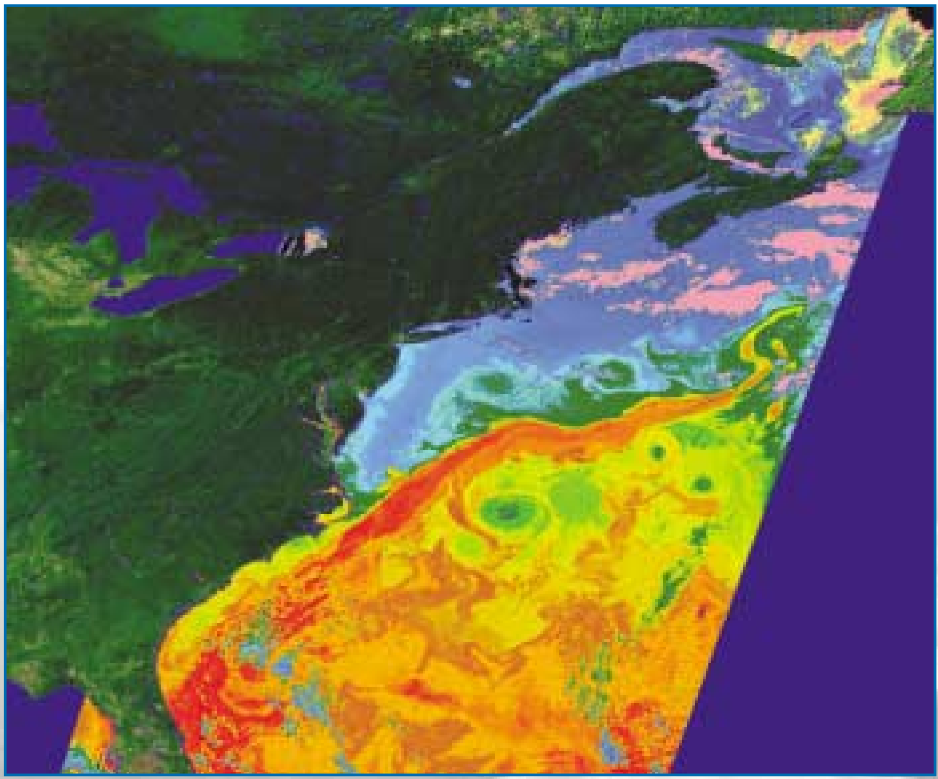
- Land Surface Temperature and Emissivity
- Atmospherically Corrected Surface Reflectance
- Surface Nadir-adjusted Bidirectional Reflectance Distribution Function and Albedo
- Land Cover Type and Land Cover Change
- Leaf Area Index and Fraction of Photosynthetically Active Radiation
- Gridded Vegetation Indices
- Vegetation Production / Net Primary Productivity
- Vegetation Cover Conversion
- Thermal Anomalies – Fires
- Burn Scars
- Sea Ice Cover
- Snow Cover
- Snow and Sea Ice Albedo

Each of these products is described in the *EOS Data Products Handbook,* Volume 2.

MODIS contains 36 data channels, each covering a band of wavelengths of visible and / or infrared radiation, with the full wavelength range being from 0.4 to 14.5 µm. The MODIS data are generated at horizontal resolutions at nadir of 250 m, 500 m, and 1000 m, depending on the particular band and data product. With such resolutions, MODIS provides the most detailed spatial information of all the Aqua instruments, although the surface observations are generally obscured in the presence of clouds.

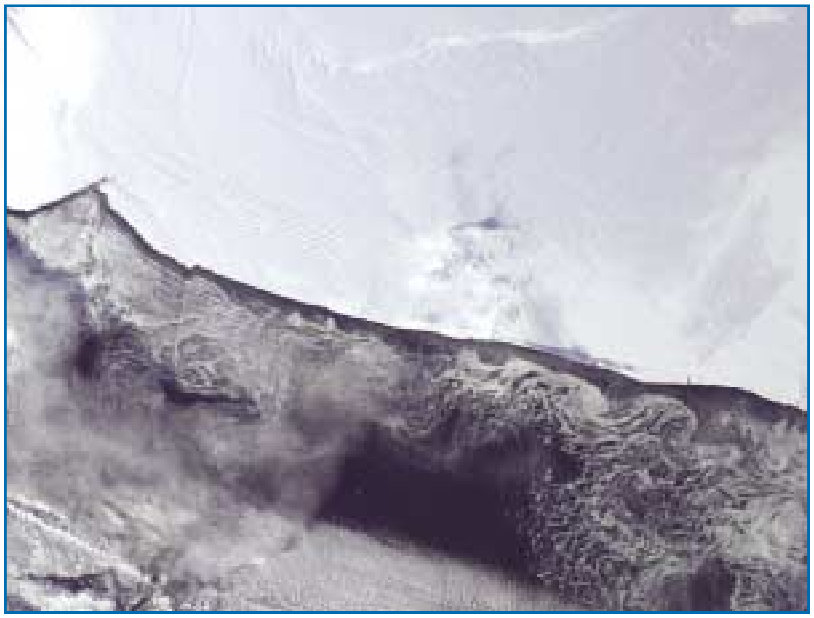
The first satellite-based MODIS was launched on Terra in December 1999, and the second will be on Aqua. The two MODIS instruments are identical in many aspects, although not all. Most importantly, two of the bands (bands 31 and 32) of the Aqua MODIS, used for examining sea surface temperatures and land-based fires, saturate at a temperature of about 340 K, meaning that no temperatures above that level can be distinguished, whereas the same bands on the Terra MODIS saturate at 400 K. By not saturating until 400 K, bands 31-32 on the Terra MODIS can provide details about fires at temperatures of 340-400 K that will not be obtainable from the Aqua MODIS. At the same time, by saturating at about 340 K, bands 31-32 on the Aqua MODIS will provide more detail at temperatures below 340 K, thereby obtaining, for instance, improved sea surface temperature information. Other changes made to the Aqua MODIS as a result of analysis of the Terra MODIS characteristics are: a reduction of optical cross-talk from one band (band 31) into five other bands (bands 32-36); a reduction in electronic cross-talk amongst two sets of bands (bands 5-7 and 20-26); and an improved radiative response versus scan-angle for the thermal emissive bands. Each of these changes should improve the Aqua results.

The MODIS efforts build on the heritage of work with several earlier satellite sensors, including the Landsat Thematic Mapper, the Nimbus 7 Coastal Zone Color Scanner (CZCS), the Sea-viewing Wide-Field-of-view Sensor (SeaWiFS), and the NOAA Advanced Very High Resolution Radiometer (AVHRR). Improvements over these earlier instruments include corrections built into the MODIS land algorithms, a 2.20 µm channel that sees through fire, smoke, and aerosols, and a simpler calculation for leaf area index. Sample images from the data of the Terra MODIS on the next several pages illustrate the types of images to be expected from the Aqua MODIS.

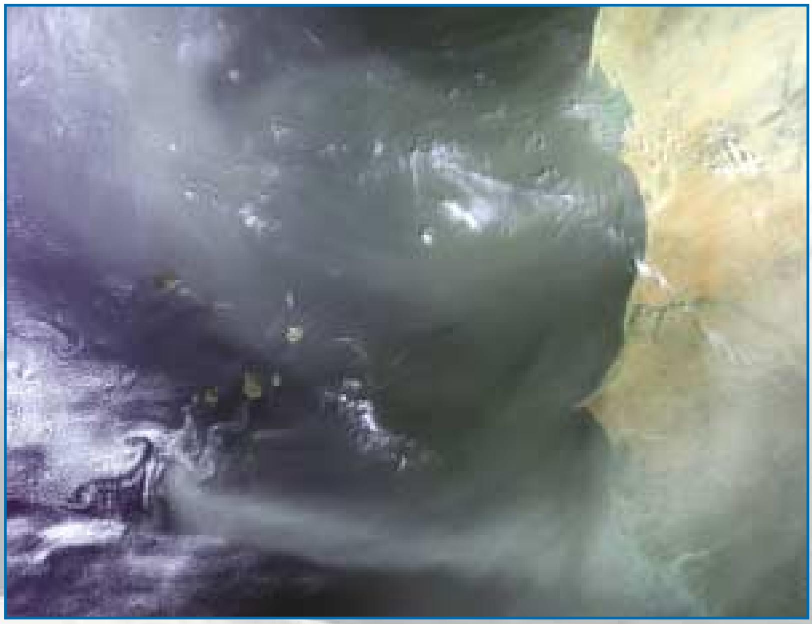


Sea surface temperatures off the East Coast of the United States on May 8, 2000, as calculated from the data of the Terra MODIS. The coldest temperatures are depicted in purple and blue, the warmest in red, with the warmest waters showing the Gulf Stream as it winds its way northeastward. The MODIS observations reveal the existence and structure of several eddies on either side of the Gulf Stream. Blue patches interspersed within some of the warmer water (orange and red coloring) result from clouds. (Image courtesy of Bob Evans, Peter Minnett, and colleagues at the University of Miami's Rosenstiel School of Marine and Atmospheric Science, plus the Goddard Space Flight Center's Scientific Visualization Studio.)

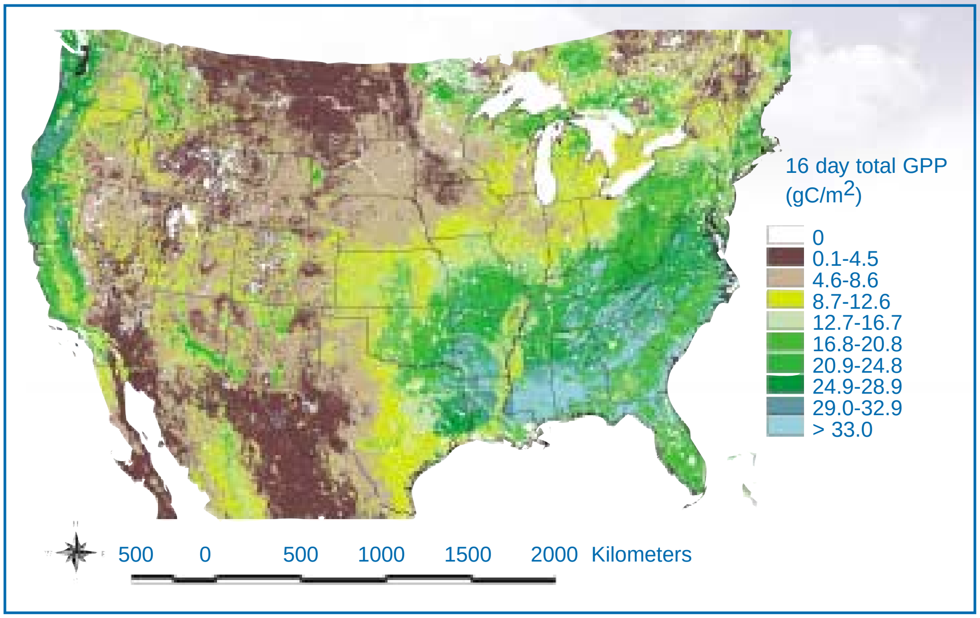
Calving of a massive iceberg off the Ross Ice Shelf at the edge of Antarctica, as captured by the Terra MODIS. The top image shows the ice shelf on March 3, 2000, prior to the calving of the iceberg. The bottom image shows the ice shelf on March 28, 2000, with the gigantic B-15 iceberg splitting away. B-15 is approximately 40 km x 300 km, with a total area roughly twice the size of Delaware. (Image courtesy of Jacques Descloitres, MODIS Land Science Team.)



Terra MODIS image of a major dust storm as it transports material from the Sahara Desert westward over the Atlantic. The image was taken on February 29, 2000, during one of the first few days of MODIS operations. (Image courtesy of the MODIS Atmosphere Science Team.)

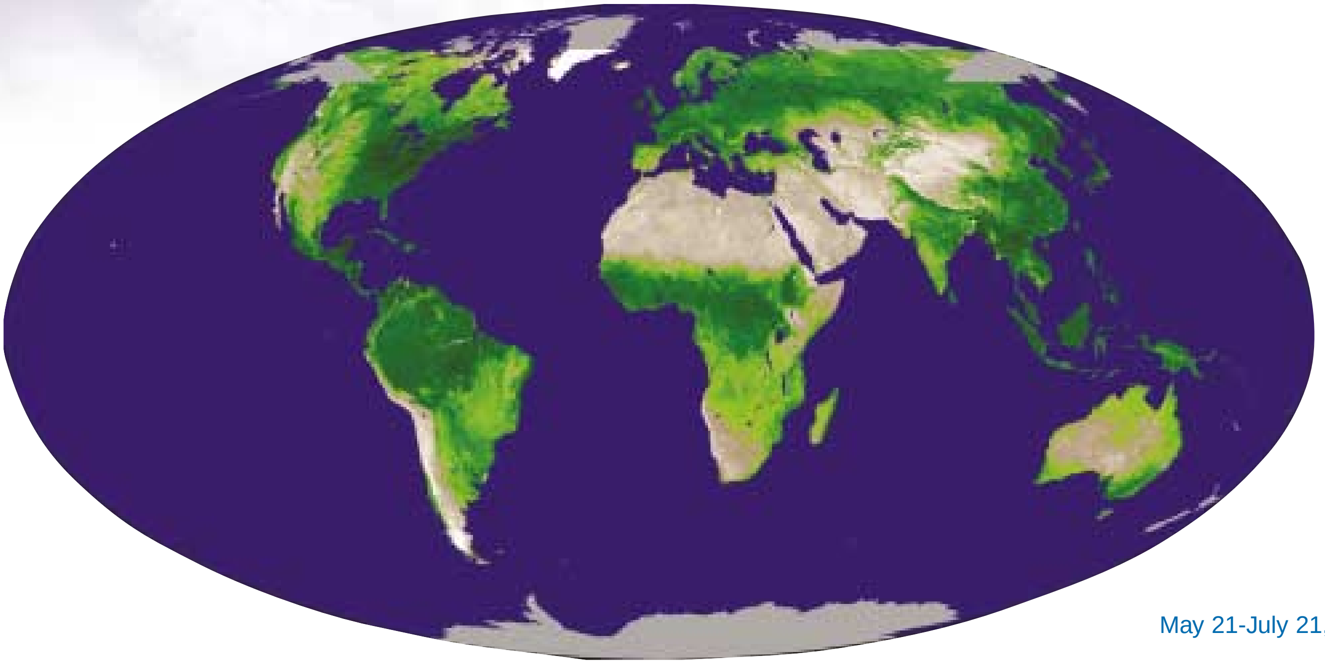


Gross primary production (i.e., total plant photosynthesis) in the continental United States over the 16 days March 26 – April 10, 2000, as determined from the data of the Terra MODIS. The colors indicate the calculated number of grams of carbon (gC) absorbed per square meter of land area as plants took in carbon dioxide from the atmosphere for the process of photosynthesis. (Image courtesy of Steve Running, University of Montana and MODIS Land Science Team.)

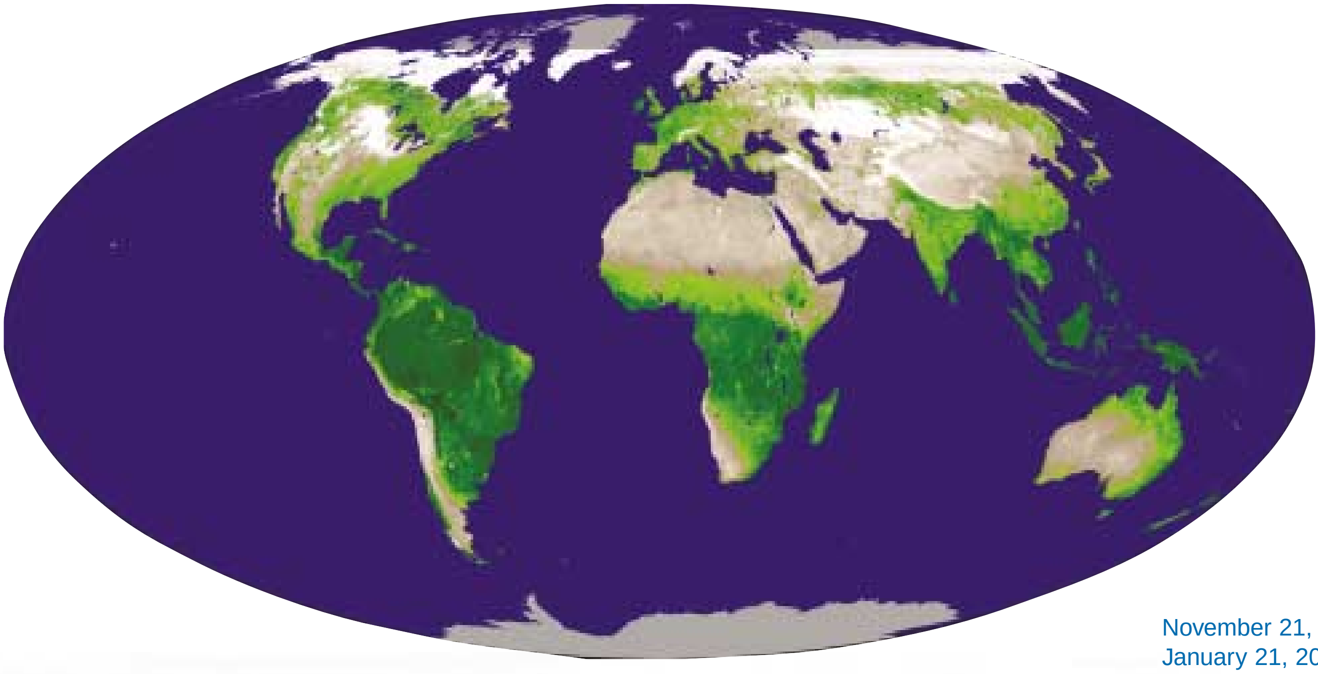


The Nile River and surrounding areas of northeast Africa and the Near East, as viewed by the Terra MODIS on February 28, 2000. (Image courtesy of Jacques Descloitres, MODIS Land Science Team.)

Wildfires in Siberia on August 4, 2001, as viewed by the Terra MODIS. (Image courtesy of Jacques Descloitres, MODIS Land Science Team.)



May 21-July 21, 2000



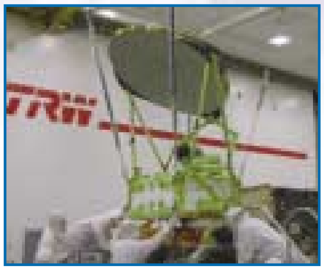
November 21, 2000-
January 21, 2001

Global images of the Enhanced Vegetation Index, as calculated from the data of the Terra MODIS for the two-month time periods May 21 - July 21, 2000 and November 21, 2000 - January 21, 2001, centered on the winter and summer solstices. The index values range from 0, indicating no vegetation, to 1, indicating the densest vegetation. Gray indicates areas with no data. The seasonal contrast is especially marked in the middle and high latitudes of the Northern Hemisphere, whereas major deserts, such as the Sahara, remain unvegetated throughout the year. (Images courtesy of Alfredo Huete and colleagues at the University of Arizona, plus the MODIS Land Science Team.)

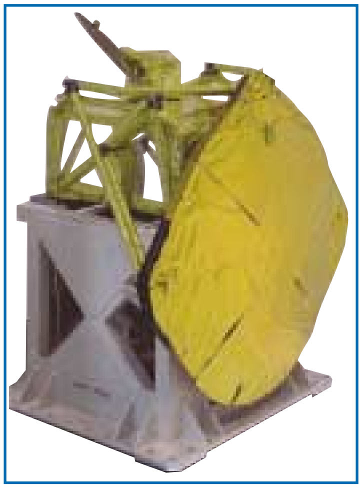
Advanced Microwave Scanning Radiometer for EOS (AMSR-E)

AMSR-E is a passive-microwave scanning radiometer built for Aqua by the National Space Development Agency of Japan (NASDA). AMSR-E, like MODIS, is not focused on a single parameter but instead will obtain information about a wide range of variables. In fact, some of the variables that AMSR-E data will be used to examine are also being examined with MODIS data. The major anticipated derived products from AMSR-E are sea surface temperature, sea ice concentration and temperature, snow-water equivalent on land, snow depth on sea ice, surface soil moisture (at land locations with no snow cover and no major vegetation cover), wind speed over the oceans, cloud liquid water over the oceans, water vapor over the oceans, and rainfall over both the land and the oceans.

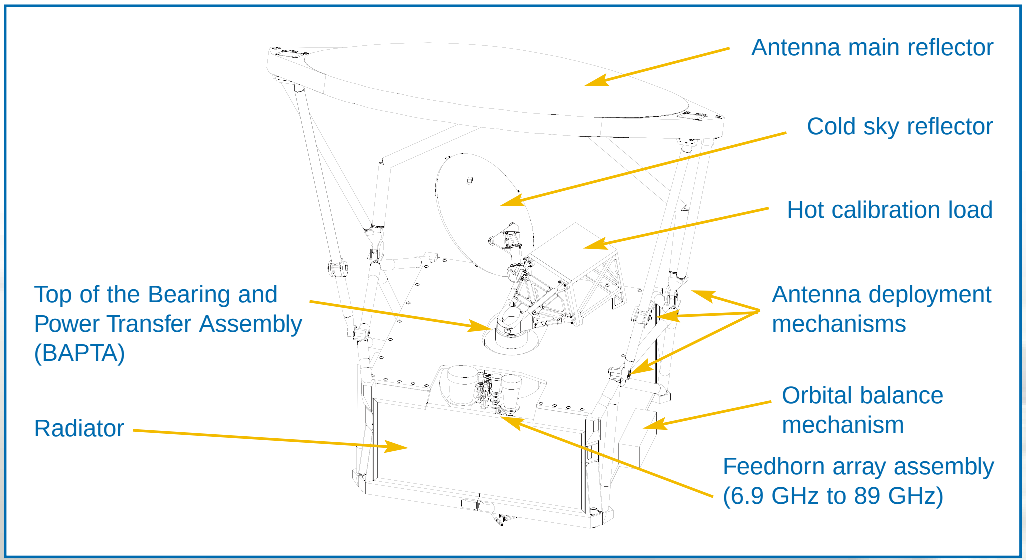
In cases where information about the same variable is being obtained from both AMSR-E and MODIS, the information from the two instruments will complement each other. Largely because MODIS collects radiation having shorter wavelengths, in the visible and infrared portions of the electromagnetic spectrum, MODIS will obtain finer detail spatially. However, its surface data will be obscured under cloudy or dark conditions. Just as humans, whose eyes sense visible light, cannot see the Earth's surface from an airplane when a heavy cloud cover intervenes between the surface and the plane, so the MODIS visible channels cannot see the surface when a heavy cloud cover intervenes between the surface and the satellite. The AMSR-E data have coarser horizontal resolutions, generally between 5 and 60 km, than the MODIS data, but they will be obtainable during darkness as well as sunlight and under cloudy as well as cloud-free conditions. Also, the coarser resolution will allow the instrument to collect data from most of the Earth's surface during the course of a day at a relatively low data rate (87.4 kilobits per second, versus 6,847 kilobits per second for MODIS data).



The AMSR-E instrument at TRW, with its antenna in its deployed configuration. (Photo courtesy of NASDA.)



The AMSR-E instrument with its antenna in its stowed configuration for the Aqua launch. (Photo courtesy of NASDA.)



Labeled line drawing of the AMSR-E instrument. The cold sky reflector and hot calibration load together constitute the despun (non-rotating) assembly. The rest of the structure is the spun (rotating) assembly, shown in its deployed configuration. When operating, the instrument will rotate at 40 revolutions per minute (rpm). The yellow/gold portions visible in the photographs are parts of the protective thermal blanket. (Line drawing courtesy of TRW; labels added later.)

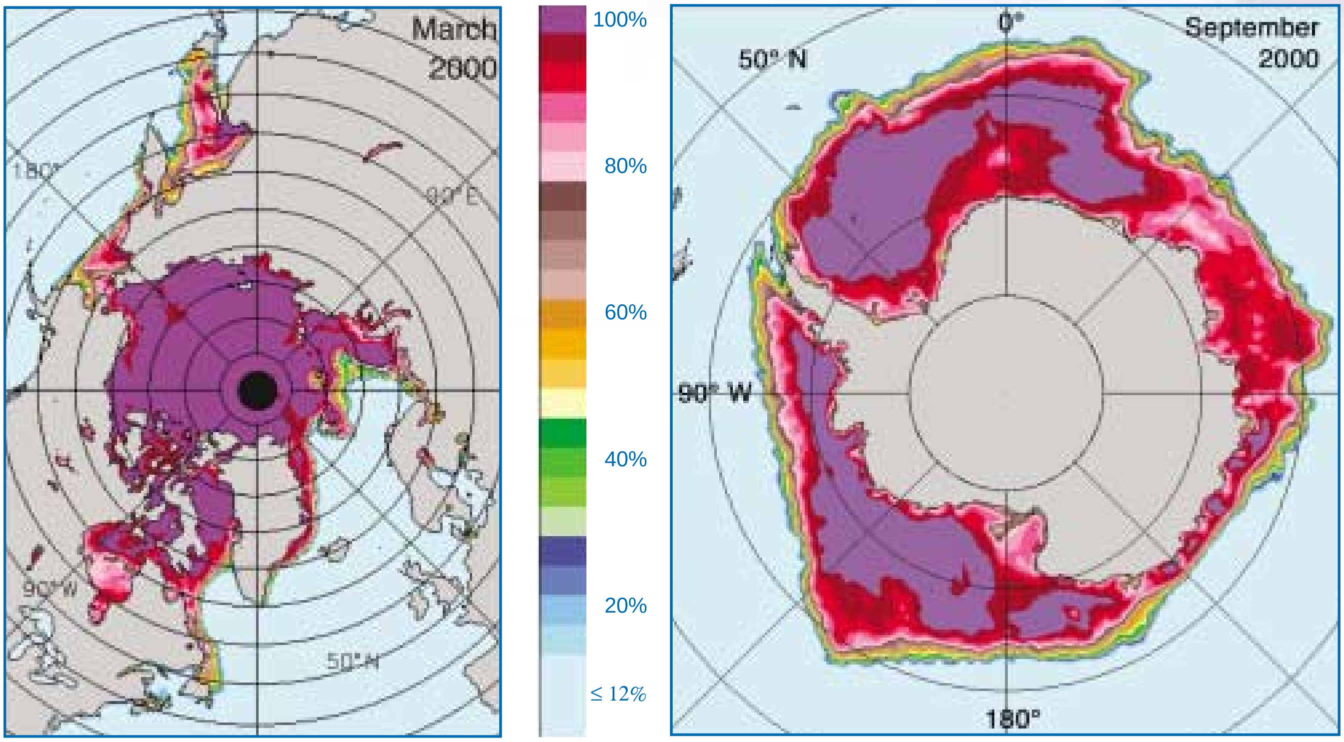
AMSR-E has 12 channels, collecting horizontally and vertically polarized data at frequencies of 6.9, 10.7, 18.7, 23.8, 36.5, and 89 GHz. It will provide global observations of a variety of surface and atmospheric variables under both daylight and darkness and under most weather conditions. The AMSR-E on Aqua is scheduled to be the first AMSR in space, with a second AMSR instrument scheduled for launch on the Japanese ADEOS II spacecraft in late 2002.

AMSR-E builds on the heritage of the following earlier passive-microwave instruments: the single-channel Electrically Scanning Microwave Radiometer (ESMR) launched in December 1972 on NASA's Nimbus 5 satellite, the Scanning Multichannel Microwave Radiometer (SMMR) launched in October 1978 on NASA's Nimbus 7 satellite, the Special Sensor Microwave Imagers (SSMIs), the first of which was launched in June 1987 on the F8 satellite of the Defense Meteorological Satellite Program (DMSP), and the TRMM Microwave Imager (TMI) launched in November 1997 on the Tropical Rainfall Measuring Mission (TRMM). Advantages of the AMSR-E over the currently operating SSMIs include: (a) inclusion of channels measuring at frequencies of 6.9 and 10.7 GHz, enabling determination of sea surface temperatures, ice temperatures, and an indication of soil moisture; (b) inclusion of channels measuring at 18.7 GHz rather than 19.4 GHz, allowing calculation of surface variables with less atmospheric interference; and (c) improved (finer) spatial resolution. Advantages of the AMSR-E over the TMI include: (a) inclusion of channels measuring at 6.9 GHz, (b) inclusion of channels measuring at 18.7 GHz rather than 19.4 GHz, and (c) the ability to obtain global measurements, because of Aqua's having a near-global orbit versus the restriction of the TRMM orbit to low and middle latitudes, in line with the TRMM mission's concentration on the tropical regions.

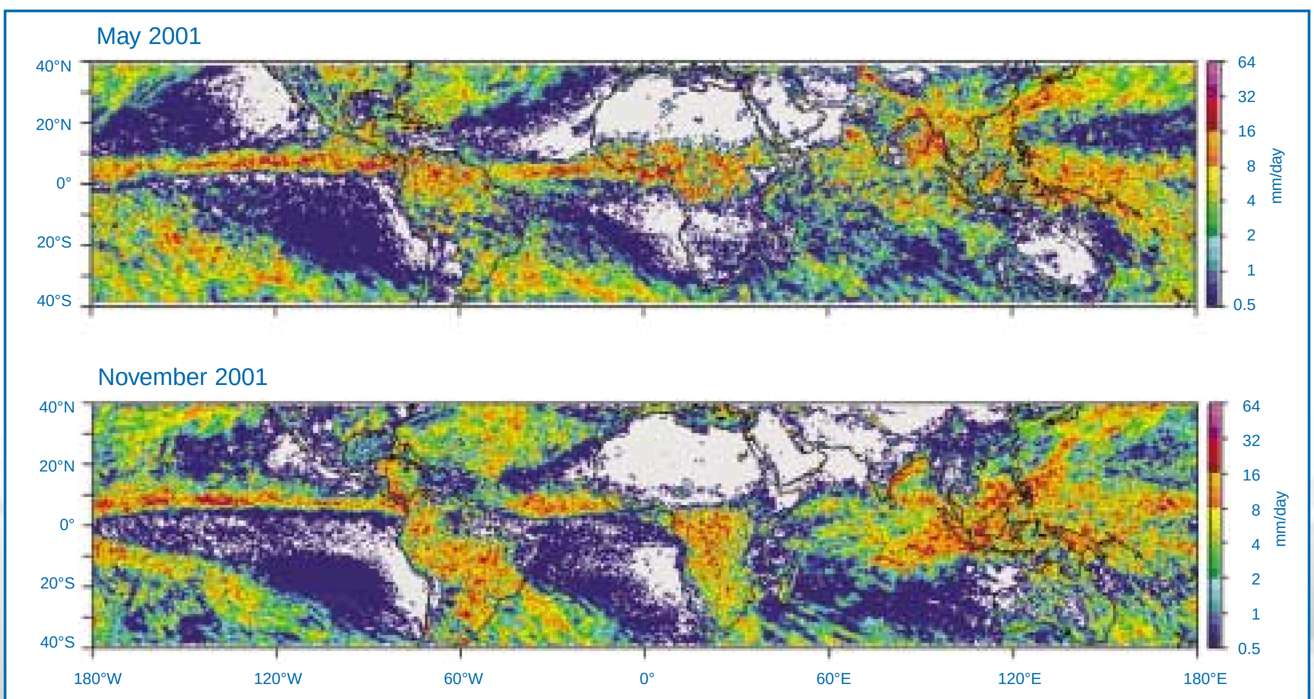
Data Products from AMSR-E

Level 2A Brightness Temperatures
Level 2 Rainfall
Level 3 Rainfall
Columnar Cloud Water over the Oceans
Columnar Water Vapor over the Oceans
Sea Surface Temperature
Sea Surface Wind Speed
Sea Ice Concentration
Sea Ice Temperature
Snow Depth on Sea Ice
Snow-Water Equivalent on Land
Surface Soil Moisture

Each of these products is described in the *EOS Data Products Handbook*, Volume 2.



Late-winter sea ice concentrations (percent areal coverages) in the Arctic averaged for March 2000 and in the Antarctic averaged for September 2000, from data of the DMSP Special Sensor Microwave Imager. The AMSR-E data will be used to generate similar images, with improved resolution. (Left image, with ice concentrations generated using a “NASA team" algorithm, courtesy of the Goddard Space Flight Center sea ice group; right image, with ice concentrations generated using an alternative, "bootstrap" algorithm, courtesy of Joey Comiso, with labels added later.)



Average surface rainfall for the months of May and November 2001, as determined from data of the TRMM Microwave Imager (TMI). The AMSR-E data will be used to generate similar images, although the AMSR-E images will be near-global and not restricted to the latitudes between 40° S and 40° N. (Images courtesy of Chris Kummerow.)

Data Flow and Data Processing

The data collected by the Aqua instruments will be stored on board the spacecraft during each orbit, then relayed to the ground when the satellite overflies ground stations in Poker Flat, Alaska (near Fairbanks), and in Svalbard, Norway. From the ground stations, the data will be transmitted to Goddard Space Flight Center in Greenbelt, Maryland, where the data processing will be done for the MODIS, AIRS, AMSU, and HSB data. The CERES data will be sent to Langley Research Center for processing, and the AMSR-E data will be sent to NASDA's Earth Observation Center (EOC) in Hatoyama, Japan, for initial processing, then to Remote Sensing Systems in Santa Rosa, California, and Marshall Space Flight Center in Huntsville, Alabama, for two subsequent levels of processing.

The data from all the Aqua instruments will be available to scientists around the world at various levels to accommodate different needs. The first step in the data processing is the removal of various communications artifacts, after which the data are labeled "Level 0" data. The next step is time-referencing and annotation with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters. Upon completion of this step, the data are labeled "Level 1" data. It is after this step that the radiative data are converted into the desired derived geophysical variables, such as atmospheric temperatures, sea ice concentrations, or chlorophyll fluorescence. When still at the same resolution and location as the Level 1 source data, these derived variables are considered "Level 2". In "Level 3" data, the variables have been mapped onto uniform space-time grids, making the Level 3 data the data that many users are most interested in receiving. The uniform grids make the Level 3 data generally more convenient than the lower level data for analysis of the data records or for use as input to climate models. Other users, however, desire the lower-level data, for instance to calculate their own derived products. In either case, the data can be obtained from the following data centers, called Distributed Active Archive Centers (DAACs):

Data Archival and Distribution Centers

AIRS / AMSU / HSB data	Goddard Space Flight Center DAAC
CERES data	Langley Research Center DAAC
MODIS data	
Ocean and Atmosphere Products	Goddard Space Flight Center DAAC
Land Products	EROS Data Center DAAC
Snow and Ice Products	National Snow and Ice Data Center DAAC
AMSR-E data	National Snow and Ice Data Center DAAC

Internet addresses for the data centers are listed near the end of the brochure.

Determining the Accuracy of the Data Products

The data products derived from the Aqua data will be checked against in situ and other observations in order to validate how well they approximate the desired geophysical parameters. This will be done in a variety of ways, with the involvement of the science teams and others funded specifically for validation studies.

AIRS/AMSU/HSB Validation

Pre-launch validation activities undertaken by the AIRS / AMSU / HSB science team have included participation in the International Satellite Cloud Climatology Project's (ISCCP's) First ISCCP Regional Experiment (FIRE) III in the Arctic and the Florida-based Convection and Moisture Experiment (CAMEX), employing a suite of three instruments used as an airborne simulator for AIRS / AMSU / HSB. Post-launch validation will focus strongly on operational rawinsondes and dedicated radiosondes at times of overpasses of the Aqua satellite, while also including ocean buoys for recording the sea surface state. Soundings will be made from a suite of Atmospheric Radiation Measurement – Cloud and Radiation Testbed (ARM-CART) validation sites and from additional sites in Europe, Brazil, and Australia.

Launch of a radiosonde. Radiosondes are balloon-borne packages of meteorological sensors and a radio transmitter to send the data collected back to receivers on the ground. Hundreds of radiosondes are routinely launched around the globe twice daily, measuring temperature, humidity, and pressure at various levels in the atmosphere. The returned data are then sent to weather forecasting centers, for incorporation into their forecasting efforts. Radiosondes will play an important role in the validation of the AIRS/AMSU/HSB data. (Photo courtesy of the AIRS/AMSU/HSB Science Team.)

CERES Validation

Validation efforts for the three CERES instruments already in space use examination of global consistencies and anomaly patterns from the CERES data as well as comparisons with surface-based, aircraft, and balloon data from long-term validation sites in the Atmospheric Radiation Measurement (ARM) program, the Baseline Surface Radiation Network (BSRN), and the Aerosol Robotic Network (AERONET). The focus on long-term validation sites is, for reasons of practicality, necessitated by the large instantaneous variability of radiative fluxes relative to the small changes significant to climate. Because of a lack of

Chesapeake Lighthouse. The Chesapeake Lighthouse is the site for the CERES Ocean Validation Experiment (COVE), where long-term in situ radiation measurements are being made with a primary purpose of validating the data from the CERES instruments on TRMM, Terra, and, eventually, Aqua. (Photo courtesy of Bill Smith, Jr. and Ken Rutledge.)

ocean background surface sites, CERES has also instrumented the Coast Guard Chesapeake Lighthouse ocean platform 20 km east of Virginia Beach to add long-term surface optics, surface flux, and aerosol measurements. An intensive field experiment, entitled the Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS), took place from July 10 to August 2, 2001, and emphasized clear-sky solar fluxes and how they are affected by the sea surface and the atmosphere. Both the CERES Ocean Validation Experiment (COVE), centered at the Chesapeake Lighthouse, and the CERES ARM Validation Experiment (CAVE) are expected to continue during the period of Aqua data collection.

MODIS Validation

MODIS validation activities include successful pre-launch operation of an airborne instrument that simulates the MODIS, appropriately named the MODIS Airborne Simulator, in flights over the Arctic during the FIRE III experiment, establishment of 24 core land-vegetation sites around the world, a major Southern African Regional Science Initiative (SAFARI 2000) field experiment for validating Terra MODIS land and atmosphere products, and a Marine Optical Buoy (MOBY), in operation near Hawaii and tested through comparisons with data from both SeaWiFS and the Terra MODIS. Aqua MODIS validation activities will include cross-comparisons with other Aqua sensors, comparisons with data collected as part of the ARM, AERONET, Flux Network (FluxNet), and FIRE / Arctic Cloud Experiment (FIRE / ACE) programs, and surface-based measurements from the MOBY and from the White Sands Missile Range in New Mexico and the Railroad Valley Playa in Nevada.

Logo of the SAFARI 2000 field campaign to validate a range of MODIS data products through airborne and ground observations in southern Africa. The logo centers on a map of the campaign region and includes flags of the 17 nations involved and schematics of the data-collection methods and key topics being investigated. (Logo by Hailey King.)

AMSR-E Validation

Pre-launch validation activities for AMSR-E have included participation in the FIRE III flights over the Surface Heat Budget of the Arctic (SHEBA) ice camp, the Large-scale Biosphere-atmosphere experiment in Amazonia (LBA), the Southern Great Plains field campaigns in Oklahoma for soil moisture measurements, in situ snow measurements in New England, Wisconsin, and Wyoming, and Meltpond2000, an aircraft mission over the sea ice of the Canadian Arctic in June-July 2000 to examine the effects of melt ponds on the passive-microwave signal. Post-launch validation activities

The Navy P-3 aircraft used to overfly and measure sea ice in Baffin Bay and the Canadian Archipelago during the AMSR-E pre-launch validation campaign Meltpond2000 in June and July 2000. (Photo courtesy of Ed Kim.)

for AMSR-E will include intercomparisons with data from the TRMM Microwave Imager (TMI), the TRMM Precipitation Radar, the DMSP Special Sensor Microwave Imagers (SSMIs), Landsat, and Aqua's AIRS and MODIS instruments, as well as data from buoys, radiosondes, and ground, ship, and aircraft campaigns. Aircraft campaigns planned to validate AMSR-E products are soil moisture experiments in 2002 and 2004, Antarctic and Arctic sea ice missions in 2003 and 2005, a precipitation mission in Wakasa Bay, Japan, in collaboration with the Japanese AMSR Team, and a snow validation mission in Colorado, as part of the Cold Land Processes Field Experiment conducted by NOAA's National Operational Hydrologic Remote Sensing Center. These aircraft campaigns will include collection of data with an AMSR-E simulator termed the Airborne Earth Science Microwave Imaging Radiometer (AESMIR). The AMSR-E precipitation group is also active in creating a ground validation site near Eureka, California.

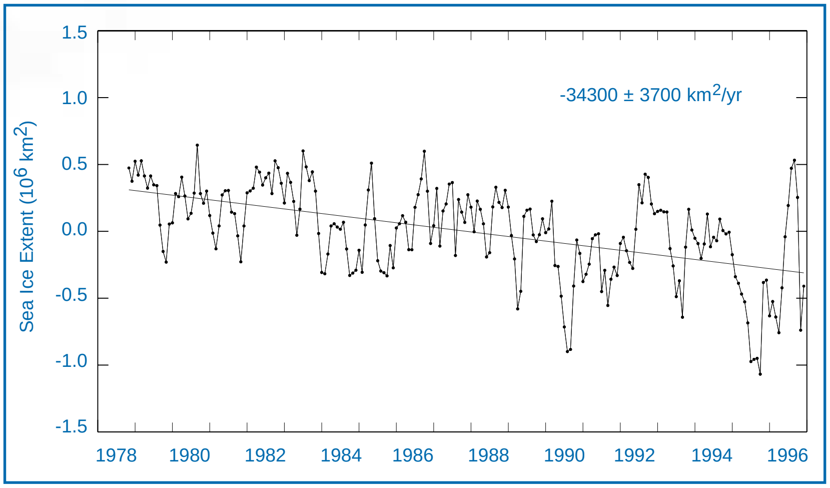
Computer rendering of the AESMIR AMSR-E simulator. (Rendering by Ed Kim.)

Key Science Topics Illustrating the Potential Value and Relevance of Aqua Data

The Aqua data will allow scientists to monitor many Earth system variables over time, as reflected in the lists of the Aqua data products, and analyze changes occurring within them. This has the potential both of revealing changes that might not have been noticed through other means, especially in uninhabited regions, and of providing information for climate-change studies. For the latter, however, it will be essential to compare the Aqua record with earlier records, because the Aqua instruments by themselves will obtain a record for a period of only about 5-6 years. Fortunately, earlier comparative records exist, such as those from ERBE for the CERES data, AVHRR, CZCS, and SeaWiFS for the MODIS data, SMMR and SSMI for the AMSR-E data, and High-Resolution Infrared Radiation Sounder / Microwave Sounding Unit (HIRS / MSU) for the AIRS / AMSU / HSB data. Some of the key variables that have experienced headline-producing changes in recent decades and that Aqua will obtain further information about are:

(1) Atmospheric temperature. Global temperature increases over the past century, determined for the first half of the record largely from land-based measurements, have received particular attention both because of their potential consequences and because of the concern that the warming might be due at least in part to human activities, particularly the insertion of carbon dioxide and other greenhouse gases into the atmosphere. Measurements from AIRS and AMSU will provide a near-global temperature record to a level of detail and accuracy never before attainable on a near-global basis. The accuracies should be comparable to those from radiosondes, for the first time from space-based measurements, while the comprehensiveness geographically will far exceed the radiosonde network.

(2) Sea ice cover. Decreases in the extent of Arctic sea ice found from satellite passive-microwave data from the late 1970s through the end of the twentieth century, although non-uniform and possibly related to long-term oscillations, have received considerable publicity because of the possible connection to regional and global warming and possible impacts on polar bears, seals, and other life forms in the Arctic region. The data from AMSR-E will help extend this record and help reveal whether the trends in the last quarter of the twentieth century continue or reverse. Additionally, sea-ice data from MODIS will reveal greater spatial detail, although not under the wide range of weather conditions possible with the AMSR-E data.



Monthly Arctic sea ice extent deviations for the period November 1978 through December 1996, as derived from satellite passive-microwave data (from C. Parkinson et al., 1999, *Journal of Geophysical Research*, volume 104, pp.20,837-20,856). This is one of the many time series that Aqua data will help extend.

(3) Vegetation cover. Humans have a long history of cutting into forested areas as their population has increased, increasing their needs for space (e.g., for agriculture, houses, recreation facilities, streets, and cities), building materials (such as wood), and fuel (wood again being an option). With much of the mid-latitudes already deforested, concern about deforestation since the mid-twentieth century has centered on tropical deforestation, in part because of the rate of deforestation in the tropics but also because of the resulting loss of habitat for millions of plant and animal species, many of which are found only in the tropical rainforests. The MODIS team will monitor land-cover type throughout the world, plus will derive and map a variety of vegetation indices, as well as net photosynthesis and net primary production. In this way, the Aqua (and Terra) MODIS results will lengthen the record of vegetation changes and identify which regions are suffering the worst destruction and which are experiencing reforestation rather than deforestation.

Cleared tropical rainforest and a squatter's cabin in Rondonia state, Brazil, circa 1996. This is representative of deforestation in the Brazilian Amazon region, where a large population of landless peasants desire to be landowners. (Photo by Compton Tucker.)

(4) Stratospheric ozone. Decreases in stratospheric ozone, especially in the region of the so-called Antarctic "ozone hole," have generated considerable concern since their discovery in the mid-1980s because of the protection that upper-atmosphere ozone provides to life at the Earth's surface by absorbing ultraviolet radiation from the Sun. Excess ultraviolet radiation is harmful to many life forms, including humans, for whom it can cause sunburn, skin cancer, eye damage, and increased immune deficiencies. Stratospheric ozone has been well monitored by satellite ultraviolet observations since the late 1970s, but the ultraviolet observations, which utilize even shorter wavelengths than visible observations, have the disadvantage of requiring sunlight. The AIRS / AMSU / HSB team plans to derive ozone concentra-

tions in 3-5 layers of the atmosphere using infrared data. If successful, this will allow the satellite monitoring of ozone to be carried out during darkness as well as daylight, a factor of particular importance in the central polar regions, where darkness extends for months at a time.

In addition to their relevance to climate monitoring and climate change studies, Aqua data will also be used to address a variety of other important topics. For a sampling:

(1) Weather forecasting. Attempts at weather forecasting extend back thousands of years, with major progress being made in the past century as understanding of the movement of weather systems has grown, the observational network has grown, and computers have spurred the development and implementation of numerical weather forecasting models. In order to project properly into the future, the models depend on accurate observations of the current weather state. These observations now come in large part from satellite data, and the AIRS / AMSU / HSB atmospheric temperature and humidity profiles should be a marked improvement over those obtained from previously operating systems. In fact, a major goal of the AIRS / AMSU / HSB team is the facilitation of improved weather forecasts through having an initial AIRS / AMSU / HSB derived data product available to weather forecasting agencies in the United States, Europe, and elsewhere within only three hours of when the radiative data have been collected.

(2) The impact of clouds on the Earth's climate. One of the largest uncertainties limiting confidence in current global climate model predictions is how best to incorporate clouds in the model formulations. At any given moment, clouds cover approximately 50% of the Earth; and so if their impacts on the climate are poorly represented in a model, the model's predictions become highly suspect. Furthermore, the most basic current limitation on cloud formulations is not centered on computer costs or capabilities but rather on the incomplete understanding of cloud processes and cloud impacts. The CERES data, in conjunction with MODIS-derived information on cloud properties, will be used by the CERES team to improve the understanding of the role of clouds in regulating the Earth's climate, including the mechanisms of cloud / climate feedback and the impact of clouds on the Earth's energy balance. This improved understanding should in turn lead to improved cloud formulations in major climate models and thereby to improved climate predictions. Of particular interest will be the ability of climate models to simulate future El Niño and La Niña phases.

(3) The radiative effects of natural hazards. Volcanic eruptions, droughts, major floods, and other natural hazards all have radiative effects that can be examined from space-based observations. For instance, the main precursor instrument to CERES, the Earth Radiation Budget Experiment (ERBE), was in orbit at the time of the 1991 eruption of Mount Pinatubo and provided data on the impact that the aerosols resulting from the eruption had on cooling the atmosphere by reflecting solar radiation back to space. In fact, it is widely thought that Northern Hemisphere temperatures in 1992 were lower than they would have been without the 1991 Mount Pinatubo eruption. The Aqua CERES will have the capability of making improved estimates of reflected solar radiation for volcanic eruptions occurring during its period of operation.

Eruption of Mount Ngauruhoe, New Zealand, January 1974. (Photo courtesy of the National Geophysical Data Center, Boulder, Colorado.)

Science Enhancements through Coordination with Data from Other Missions

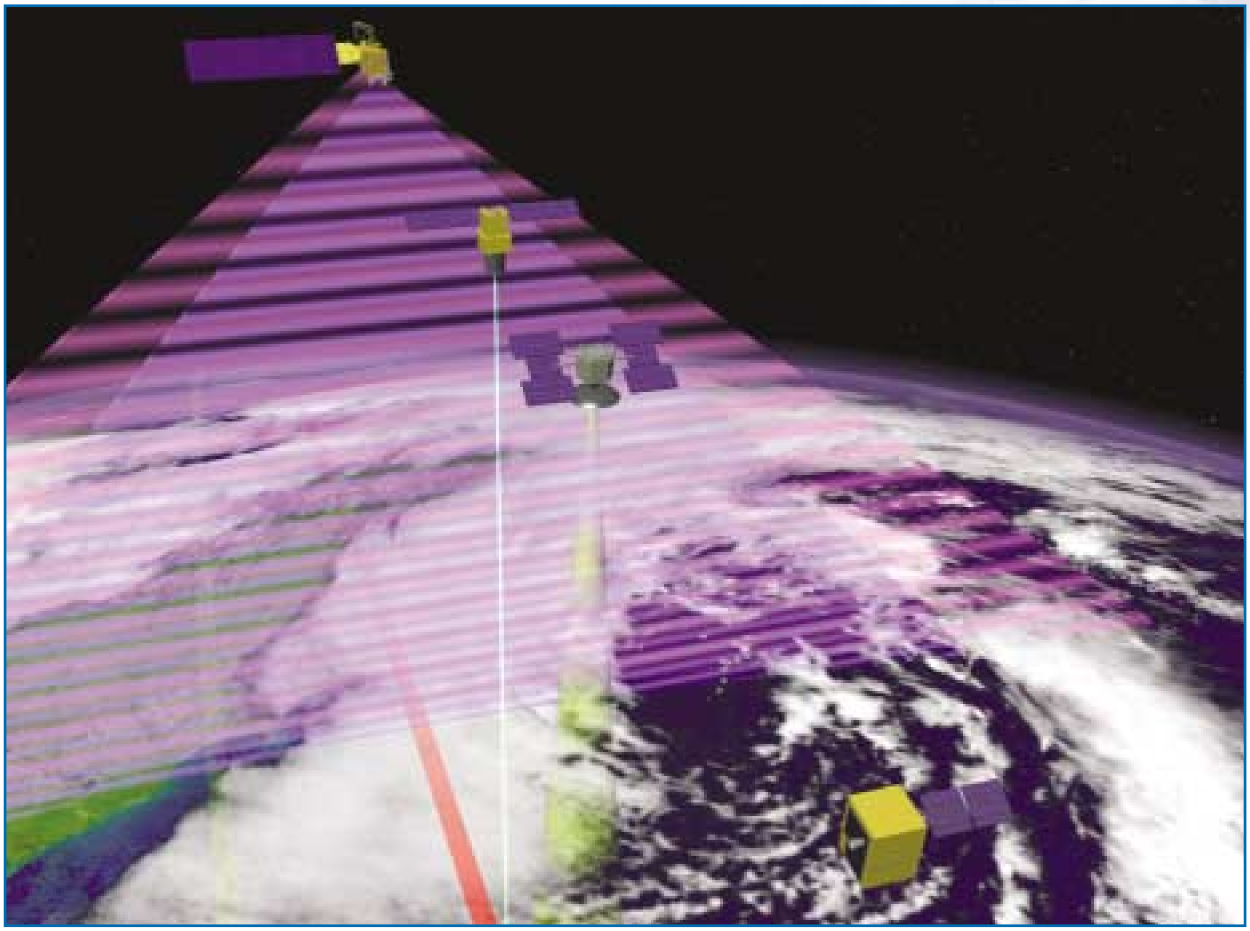
Morning and Afternoon Measurements from Terra and Aqua

Having MODIS and CERES instruments on both the Terra and Aqua satellites will provide scientists an opportunity to examine aspects of the diurnal cycle of the many parameters being measured by these instruments, with Terra providing measurements at approximately 10:30 a.m. and 10:30 p.m. directly below the satellite and Aqua providing measurements at approximately 1:30 a.m. and 1:30 p.m. For variables that can change considerably during the course of a day, such as cloud cover, aerosols, atmospheric temperatures, and reflected solar radiation, the availability of twice as many daily measurements should allow improved estimates of daily averages. Near the equator, the doubling will, in general, be from two to four measurements a day, whereas at high latitudes, the number of potential observations will be greater, due to the broad swaths of the instruments and the convergence of longitude lines at the north and south poles. In the extreme case, at the poles themselves, the number of potential observation times each day, for each satellite, is 14 or 15, depending on the day.

Formation Flying of Five EOS Afternoon Satellites: The A-Train, or PM Constellation

Observations from Aqua will be further enhanced by formation flying of Aqua with Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), CloudSat, Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar (PARASOL), and Aura, four Earth Science missions due to be launched within a year or two of the launch of Aqua. The plan is to have the five orbiting satellites all appropriately lined up at an altitude of 705 km, with Aqua in the lead, followed, in order, by CALIPSO, CloudSat, PARASOL, and Aura. With Aqua in the lead and Aura at the tail, this formation has been labeled the “A-Train.” Alternatively, in view of its early-afternoon measurements, it has also been termed the “PM constellation.”

Because of various complementarities among the instruments on the A-Train satellites, formation flying of the five missions opens the possibility of a variety of enhanced atmospheric results. For example, CALIPSO, with an active laser for aerosol and cloud vertical profiles, CloudSat, with an active radar for cloud profiles, and Aqua together will allow enhanced studies of cloud feedbacks; and CALIPSO and PARASOL will supplement the Aqua MODIS aerosol data over dark surfaces by collecting aerosol data over snow, ice, and other light-colored surfaces as well. The CloudSat science team has spent considerable effort developing optimized retrieval methods that combine multi-sensor information derived from the satellites of the A-Train.



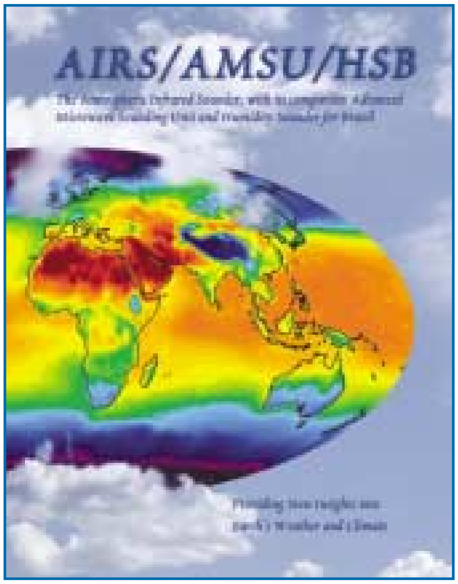
Artist's conception of the first four satellites of the A-Train, flying over the North Atlantic and North America. Aqua is in the lead, followed by CALIPSO, CloudSat, and PARASOL. Following well behind PARASOL and to its left will be Aura, at the tail of the A-train. The purple coloring extending beneath Aqua identifies the broad MODIS swath, while the blue coloring identifies the AIRS swath. The red band identifies the Aqua orbit, projected onto the surface, and the yellow/green band identifies the Aura orbit. (Rendering by Jesse Allen.)

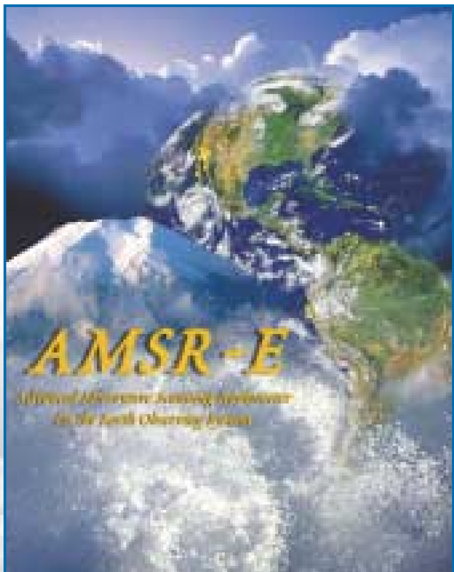
Science leaders associated with the Aqua mission

EOS Senior Project Scientist	Michael King, NASA Goddard Space Flight Center
Aqua Project Scientist	Claire Parkinson, NASA Goddard Space Flight Center
AIRS / AMSU / HSB Team Leader	Moustafa Chahine, NASA Jet Propulsion Laboratory
U.S. AMSR-E Team Leader	Roy Spencer, University of Alabama at Huntsville
Japanese AMSR-E Team Leader	Akira Shibata, Japanese Meteorological Agency
CERES Team Leaders	Bruce Wielicki and Bruce Barkstrom, NASA Langley Research Center
MODIS Team Leader	Vincent Salomonson, NASA Goddard Space Flight Center

Educational Outreach

There is considerable educational outreach being undertaken in conjunction with the Aqua mission, to help inform the public about the mission and its anticipated scientific advances. This outreach includes written materials such as this brochure, brochures for the four science teams, an Aqua lithograph, NASA Fact Sheets on the water cycle and on weather forecasting, and an Aqua science writers' guide. It also includes talks about Aqua at schools, conferences, and other forums, computer animations and visualizations, videotaping of Aqua scientists discussing their work and the climate topics associated with it, and a series of webcasts and web chats produced by the Goddard Special Project Initiatives Office. Most of these materials can be found at the Aqua science website, http://aqua.nasa.gov. The first webcast was broadcast from the TRW cleanroom on December 19, 2001, and highlighted the Aqua spacecraft. The next two webcasts were broadcast from Hawaii on February 5 and 8, 2002, and highlighted Aqua science. All the webcasts are archived at http://aqua.nasa.gov and all include web chats, whereby members of the public can send in questions to be answered by the webcast participants.





Covers of the AIRS/AMSU/HSB and AMSR-E brochures, both available in full at http://aqua.nasa.gov. (Covers designed by Winnie Humberson.)

Webcast interview of the Aqua Project Scientist in front of the Aqua spacecraft at TRW, December 19, 2001. (Photo by Elena Lobl.)

Equipment setup for the December 19, 2001 Aqua webcast and web chat from the TRW cleanroom. (Photo by Claire Parkinson.)

Technical Specifications

Aqua Spacecraft

Mass	2,958 kg
Volume	2.7 m x 2.5 m x 6.5 m stowed; 4.8 m x 16.7 m x 8.0 m deployed
Data storage	136-Gbit solid state recorder for storage of up to two orbits of data
Electrical power	4,600 W silicon cell array and an NiH_2 battery
Design life	6 years
Prime contractor	TRW
Provider	Goddard Space Flight Center

AIRS

Mass	177 kg
Volume	116.5 cm x 80 cm x 95.3 cm stowed; 116.5 cm x 158.7 cm x 95.3 cm deployed
Power	220 W
Data Rate	1,270 kbps
Spectral range	0.4-15.4 µm (0.4-1.1 µm in the Vis / NIR; 3.74-15.4 µm in the IR)
Frequency range	19-750 THz (270-750 THz in the Vis / NIR; 19-80 THz in the IR)
Channels	2382 (4 in the Vis / NIR; 2378 in the IR)
IFOV at nadir	2.3 km for the Vis / NIR; 13.5 km for the IR
Swath width	1650 km
Design life	5 years
Prime Contractor	BAE Systems (formerly Lockheed-Martin)
Provider	Jet Propulsion Laboratory

AMSU

Mass	91 kg (49 kg for AMSU-A1, 42 kg for AMSU-A2)
Volume	72 cm x 34 cm x 59 cm for AMSU-A1; 73 cm x 61 cm x 86 cm for AMSU-A2
Power	101 W (77 W for AMSU-A1, 24 W for AMSU-A2)
Data Rate	2.0 kbps (1.5 kbps for AMSU-A1, 0.5 kbps for AMSU-A2)
Spectral range	0.3-1.3 cm (0.3-0.6 cm for AMSU-A1; 0.9-1.3 cm for AMSU-A2)
Frequency range	23-90 GHz (50-90 GHz for AMSU-A1; 23-32 GHz for AMSU-A2)
Channels	15 (13 for AMSU-A1; 2 for AMSU-A2)
IFOV at nadir	40.5 km for both units
Swath width	1690 km
Design life	3 years
Prime Contractor	Aerojet
Provider	Goddard Space Flight Center

HSB

Mass	51 kg
Volume	70 cm x 65 cm x 46 cm
Power	56 W
Data Rate	4.2 kbps
Spectral range	0.16-0.20 cm
Frequency range	150-190 GHz
Channels	4

IFOV at nadir	13.5 km
Swath width	1650 km
Design life	3 years
Prime Contractor	Matra Marconi Space (United Kingdom)
Provider	Instituto Nacional de Pesquisas Espaciais (INPE, the Brazilian Institute for Space Research)

CERES (for the two instruments combined)

Mass	93 kg
Volume	2 x (60 cm x 60 cm x 57.6 cm)
Power	94 W
Data Rate	20.0 kbps
Spectral range	0.3 to > 100 µm
Frequency range	< 3 to 1000 THz
Channels	3 spectral bands (0.3-5.0 µm, 8-12 µm, and 0.3 to > 100 µm)
Resolution at nadir	20 km
Swath width	Limb to limb
Design life	5 years
Prime Contractor	TRW
Provider	Langley Research Center

MODIS

Mass	229 kg
Volume	1.0 m x 1.6 m x 1.0 m
Power	147 W
Data Rate	6,847 kbps (orbital average)
Spectral range	0.4-14.5 µm
Frequency range	20.7-750 THz
Channels	36 spectral bands
Resolution at nadir	250 m for bands 1-2, 500 m for bands 3-7, 1 km for bands 8-36
Swath width	2330 km
Design life	5 years
Prime Contractor	Raytheon / Santa Barbara Remote Sensing
Provider	Goddard Space Flight Center

AMSR-E

Mass	314 kg
Volume	1.95 m x 1.5 m x 2.2 m stowed; 1.95 m x 1.7 m x 2.4 m deployed
Power	350 W
Data Rate	87.4 kbps
Spectral range	0.34-4.35 cm
Frequency range	6.9-89.0 GHz
Channels	12
IFOV at nadir	Ranges from 74 km x 43 km for 6.9 GHz to 6 km x 4 km for 89.0 GHz
Swath width	1445 km
Design life	3 years
Prime Contractor	Mitsubishi Electric Company (MELCO)
Provider	National Space Development Agency of Japan (NASDA)

Aqua Launch Vehicle, Launch Location, and Orbit

Launch vehicle	Delta II 7920-10L, with a 10-ft diameter stretched fairing
Launch location	Vandenberg Air Force Base, California
Orbit type	Sun-synchronous, near circular, near polar
Equatorial crossing times	1:30 p.m. going north; 1:30 a.m. going south
Altitude	705 km
Inclination	98.2 degrees
Period	98.8 minutes
Repeat cycle	16 days (233 revolutions)

Sources for Additional Information

Books

King, M. D., and R. Greenstone, 1999: *1999 EOS Reference Handbook: A Guide to NASA's Earth Science Enterprise and the Earth Observing System*, NASA Goddard Space Flight Center, Greenbelt, Maryland, 361 pp. [Available on the internet at eospso.gsfc.nasa.gov or in hard copy through a request by email to lmcgrier@pop900.gsfc.nasa.gov or by phone to Lee McGrier at 301-867-2037.]

Parkinson, C. L., and R. Greenstone, 2000: *EOS Data Products Handbook, Volume 2: ACRIMSAT, Aqua, Jason-1, Landsat 7, Meteor 3M/SAGE III, QuikScat, QuikTOMS, and VCL*, NASA Goddard Space Flight Center, Greenbelt, Maryland, 253 pp. [Available on the internet at eospso.gsfc.nasa.gov or in hard copy through a request by email to lmcgrier@pop900.gsfc.nasa.gov or by phone to Lee McGrier at 301-867-2037 or Steve Graham at 301-614-5561.]

Internet sites for Aqua data

For AIRS / AMSU / HSB data: daac.gsfc.nasa.gov (Goddard Space Flight Center DAAC).
For AMSR-E data: www-nsidc.colorado.edu (National Snow and Ice Data Center DAAC).
For CERES data: eosweb.larc.nasa.gov (Langley Research Center DAAC).
For MODIS data: daac.gsfc.nasa.gov (Goddard Space Flight Center DAAC), edcwww.cr.usgs.gov / landdaac (EROS Data Center DAAC), and www-nsidc.colorado.edu (National Snow and Ice Data Center DAAC).

Other relevant internet sites

AIRS / AMSU / HSB Science Team website: www-airs.jpl.nasa.gov.
AMSR-E Science Team website: www.ghcc.msfc.nasa.gov / AMSR.
Aqua Project website: aqua.gsfc.nasa.gov.
Aqua Science website: aqua.nasa.gov.
CERES Science Team website: asd-www.larc.nasa.gov / ceres.
EOS Earth Observatory website: earthobservatory.nasa.gov.
EOS Project Science Office website: eospso.gsfc.nasa.gov.
Japanese website for AMSR-E: yyy.tksc.nasda.go.jp / Home / Projects / EOS-PMI / tback_ e.html.
MODIS Science Team website: modis.gsfc.nasa.gov.

Acronyms and Abbreviations

ADEOS	Advanced Earth Observing Satellite
AERONET	Aerosol Robotic Network
AESMIR	Airborne Earth Science Microwave Imaging Radiometer
AIRS	Atmospheric Infrared Sounder
AMSR	Advanced Microwave Scanning Radiometer
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
AMSU	Advanced Microwave Sounding Unit
ARM	Atmospheric Radiation Measurement program
AVHRR	Advanced Very High Resolution Radiometer
BAPTA	Bearing and Power Transfer Assembly
BSRN	Baseline Surface Radiation Network
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMEX	Convection and Moisture Experiment
CART	Cloud and Radiation Testbed
CAVE	CERES ARM Validation Experiment
CERES	Clouds and the Earth's Radiant Energy System
CLAMS	Chesapeake Lighthouse and Aircraft Measurements for Satellites
cm	centimeter
COVE	CERES Ocean Validation Experiment
CSIR	Council for Scientific and Industrial Research (South Africa)
CZCS	Coastal Zone Color Scanner
DAAC	Distributed Active Archive Center
DMSP	Defense Meteorological Satellite Program
EOC	Earth Observation Center (a NASDA center in Hatoyama, Japan)
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
ERBE	Earth Radiation Budget Experiment
EROS	Earth Resources Observation System
ESMR	Electrically Scanning Microwave Radiometer
FIRE	First ISCCP Regional Experiment
FIRE / ACE	FIRE / Arctic Cloud Experiment
FluxNet	Flux Network
ft	Foot
Gbit	Gigabit (10^9 bits)
GHz	GigaHertz (10^9 Hertz)
GSFC	Goddard Space Flight Center
HIRS	High-Resolution Infrared Radiation Sounder
HSB	Humidity Sounder for Brazil
IFOV	Instrument Field of View
INPE	Instituto Nacional de Pesquisas Espaciais (the Brazilian National Institute for Space Research)
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project
JMA	Japanese Meteorological Agency
JPL	Jet Propulsion Laboratory
K	Kelvin
kbps	kilobits per second

kg	kilogram (1000 grams)
km	kilometer (1000 meters)
LaRC	Langley Research Center
LBA	Large-scale Biosphere-atmosphere experiment in Amazonia
m	meter
MAM	Mirror Attenuator Mosaic
MELCO	Mitsubishi Electric Company
MOBY	Marine Optical Buoy
MODIS	Moderate Resolution Imaging Spectroradiometer
MSFC	Marshall Space Flight Center
MSU	Microwave Sounding Unit
µm	micrometer (10^{-6} meters)
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NiH_2	Nickel hydrogen
NIR	Near-Infrared
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NSIDC	National Snow and Ice Data Center
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar
QuikScat	Quick Scatterometer
QuikTOMS	Quick Total Ozone Mapping Spectrometer
rpm	Revolutions per minute
SAFARI	Southern African Regional Science Initiative
SAGE	Stratospheric Aerosol and Gas Experiment
SeaWiFS	Sea-viewing Wide-Field-of-view Sensor
SHEBA	Surface Heat Budget of the Arctic
SMMR	Scanning Multichannel Microwave Radiometer
SSMI	Special Sensor Microwave Imager
THz	TeraHertz (10^{12} Hertz)
TIROS	Television Infrared Observation Satellite
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
UB	University of Botswana
U.S.	United States
VCL	Vegetation Canopy Lidar
Vis / NIR	Visible / Near-Infrared
W	Watt
WITS	University of the Witwatersrand
ZMD	Zambian Meteorological Department

Photos courtesy of Dave Beverley, Jeff Caplan, Carolyn Green, Dorothy Hall, and the AMSR-E Science Team.

Brochure credits:

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Designer: Winnie Humberson

Reviewers: Moustafa Chahine, Mike Gunson, Michael D. King, Elena Lobl, Vincent Salomonson, Akira Shibata, Roy Spencer, and Bruce A. Wielicki.

Aqua being lowered into the thermal vacuum chamber at TRW, August 2001. (Photo by Sally Aristei.)

Back cover: The computer rendering of the launch of the Aqua spacecraft was done by Reto Stöckli.

"The truth is, the science of Nature has been already too long made only a work of the brain and the fancy. It is now high time that it should return to the plainness and soundness of observations on material and obvious things."

Robert Hooke, 1665

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Greenbelt, Maryland 20771
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