Aqua: An Earth-Observing Satellite Mission to Examine Water and Other Climate Variables

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***Abstract*—Aqua is a major satellite mission of the Earth Observing System (EOS), an international program centered at the U.S. National Aeronautics and Space Administration (NASA). The Aqua satellite carries six distinct earth-observing instruments to measure numerous aspects of earth's atmosphere, land, oceans, biosphere, and cryosphere, with a concentration on water in the earth system. Launched on May 4, 2002, the satellite is in a sun-synchronous orbit at an altitude of 705 km, with a track that takes it north across the equator at 1:30 P.M. and south across the equator at 1:30 A.M. All of its earth-observing instruments are operating, and all have the ability to obtain global measurements within two days. The Aqua data will be archived and available to the research community through four Distributed Active Archive Centers (DAACs).**

***Index Terms*—Aqua, Earth Observing System (EOS), remote sensing, satellites, water cycle.**

I. INTRODUCTION

LAUNCHED IN THE early morning hours of May 4, 2002, Aqua is a major satellite mission of the Earth Observing System (EOS), an international program for satellite observations of earth, centered at the National Aeronautics and Space Administration (NASA) [1], [2]. Aqua is the second of the large satellite observatories of the EOS program, essentially a sister satellite to Terra [3], the first of the large EOS observatories, launched in December 1999. Following the phraseology of Y. Kaufman, Terra Project Scientist at the time of the Terra launch, the Terra and Aqua satellites are aimed at monitoring the "health of the planet," with Terra emphasizing land and Aqua emphasizing water. Both satellites, however, measure many variables in the atmosphere, on the land, and in and on the oceans. In fact, two of the key EOS instruments are on both the Terra and Aqua platforms.

Fig. 1. Aqua spacecraft, August 2001, at TRW, Redondo Beach, CA. TRW was the prime contractor for the Aqua spacecraft bus. The two CERES instruments are visible near the bottom of the spacecraft, both with protective covers. The HSB is immediately above the rightmost CERES, and the AIRS is to its left. Above the HSB is one of the two major units of the AMSU (AMSU-A2), and above the AIRS is the other (the AMSU-A1). MODIS is at the top left, and AMSR-E is at the top right (photo by S. Aristei/TRW).

Aqua data are providing information on water in its many forms: water vapor in the atmosphere; liquid water in the atmosphere in the form of rainfall and water droplets in clouds; solid water in the atmosphere in the form of ice particles in clouds; liquid water on land in the form of soil moisture; solid water on land in the form of snow cover and glacial ice; liquid water in the surface layer of the oceans; and solid water in the oceans in the form of sea ice floating in the north and south polar seas. Aqua data are also providing information on land and ocean vegetation, heavily dependent on water, and on many other aspects of the earth's climate system. A particular highlight, in addition to the data on the water cycle, are improved atmospheric temperature data, which, along with the humidity measurements, have the potential of leading to improved weather forecasts.

Aqua carries on board six distinct earth-observing instruments: the Atmospheric Infrared Sounder (AIRS), the Advanced Microwave Sounding Unit (AMSU), the Humidity Sounder for Brazil (HSB), which was provided by the Brazilian National Institute for Space Research, the Advanced Microwave Scanning Radiometer for EOS (AMSR-E), which was provided by Japan's National Space Development Agency, the Moderate Resolution Imaging Spectroradiometer (MODIS), and Clouds and the Earth's Radiant Energy System (CERES) (see Fig. 1). The data from these instruments are being used to examine

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dozens of earth system variables and their interactions. The multiple goals of the mission include enhanced understanding of the global water cycle, enhanced understanding of many additional elements of earth's climate system, enhanced understanding of climate interactions and climate change, enhanced understanding of the diurnal cycle of variables measured by both Aqua and Terra, and improved weather forecasting. The mission is planned to last on orbit for six years.

Although the Aqua data are available to the research community as a whole, the science development efforts for the Aqua mission, including the development of the algorithms to be used in the data processing of the standard data products, are centered in the following five science teams:

- the AIRS/AMSU/HSB Science Team, led by M. Chahine of NASA's Jet Propulsion Laboratory;
- the U.S. AMSR-E Science Team, led by R. Spencer of the University of Alabama, Huntsville;
- the Japanese AMSR-E Science Team, led by A. Shibata of the Japan Meteorological Agency;
- the CERES Science Team, led by B. Wielicki of NASA's Langley Research Center;
- the MODIS Science Team, led by V. Salomonson of NASA's Goddard Space Flight Center.

This paper provides an overview of the Aqua mission and an introduction to the more specific papers in the remainder of this Aqua special issue of the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING (TGARS).

II. INSTRUMENTS

The earth-observing instruments on Aqua include two (CERES and MODIS) that are near copies of instruments flying on Terra, two (AMSU and HSB) that are very similar to instruments flying on satellites of the National Oceanic and Atmospheric Administration (NOAA), and two (AIRS and AMSR-E) that are new. Three of the instruments work closely together as an atmospheric sounding suite, and these will be discussed first.

A. Aqua Sounding Suite: AIRS/AMSU/HSB

The three components of the Aqua sounding suite are the AIRS, the AMSU, and the HSB. All three are cross-track scanners obtaining information at multiple levels of the atmosphere and, depending upon atmospheric conditions, sometimes also at the surface.

AIRS is a 2382-channel high-spectral-resolution sounder, with 2378 channels measuring infrared radiation at wavelengths in the range 3.7–15.4 μm and the remaining four channels measuring visible and near-infrared radiation in the range 0.4–0.94 μm. Its primary purpose is to obtain atmospheric temperature and humidity profiles from the surface upward to an altitude of 40 km, and it is expected to provide substantial improvements, especially in the temperature measurements, over any previous spaceborne instrument. Its infrared measurements have horizontal spatial resolutions of 13.5 km at nadir, and its visible and near-infrared measurements have horizontal spatial resolutions of 2.3 km at nadir. Vertically, the AIRS data are being processed to provide measurements for 1-km layers in the troposphere (the lower part of the atmosphere) and 3–5-km layers in the stratosphere [4]. AIRS is the Aqua instrument with the most substantial technological advances developed for the Aqua program. Among the advances are a temperature-controlled grating and infrared detectors cooled to 60 K by an active pulse tube cryogenic cooler [5].

Further information about the AIRS instrument can be found in [5]–[9]. Specifically, Aumann *et al.* [6] provide an instrument overview; Gautier *et al.* [7] describe the visible and near-infrared portion of the AIRS; Strow *et al.* [8] describe the prelaunch spectral calibration; and Gaiser *et al.* [9] describe the in-flight spectral calibration. Pagano *et al.* [5] describe the prelaunch and in-flight radiometric calibration. The 2378 infrared channels on AIRS are radiometrically calibrated to standards of the National Institute of Standards and Technology [5]. Tests using simulated AIRS data, sample actual AIRS data for June 14–18, 2002, and actual MODIS data indicate that a geolocation accuracy of 1.7 km is easily achievable for the AIRS measurements [10].

The primary purpose of the four visible and near-infrared channels on AIRS is to provide diagnostic support for the infrared retrievals, principally through higher spatial resolution cloud and land data [7]. The secondary purpose centers on research products, including the surface solar radiation flux and the height of low-level clouds [7].

Powerful as the AIRS is, it shares with all satellite visible and infrared instruments the limitation of having data from underneath clouds obscured by the clouds. Clouds cover approximately half the earth at any time, and simulations suggest that no more than about 5% of the AIRS fields of view will be cloud-free [11]. Hence, it is extremely important for the Aqua program that the AIRS efforts include cloud-clearing techniques [4], [12] and that the AIRS infrared measurements are complemented by the measurements from Aqua's two microwave sounders, the AMSU and the HSB [6].

AMSU, also referred to as AMSU-A, is a 15-channel sounder consisting of two physically separate units AMSU-A1 and AMSU-A2. The AMSU data are used in conjunction with the AIRS data to obtain atmospheric temperature profiles, with the AMSU being of particular value for obtaining upper-atmosphere temperatures and for providing a cloud-filtering capability for tropospheric temperature measurements. Twelve of AMSU's channels measure radiation with frequencies between 50 and 60 GHz and are used predominantly for temperature sounding, whereas the other three channels measure radiation at frequencies of 23.8, 31.4, and 89 GHz and are used predominantly for water vapor and precipitation measurements. The horizontal resolution of the AMSU data at nadir is 40.5 km, three times as coarse as the AIRS data.

The first AMSU instrument was on the NOAA 15 satellite, launched in May 1998, following 20 years of successful NOAA operations with the precursor Microwave Sounding Unit (MSU). The AMSU capabilities significantly exceed those of the MSU, which had four rather than 15 channels, a much lower sampling rate, and a nadir resolution twice as coarse as that of the AMSU. The additional channels on the AMSU result in denser spectral sampling and greater vertical resolution than the precursor MSU. Further information about the AMSU, including its radiometric calibration, can be found in [13].

HSB is a microwave humidity sounder provided to the Aqua program by Brazil's Instituto Nacional de Pesquisas Espaciais (National Institute for Space Research; INPE) following a December 1996 memorandum of understanding between NASA and the Agência Espacial Brasileira (the Brazilian Space Agency; AEB). It has four channels, one measuring radiation at 150 GHz and the other three measuring radiation bands centered on a strong water vapor absorption line at 183.31 GHz. The HSB measurements are used to determine humidity, cloud liquid water, precipitation, and precipitable water. In the AIRS/AMSU/HSB triplet, the HSB is particularly important for allowing accurate humidity profiles to be obtained under overcast conditions and for determining when the cloud liquid water content is too high for the AMSU channels to be effective in cloud clearing. Like the AIRS infrared data, the HSB data have horizontal resolutions of 13.5 km at nadir.

The HSB is a modified version of NOAA's AMSU-B instruments, flown along with the AMSU-A since May 1998, on NOAA 15 and NOAA 16. The AMSU-B is being replaced on the NOAA satellites by the similar Microwave Humidity Sounder (MHS) starting with NOAA 17. The NOAA 15 AMSU-B experienced excessive interference from the spacecraft transmitters, impacting the instrument performance, but this problem has been solved through enhanced shielding on the subsequent AMSU-Bs, the HSB, and the MHS. Further information about the HSB and its radiometric calibration can be found in [12] and [13], respectively. The calibrations of AMSU and HSB are both based on the calibration approach used by NOAA for the AMSU-A and AMSU-B [13].

Together, the AIRS/AMSU/HSB combination is regarded as the most advanced sounding system ever deployed in space. It incorporates the advances of the NOAA AMSU-A and AMSU-B microwave instruments plus the new advances provided by the AIRS. Its primary purpose centers on accurate temperature and humidity profiles, but its data are also being used to obtain information about several atmospheric trace gases, precipitable water, cloud liquid-water content, the heights of the tropopause and stratopause, cloud properties, sea and land surface temperature, surface spectral emissivity, and shortwave and longwave radiative fluxes [14]. Algorithms have been developed for obtaining temperature and moisture profiles from the microwave sounders alone [15], [16], initial temperature and moisture profiles incorporating the infrared data, to be used in operational weather prediction [11], and a full suite of research-quality AIRS/AMSU/HSB data products [4], [17]. Microwave-only retrievals are generally used for fields of view where the cloudiness exceeds 80% [12]. Precipitation is also being calculated from the AMSU/HSB microwave data, using a neural-network technique described in [18].

Details of the AIRS radiative transfer model can be found in [19], and details on the creation and validation of AIRS simulated data, used in the development of the retrieval algorithms, can be found in [20]. For the system to perform as planned, the AIRS, AMSU, and HSB instruments need to be aligned and synchronized so that, as much as possible, simultaneous observations are being made of the same air mass with all instruments. Lambrigtsen and Lee [21] describe the scheme for doing this and the various difficulties involved.

B. CERES

CERES is a broadband scanning radiometer with three channels, one measuring the shortwave, solar radiation reflected from the earth/atmosphere system in the wavelength band 0.3–5.0 μm, one measuring top-of-the-atmosphere total reflected and emitted radiative energy in a band from 0.3 μm to greater than 100 μm, and one measuring top-of-the-atmosphere radiation emitted in the 8–12-μm atmospheric window. Subtraction of the shortwave measurements from the 0.3–100 μm measurements yields a measure of the broadband thermal emitted radiation, so that CERES isolates both the shortwave and longwave broadband components of earth's radiation budget. Spatial resolution of the CERES data at nadir is 20 km.

Aqua carries two CERES instruments, and these are the fourth and fifth CERES in space. The first CERES was launched in November 1997 on board the Tropical Rainfall Measuring Mission (TRMM) satellite; and the second and third CERES were launched in December 1999 on board the Terra satellite.

Each CERES has the capability of scanning in either of two scanning modes: fixed azimuth plane and rotating azimuth plane. During routine operations, one of the Aqua CERES is generally scanning in the fixed azimuth plane mode (cross-track scanning), and the other is generally scanning in the rotating azimuth plane mode. Used alone, the data from the fixed azimuth plane scanning provide a continuation of the measurements begun in 1984 at the start of the long-running Earth Radiation Budget Experiment (ERBE) [22], [23], although with improved spatial resolution and improved accuracies. The rotating azimuth plane scanning is designed to optimize the sampling from different viewing angles. The measurements from the rotating scanning mode are used to convert the fluxes determined from the fixed scanning mode into appropriate fluxes over all view angles, leading to highly accurate radiation budget measurements.

The combination of the broadband thermal emitted radiation with the measurements for the 8–12-μm atmospheric window allows an improved isolation of the greenhouse effect of gases such as water vapor. Furthermore, using CERES data in combination with AIRS data allows a direct measurement of the far-infrared emission at 15–100 μm, wavelengths dominated by the greenhouse effect of upper tropospheric water vapor. The CERES data are additionally being used in conjunction with MODIS data, to obtain information on cloud and aerosol properties and to examine the role of these components in the climate system.

Further information about the CERES instrument and algorithms can be found in [24] and [25], and a broader overview of the EOS studies in radiation and clouds, as well as water vapor, precipitation, and atmospheric circulation, can be found in [26]. The CERES Science Team has done considerable work with the CERES data from the TRMM and Terra satellites, finding, for instance, large decadal variability in the mean radiative energy budget of the tropics [27] and evidence of a strengthening of the tropical atmospheric circulation in the 1990s [28]. Data from the Aqua CERES will allow scientists to extend those studies with improved diurnal sampling and to benefit from the synergism of the broadband CERES radiative data with the cloud, vapor, precipitation, and other measurements from the Aqua MODIS, AIRS, AMSU, HSB, and AMSR-E instruments.

C. MODIS

MODIS is a cross-track scanning radiometer with 36 channels measuring visible and infrared spectral bands in the wavelength range 0.4–14.5 μm. It is the one instrument on Aqua with a science team focused on biological as well as physical measurements of the earth/atmosphere system, and its data are being used to generate a wide variety of ocean, land, and atmosphere products. For the oceans, these include primary productivity, photosynthetically active radiation, coccolith concentration, chlorophyll fluorescence, suspended solids and organic matter concentrations, sea surface temperature, sea ice cover, sea ice albedo, and others. For the land, they include net primary productivity, land cover type, a variety of vegetation indices, fires, land surface temperature and emissivity, snow cover, snow albedo, and others. For the atmosphere, they include a cloud mask, cloud optical thickness and microphysical properties, cloud top properties, cloud thermodynamic phase, aerosol optical depth, aerosol size distribution, total ozone, total precipitable water, and temperature and water vapor profiles [14]. The data products are at spatial resolutions of 1 km, 500 m, and 250 m, which is the finest spatial resolution for data from any of the Aqua instruments.

Because MODIS measures visible and infrared radiation, surface conditions are obscured in the presence of a substantial cloud cover. Hence, considerable effort has gone into the development of a MODIS cloud mask [29], [30], which serves as a primary input to many of the other MODIS algorithms, including those for many of the MODIS atmosphere products as well as the ocean and land products.

The Aqua MODIS is the second MODIS instrument in space, the first being on Terra. The Aqua MODIS incorporates some improvements over the Terra MODIS, notably a reduction in optical and electronic cross talk among the different bands and an improved radiative response versus scan-angle for the thermal emissive bands. Also, a gain change has been made in two of the Aqua MODIS bands (bands 31 and 32, measuring at wavelengths of 10.78–11.28 μm and 11.77–12.27 μm, respectively) in order to have these bands saturate at a temperature of about 340 K rather than saturating at about 400 K as on Terra. The gain change allows greater detail for temperatures below 340 K but eliminates all detail in temperatures above 340 K. The change is aimed at improving the MODIS-derived sea surface temperatures calculated from the data of these two bands.

Further information about the MODIS instrument can be found in [31], and further information about its use in land research and ocean research can be found in [32]–[34]. Running *et al.* [32] further place the MODIS land effort in the larger context of the full EOS effort in land ecosystems and hydrology. The MODIS atmosphere products are described in [29] and [30], with the latter covering the cloud products. Gao *et al.* [35] and Key *et al.* [36] look more specifically at the use of MODIS data for deriving information about high clouds [35] and tropospheric winds [36] in the polar regions.

D. AMSR-E

AMSR-E, provided to the Aqua program by the National Space Development Agency of Japan (NASDA), is a 12-channel conically scanning passive-microwave radiometer measuring vertically and horizontally polarized radiation at the microwave frequencies of 6.9, 10.7, 18.7, 23.8, 36.5, and 89.0 GHz. It builds on the heritage of previous satellite passive-microwave instruments, including the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR), operational from late 1978 through mid-1987, the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I), operational since mid-1987, the Marine Observation Satellite-1 (MOS-1) and MOS-1b Microwave Scanning Radiometers (MSRs), first launched in 1987, and the TRMM Microwave Imager (TMI), launched in November 1997. The AMSR-E provides improved spatial resolutions over the earlier satellite passive-microwave instruments, and its 6.9- and 10.7-GHz channels allow soil moisture, sea ice temperature, and sea surface temperature measurements that are not obtainable with the SSM/I.

The data products that will be produced and archived routinely from the AMSR-E measurements are rainfall, total column water vapor, total column cloud water, sea surface temperature, sea surface wind speed, sea ice concentration, sea ice temperature, snow depth on sea ice, snow-water equivalent and snow depth on land, and surface soil moisture [14]. Spatial resolutions of the data vary from approximately 5 km for the 89-GHz channels to approximately 56 km for the 6.9-GHz channels.

Several of the variables measured by AMSR-E, such as sea ice, snow cover, and sea surface temperature, are also measured by MODIS, which obtains finer spatial resolution. The advantage of AMSR-E for these variables is the ability of the microwave instrument to obtain surface data even in the presence of a substantial cloud cover. This is possible through the inclusion on AMSR-E of several channels measuring at wavelengths where there is little atmospheric interference with the signal. A second salient feature relevant to the AMSR-E observations is the fact that the radiation measured (microwave) is being emitted by the earth/atmosphere system, and therefore the measurements can be made irrespective of whether sunlight is available. Combined, these two features mean that the AMSR-E provides Aqua with an all-weather, day-or-night capability even for surface variables. This capability complements the finer spatial resolution of the MODIS data and greatly enhances the value of the Aqua mission for climate studies.

Further information about the AMSR-E instrument and data processing can be found in [37], and further information about AMSR-E algorithm development and data validation plans of NASDA can be found in [38]. The U.S. and Japanese Science Teams have the same algorithms for some variables and separate algorithms for others. The U.S. algorithms are detailed in AMSR-E Algorithm Theoretical Basis Documents (ATBDs) available on the Internet [39], with some of these algorithms also described and updated in this TGARS Aqua

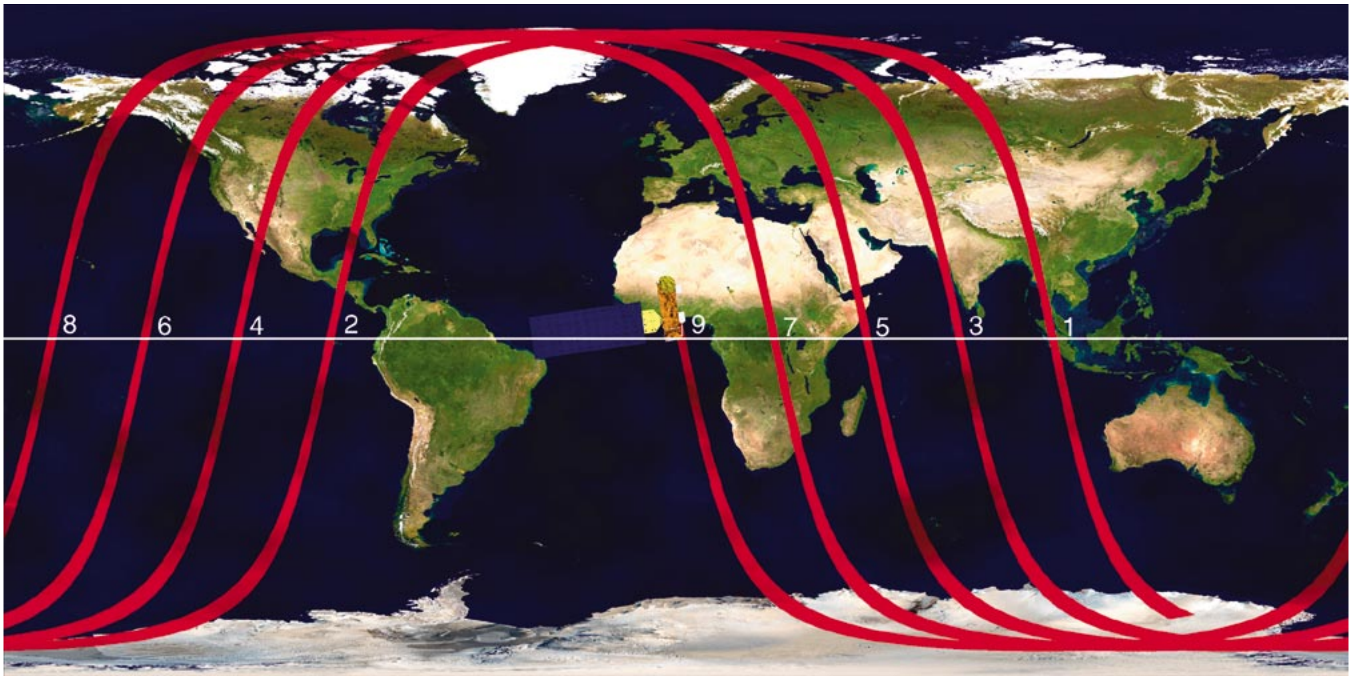

Fig. 2. Schematic of the Aqua orbit, with labels for nine consecutive passes over the equator. The satellite travels north across the equator at 1:30 P.M. and south across the equator at 1:30 A.M. (schematic by J. Allen).

special issue [40]–[43]. The U.S. rainfall calculations employ separate schemes for over the oceans versus over the land, due to the impact on the retrievals of the vastly different underlying surface, and these are described in [40]. The sea ice concentration calculations employ separate schemes for the Northern and Southern Hemispheres. The algorithm for the Northern Hemisphere standard product distinguishes two ice types (first-year and multiyear ice) that are distinct and abundant in the Arctic, whereas the algorithm for the standard product in the Southern Hemisphere, where there is relatively little multiyear ice, does not discriminate among ice types [41]. Comiso *et al.* [41] describe the ice concentration algorithms for both hemispheres, along with the algorithms for ice temperature and snow depth on sea ice. The soil moisture algorithm is based on a multichannel iterative approach described in [42], and the algorithm for snow depth on land is based on a dense media radiative transfer model and a basic model of the evolution of snow grain radius, described in [43]. The snow depth algorithm assumes spatially and temporally dynamic snow pack properties and was selected over an alternative algorithm assuming static properties, as a result of superior performance with test SSM/I data [43].

Additional information about each of the Aqua instruments and the full suite of standard data products can be found in [1] and [14]. Details of the data-product algorithms from the four U.S. Science Teams can be found in the ATBDs [44].

III. LAUNCH AND ORBIT

Aqua was launched on board a Delta II 7920-10L rocket from Vandenberg Air Force Base in California at 2:55 A.M. Pacific Daylight Time on May 4, 2002. As planned, the rocket lifted the spacecraft to an altitude of 685 km, and over the next 44 days there were six ascent burns, concluding on June 17 with Aqua's reaching its operational altitude of 705 km. The operational orbit is near-polar and sun-synchronous, with an inclination of 98.2° (Fig. 2). Aqua orbits the earth every 98.8 min, each time crossing the equator going north at 1:30 P.M. local time and going south at 1:30 A.M. Because of the broad swaths of the instruments, the local times of data collection along the equator range over the intervals of about 12:50–2:10 P.M. and about 12:50–2:10 A.M., with a somewhat larger range for MODIS and CERES data and a somewhat smaller range for the other four instruments, all dependent on the respective swath widths. Further, because of the convergence of longitude lines near the poles, the time range of data collection broadens as one moves from the equator toward either pole, with the ranges in the polar regions including all times of day and night. For the poles themselves, data are collected on each orbit, i.e., every 98.8 min. This translates to 14 or 15 times a day, depending on the day.

The Aqua orbit allows all six earth-observing instruments to obtain global data coverage, although only the CERES instruments have a broad enough swath (limb to limb) to allow global daytime and nighttime coverage in the course of a single day. The other instruments, with swath widths ranging from 1445 km for AMSR-E to 2330 km for MODIS, have low-latitude data gaps between successive orbits, preventing full global daytime or nighttime coverage within a day. These data gaps are filled in on subsequent days, with full global coverage from each instrument obtainable in two days.

In contrast to the Aqua orbit, the Terra satellite moves south across the equator at 10:30–10:45 A.M. and north across the equator at 10:30–10:45 P.M. As with Aqua, the broad swaths of the Terra instruments and the convergence of longitude lines greatly increase the range of times of data collection. With Terra and Aqua both flying, the amount of potential daily data from

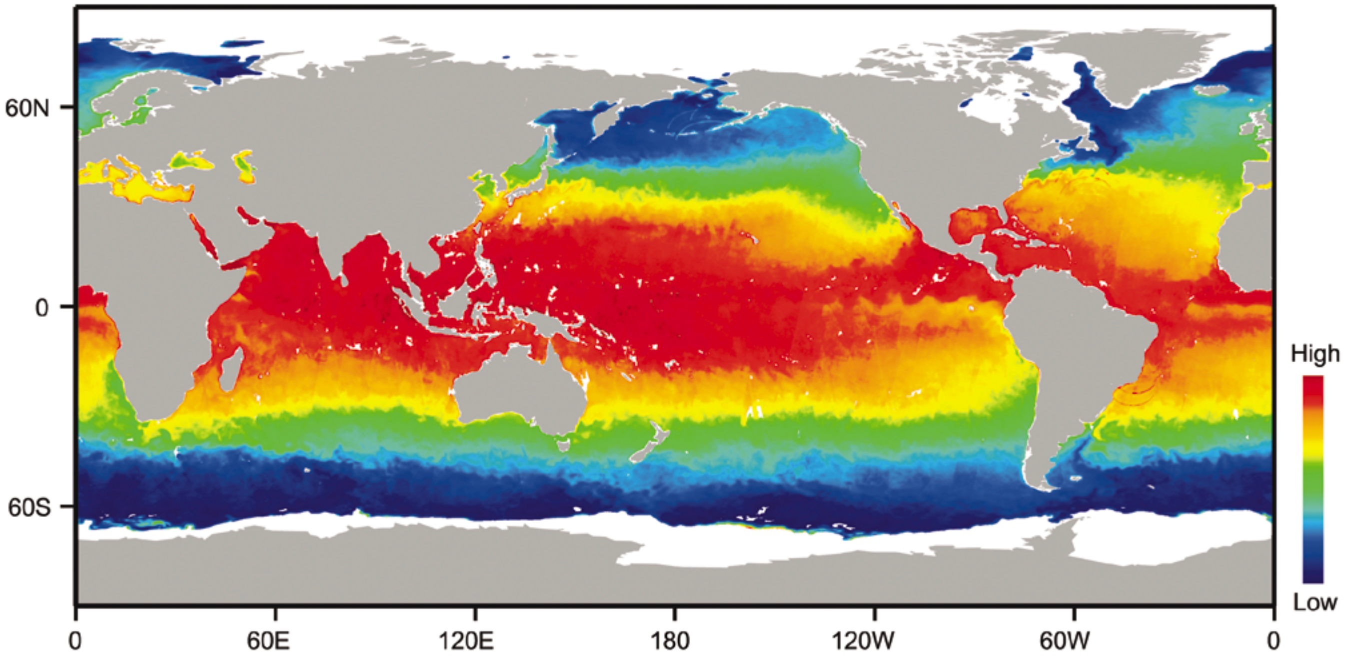

Fig. 3. Global sea surface temperatures averaged for June 2–4, 2002, as derived from early uncalibrated AMSR-E data (image courtesy of NASDA).

the two instruments common to both spacecraft, MODIS and CERES, is double the amount obtainable from either satellite alone. This is of significant value in providing information on the diurnal cycle of some of the rapidly changing variables being examined, such as clouds and aerosols, and in providing improved daily and longer term statistics on those variables.

Because of the respective late morning and early afternoon data collection times, Terra and Aqua were formerly named EOS AM and EOS PM, respectively.

IV. Early On-Orbit Progress

After launch, Aqua underwent a 120-day checkout period, during which the functionalities of the six earth-observing instruments and many other hardware and software pieces were thoroughly checked out. The six earth-observing instruments were turned on to earth-observing mode in a carefully scripted sequence that began with the AMSU on May 12, followed two days later by the HSB. Within days, the AIRS/AMSU/HSB Science Team created images from these data streams, mapping color-coded brightness temperatures for individual channels of data across the eastern U.S., the western U.S., and Brazil.

The next instrument to be turned on was NASDA's AMSR-E, with its dataflow beginning on May 24. Some initial complications with the AMSR-E data were analyzed by NASDA and solved only eight days after the initial turn on of the instrument, when on June 1 a command was sent to the instrument to adjust the automatic gain control. Several days later, NASDA created two global maps illustrative of the high-quality data from the AMSR-E, one map showing sea surface temperatures (Fig. 3) and the other showing a color-composite produced from three of the AMSR-E channels. On June 24, 2002, these two images became the centerpiece of the first NASA press release including actual Aqua images.

The dataflow from the AIRS visible channels began on May 26 and from the AIRS infrared channels began on June 12, 2002. The CERES dataflow began on June 18, and the MODIS dataflow began on June 24. In each case, very quickly after the instrument was turned on, the relevant science team had created images illustrating the successful performance of the instrument. Highlights abounded, one being the first infrared spectrum from AIRS, establishing that all 2378 infrared channels on AIRS were working. A highlight for MODIS was the consistently clean images, free of an undesired striping that had been a problem with some of the initial images from the Terra MODIS. Within 24 hours of when MODIS was first turned on in its science mode, June 24, a quality image was created of fires occurring in Australia, a tribute to advances in the data processing system as well as to the performance of the instrument.

On July 12, after all six instruments were operating, the Aqua direct broadcast system was turned on. This system allows direct access to the raw Aqua data by anyone with direct broadcast receiving equipment. The next major transition occurred on September 1, when the Aqua mission completed its 120-day checkout period and was declared operational.

V. Dataflow, Processing, Availability, and Validation

With all instruments operating, the Aqua dataflow is approximately 8.23 Mb/s (89 GB/day): 6847 kb/s from MODIS, 1270 kb/s from AIRS, 87.4 kb/s from AMSR-E, 20.0 kb/s from the two CERES combined, 4.2 kb/s from HSB, and 2.0 kb/s from AMSU. These data are stored on the spacecraft during each orbit, then relayed through Aqua's X-band antenna from the spacecraft to ground stations in Poker Flat, AK, Svalbard, Norway, and, on occasion, Wallops Flight Facility, Wallops Island, VA. From the ground stations, the data are sent to the EOS Data and Operations System (EDOS) at Goddard Space Flight Center (GSFC) in Greenbelt, MD.

The CERES data move directly from GSFC to Langley Research Center, where the CERES data processing is carried out. The AMSR-E data are routed instead from GSFC to NASDA's Earth Observation Center (EOC) in Hatoyama, Japan, where the initial AMSR-E data processing is done. EOC makes near-real-time products available to the Japan Meteorological Agency, the Japan Fishery Information Center, and other operational users [37], and transmits processed data back to the U.S. for two subsequent levels of processing, the first at Remote Sensing Systems in Santa Rosa, CA, and the second at Marshall Space Flight Center's Global Hydrology and Climate Center in Huntsville, AL. MODIS data processing is done at GSFC, as is much of the data processing for the AIRS/AMSU/HSB sounding suite. In the case of the AIRS/AMSU/HSB, however, the raw data are also transmitted to NOAA's National Environmental Satellite, Data, and Information Service (NESDIS). At NOAA NESDIS, the data are reduced to the subset needed for near-real-time weather forecasting and this subset is sent to weather forecasting centers, all within three hours of data receipt on the ground. Separately, the standard processing of the AIRS/AMSU/HSB data for purposes other than weather forecasting is done at GSFC, using the software supplied by the AIRS/AMSU/HSB Science Team.

The processed data from Aqua are available from NASA's Distributed Active Archive Centers (DAACs) as follows.

- AIRS/AMSU/HSB data products are available from the Goddard Space Flight Center DAAC at http://daac.gsfc.nasa.gov.
- CERES data products are available from the Langley Research Center DAAC at http://eosweb.larc.nasa.gov.
- MODIS ocean and atmosphere data products are available from the Goddard Space Flight Center DAAC at http://daac.gsfc.nasa.gov.
- MODIS land data products are available from the Earth Resources Observation System (EROS) Data Center DAAC at http://edcwww.cr.usgs.gov/landdaac.
- MODIS snow and ice data products are available from the National Snow and Ice Data Center DAAC at http://www-nsidc.colorado.edu.
- AMSR-E data products are available from the National Snow and Ice Data Center DAAC at http://www-nsidc.colorado.edu.

The data products are being analyzed for their accuracy through numerous validation efforts. All of the Aqua Science Teams have extensive validation programs, and all are using aircraft, ships, and field campaigns in a variety of climatic zones, as well as intercomparisons with other satellite data. Only the AIRS/AMSU/HSB validation plans are described in detail in this volume (see the following paragraph), although King *et al.* [29] mention several of the validation efforts for the MODIS atmosphere products, and Njoku *et al.* [42] describe U.S. validation plans for the AMSR-E soil measurements. Shibata *et al.* [38] provide an overview of the Japanese AMSR-E Science Team's validation plans, some of which are being done jointly with the U.S. AMSR-E Science Team. The U.S. Team's plans are outlined on the Internet [45].

Prelaunch, the spectroscopy used in the AIRS radiative transfer algorithm was validated with data from the Winter Experiment (WINTEX) in March 1999 and from the Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS) aircraft campaign in July 2001 [19]. Fetzer *et al.* [46] provide an overview of the entire AIRS/AMSU/HSB postlaunch validation program, including a worldwide radiosonde network, Atmospheric Radiation Measurement (ARM) sites, aircraft campaigns, and 11 individually funded focused validation efforts on specific AIRS/AMSU/HSB data products. Other articles in this TGARS special issue include, more specifically, descriptions of planned efforts for validation of the AIRS visible/near infrared observations [7], validation of the AIRS/AMSU/HSB precipitation measurements [18], South American validation sites for the HSB [12], and early validation (during the first six months after launch) of the AIRS radiances over oceans [47].

VI. ANTICIPATED IMPROVEMENTS RELEVANT TO WEATHER FORECASTING

Certain data products are particularly noteworthy for the level of accuracy anticipated from the Aqua data. Prominent among these are the atmospheric temperatures anticipated from the AIRS/AMSU/HSB instrument triplet. The goal is to have global rms temperature accuracies of 1 K for every 1-km layer of the troposphere [46] and every 3–5-km layer of the stratosphere [4], [6]. This would match the accuracies now obtained from balloon-borne radiosondes released at various land locations around the world [46], with AIRS/AMSU/HSB making such accuracies available globally, over ocean as well as land and at all latitudes. Current satellite atmospheric temperature accuracies for the troposphere are instead approximately 1.6 K, in 2-km-thick layers, from NOAA operational satellites [21]. Complementing the temperature improvements, the aim for the AIRS/AMSU/HSB humidity measurements is to obtain accuracies of 10% in 2-km atmospheric layers [6], [46], improved from accuracies of approximately 50% for the NOAA data [62] and again matching, and perhaps exceeding, the 10% radiosonde accuracies in 2-km layers [6], [46]. For 1-km layers, the aim is for humidity accuracies of 20% [4]. Furthermore, the AIRS/AMSU/HSB suite can measure water vapor in the upper troposphere, to pressure levels of about 100 mb, well above the 300-mb level (about 12 km) that tends to be the upper limit for conventional radiosondes [6].

There is much anticipation that the improved atmospheric temperature and humidity profiles have the potential of resulting in improved weather forecasts, through incorporation of the AIRS/AMSU/HSB data in weather forecasting models [6], [11]. NASA and NOAA have worked closely on this aspect of the Aqua mission, with NOAA scientists prominently involved in the development of the algorithms needed for near real-time products to be available to NOAA and other weather forecasting agencies around the world within three hours of data collection. Details on the near real-time products in support of data assimilation for weather forecasting, and on the importance of assimilating cloud-cleared radiances as well as radiances from cloud-free fields of view, can be found in [11]. No more than about 5% of the AIRS/AMSU/HSB retrievals are fully cloud-free, and, hence, assimilating only cloud-free

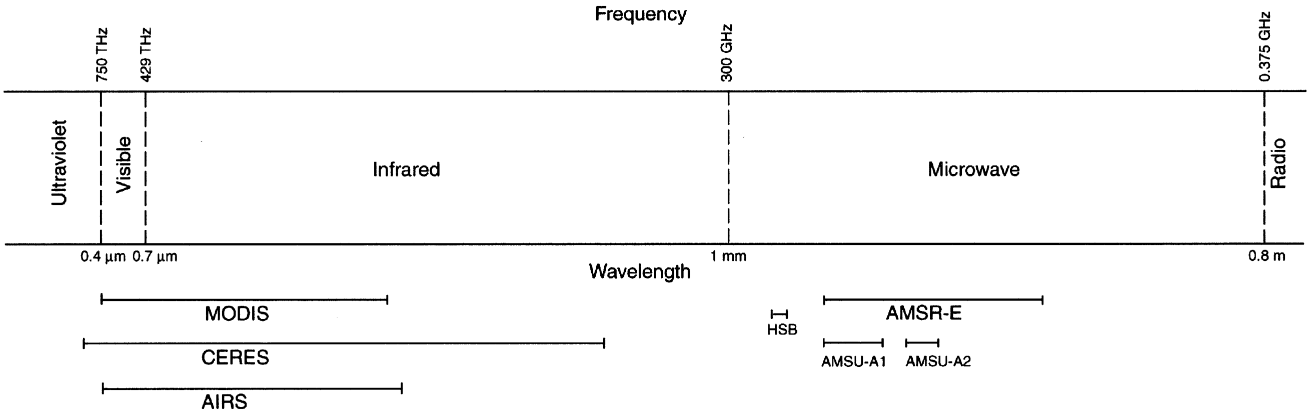

Fig. 4. Schematic indicating the wavelength and frequency ranges of the measurements from each of Aqua's six earth-observing instruments.

fields of view would greatly limit the value of incorporating the AIRS/AMSU/HSB data in the forecast models [11]. Cloud-clearing methodologies for these data are described in [4] and [17].

Although the Aqua data most frequently referred to as having the potential for improving weather forecasts are the AIRS/AMSU/HSB atmospheric temperatures and humidities, other Aqua data products are also potentially of value for forecasting purposes. For a prime example, the MODIS polar tropospheric winds show great promise in improving forecasts at high latitudes. Some numerical weather prediction models have incorporated wind products from geostationary satellites since the late 1990s, but geostationary satellites are positioned over the equator and rarely collect useful data for the polar regions. Conveniently, these are precisely the regions for which the polar orbiting satellites, such as Aqua, provide the most frequent coverage. Key *et al.* [36] have modified the algorithms for the geostationary satellites to be appropriate for the MODIS data and have tested the modified algorithms on a 30-day Terra MODIS dataset. The test dataset demonstrates that assimilating the MODIS winds into the forecasting models of the European Centre for Medium Range Weather Forecasts (ECMWF) and the NASA Goddard Space Flight Center Data Assimilation Office (DAO) yields significantly improved forecasts for both the Arctic and the Antarctic [36].

VII. SELECTED ANTICIPATED ADDITIONAL ADVANCES

The suite of instruments on Aqua, with its visible, infrared, and microwave measurements (Fig. 4), will allow scientists to monitor many earth/atmosphere variables, extend records from many previous satellite instruments, and analyze changes in and interconnections among elements of the total climate system. The following are a few highlights of what can be expected beyond those already described.

1) Lengthened Climate Records

All of the Aqua instruments build on the heritage of previous satellite instruments and will extend records created with the data from the earlier instruments. For instance, CERES is built on the heritage of the Earth Radiation Budget Experiment (ERBE), and the CERES data are being used to extend ERBE records [27], [28] as well as to produce considerably more advanced products. MODIS is built on the heritage of the Advanced Very High Resolution Radiometer (AVHRR), the Landsat Thematic Mapper, and the Nimbus 7 Coastal Zone Color Scanner (CZCS), and the MODIS data are being used to extend records from all of those sensors. For instance, the MODIS data are being used to extend the records of the normalized difference vegetation index (NDVI) from AVHRR (e.g., [48] and [49]), while also being used to generate an enhanced vegetation index that obtains better detail than the NDVI, especially in heavily vegetated regions such as the tropical rainforests [14]. AMSR-E is built on the heritage of SMMR and SSM/I and its data will be used to extend time series generated from the precursor instruments for such variables as sea ice and continental snow cover. Sea ice scientists are particularly interested to see whether the downward trend in ice extents in the Arctic [50] continues, as expected in a strong global warming scenario, or whether it stabilizes or even reverses. Extending these and other climate records will aid in the analysis of issues related to global warming and climate change.

2) Improved Understanding of the Role of Clouds in Global Climate Change

Clouds cover approximately 50% of the globe at any moment, are often highly reflective of incoming solar radiation, and often absorb significant amounts of outgoing longwave radiation, all of which ensure their importance to the global climate system. The Intergovernmental Panel on Climate Change (IPCC) has declared clouds and their effects to be the greatest uncertainty in determining climate sensitivity to either natural or anthropogenic changes [51], [52] and has further indicated the critical importance of improved global cloud observations [52]. The CERES Science Team and colleagues have made notable progress recently using data from the TRMM and Terra CERES in conjunction with earlier datasets. For instance, they have provided evidence that the tropical radiative energy budget is much more variable than previously thought and that this depends critically on changes in mean cloudiness [27]. They have also used the TRMM CERES data to examine aspects of the iris hypothesis [53] that surface temperature increases in the tropics could lead to cloud cover decreases, letting more infrared radiation out of the earth/atmosphere system (analogous to opening the eye's iris) and perhaps thereby providing a negative feedback in the global climate system. Analyses of the CERES data indicate that the relevant tropical clouds are brighter and warmer than previously assumed, in fact so much so that the hypothesized negative feedback based on an infrared iris [53] is more than counterbalanced by a positive feedback based on visible radiation [54].

Adding the data from the Aqua CERES and MODIS to the data from the TRMM CERES and Terra CERES and MODIS doubles the incoming dataflow (the TRMM CERES is no longer operating) and allows much greater detail in measuring the diurnal variations of clouds and radiation components. This should further improve the ability to monitor and analyze clouds and their effects.

3) New Spaceborne Observations

Most of the Aqua data products are products that have been generated previously from other spacecraft (although perhaps from different algorithms and at different resolutions or accuracies). For instance, the MODIS and CERES products have almost all been generated previously from the Terra MODIS and CERES data; most of the AMSR-E products have been generated previously from SMMR and/or SSM/I data; and many of the AIRS/AMSU/HSB products have been generated previously from NOAA data. Still, there are some important new products (or new aspects), among them being a land evaporation fraction from MODIS data, nighttime ozone measurements from AIRS/AMSU/HSB data, and validated global soil moisture from AMSR-E data.

The MODIS land evaporation fraction is the energy budget equivalent of the ratio of actual to potential evapotranspiration and is calculated by a method based on normalizing the radiometric surface temperature with NDVI values [55]. Potential applications include water resources management and analysis of vegetation stress and wildlife fire risk. The evaporation fraction is not being derived routinely from the Terra MODIS data, as it is expected to be from the Aqua MODIS data, but it has been tested on the Terra data in preparation for Aqua [55]. The advantages of Aqua over Terra for this product include the early-afternoon timing (for much of the globe) of the Aqua daytime passes [63] and the synergistic value of having AIRS, AMSU, HSB, and AMSR-E flying along with MODIS on Aqua. Regarding the latter, of particular importance are the temperature and water vapor profiles provided by AIRS/AMSU/HSB and the soil moisture information provided by AMSR-E [55].

The AIRS/AMSU/HSB ozone measurements have an advantage over previous satellite-derived ozone measurements in not requiring solar radiation and therefore allowing a nighttime as well as a daytime product. The Total Ozone Mapping Spectrometer (TOMS) has provided a strong record of satellite-derived ozone measurements since late 1978 [56], and the TOMS data will serve as a primary standard against which to validate the AIRS/AMSU/HSB ozone product under daylight conditions. However, the TOMS measures ultraviolet radiation and therefore requires sunlight. This is restrictive for examining polar phenomena, such as the Antarctic ozone hole, because of the absence of sunlight in the high polar latitudes for months at a time [57]. The AIRS/AMSU/HSB data are obtainable for all latitudes throughout the year and thus offer the exciting possibility of space-based observations of the Antarctic ozone hole in the midst of the Antarctic winter, supplementing the current TOMS observations for the rest of the year.

Another atmospheric trace gas that might be derived from the AIRS/AMSU/HSB data is carbon dioxide (CO_2). CO_2 is not a standard product for the Aqua mission but is a research effort within the AIRS/AMSU/HSB Science Team. If successful, this effort could lead to the first satellite-derived global monitoring of the second most important greenhouse gas in earth's environment, exceeded in importance only by water vapor.

AMSR-E is expected to provide the first routinely produced and scientifically validated spaceborne measurements of global soil moisture [61], advancing on earlier, more limited studies using data from SMMR, SSM/I, and TMI (e.g., [58] and [59]). Soil moisture is a key determinant of surface evaporation, runoff, and water availability for agriculture and other human uses, and is a key for improved hydrologic modeling, weather and climate prediction, and flood and drought monitoring [42]. None of the Aqua instruments is ideal for measuring soil moisture, but the AMSR-E provides a start. Satellite-based soil moisture measurements would most likely be better from instruments measuring at frequencies of about 1–2 GHz (L-band), although somewhat higher frequencies, as in the lower frequency channels of AMSR-E, are also useable [42]. Low frequencies are desired to limit contamination by vegetation cover and atmospheric effects. Only the Nimbus 7 SMMR, operational from late 1978 through mid-1987, has so far provided long-term global data at a frequency below 10 GHz (6.6 GHz specifically). However, because of the difficulties of obtaining soil moisture and the coarse spatial resolution (140 km) of the SMMR 6.6-GHz data, there was no dedicated algorithm development program for deriving soil moisture from the SMMR data. With AMSR-E, a soil moisture product is being calculated from the 6.9-, 10.7-, and, to a lesser extent, 18.7-GHz channels, at approximately 60-km spatial resolution [42]. The derived values are representative of only about the top 1 cm of the soil layer and are valid only under conditions of little or no vegetation. However, low vegetation areas are often precisely those where issues of water availability are most crucial. Thus, despite the limitations (which also include 6.9-GHz radio frequency interference in some regions, as discussed in [42]), the AMSR-E soil moisture measurements are an exciting new possibility, and they should serve as an important step toward future dedicated soil moisture missions measuring at lower microwave frequencies [60]. The dedicated missions will obtain soil moisture representative of a deeper layer of the soil (a few centimeters) and valid over a wider range of land conditions than the AMSR-E product [60].

The 6.9- and 10.7-GHz channels on AMSR-E (not available on SSM/I) are also being used to calculate sea ice temperature [41] and sea surface temperature (SST) (Fig. 3). SSTs are currently being calculated from TMI data for the tropics, but the AMSR-E allows all-weather SST measurements to be obtainable at higher latitudes as well, not restricted to the 40°S–40°N geographic coverage of TRMM.

The examples in this section and Section VI are provided to give a flavor of some of the contributions expected from the Aqua mission. Many more details are provided in the individual papers of this special issue of *TGARS*. The Aqua mission will be routinely generating over 100 data products, only a selection of which are described in this volume. For a more comprehensive listing and brief descriptions of the data products, the reader is referred to [14]. For up-to-date information on the mission, interested readers can check the Aqua science Web site at aqua.nasa.gov and the science team Web sites at www-airs.jpl.nasa.gov, www.ghcc.msfc.nasa.gov/AMSR, asd-www.larc.nasa.gov/ceres, and modis.gsfc.nasa.gov.

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