# AIRS/AMSU/HSB on the Aqua Mission: Design, Science Objectives, Data Products, and Processing Systems

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***Abstract*—The Atmospheric Infrared Sounder (AIRS), the Advanced Microwave Sounding Unit (AMSU), and the Humidity Sounder for Brazil (HSB) form an integrated cross-track scanning temperature and humidity sounding system on the Aqua satellite of the Earth Observing System (EOS). AIRS is an infrared spectrometer/radiometer that covers the 3.7–15.4-$\mu$m spectral range with 2378 spectral channels. AMSU is a 15-channel microwave radiometer operating between 23 and 89 GHz. HSB is a four-channel microwave radiometer that makes measurements between 150 and 190 GHz. In addition to supporting the National Aeronautics and Space Administration's interest in process study and climate research, AIRS is the first hyperspectral infrared radiometer designed to support the operational requirements for medium-range weather forecasting of the National Ocean and Atmospheric Administration's National Centers for Environmental Prediction (NCEP) and other numerical weather forecasting centers. AIRS, together with the AMSU and HSB microwave radiometers, will achieve global retrieval accuracy of better than 1 K in the lower troposphere under clear and partly cloudy conditions. This paper presents an overview of the science objectives, AIRS/AMSU/HSB data products, retrieval algorithms, and the ground-data processing concepts. The EOS Aqua was launched on May 4, 2002 from Vandenberg AFB, CA, into a 705-km-high, sun-synchronous orbit. Based on the excellent radiometric and spectral performance demonstrated by AIRS during prelaunch testing, which has by now been verified during on-orbit testing, we expect the assimilation of AIRS data into the numerical weather forecast to result in significant forecast range and reliability improvements.**

***Index Terms*—Climate, greenhouse gases, humidity sounder, hyperspectral, infrared, microwave, temperature sounder, weather forecasting.**

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## I. AIRS Mission Background and Overview

The BASIC physics involved in using the wavelength-dependent transmission of $CO_2$ between 13 and 15 $\mu$m for temperature sounders from earth orbit was published in 1959 by Kaplan [1]. In 1969, shortly after Chahine [2] published the relaxation algorithm to invert spectral radiances to temperature profiles, Wark and Hilleary [3] made the first experimental temperature soundings from space using the Satellite Infrared Radiation Spectrometer (SIRS). SIRS was a seven-channel grating spectrometer with a resolution of $\lambda/\Delta\lambda = 100$ in the 15-$\mu$m $CO_2$ band on Nimbus-4. By 1978, the High Resolution Infrared Sounder (HIRS), a filter-wheel radiometer with a spectral resolution of $\lambda/\Delta\lambda = 75$ and 19 channels between 3.7 and 15 $\mu$m, and the Microwave Sounding Unit (MSU), with four channels in the 50–57-GHz wings of the oxygen band, became the first of the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS). The four-channel MSU was replaced starting with NOAA-15 in 1998 by the Advanced Microwave Sounding Unit (AMSU), the combination of the AMSU-A1, AMSU-A2, and AMSU-B, with 19 channels between 23 and 190 GHz. The combination of HIRS/3, AMSU-A, and AMSU-B constitutes the current operational sounding system of the National Oceanic and Atmospheric Administration (NOAA).

The limiting effects of cloud contamination in the field of view of the infrared (IR) sounder were quickly recognized. There are several ways to deal with the cloud effects, including carefully detecting and rejecting data from cloud-contaminated footprints or eliminating the effects of clouds from the data.

The reliable identification of cloud-free IR footprints is a difficult and somewhat subjective task. The United Kingdom's Met Office [4] found that only 6.5% of the HIRS footprints are "clear" based on the analysis of overlapping HIRS 17-km and AVHRR 1-km footprints. Using AIRS simulated data, Goldberg *et al.* [5] found 4.5% of the fields of view over ocean with less than 0.6% cloud contamination. Since the European Centre for Medium Range Weather Forecasting (ECMWF) and the National Centers for Environment Prediction (NCEP) currently use only "clear" data from IR sounders for assimilation into forecast analysis fields [6], the small fraction of "clear" data from IR sounders has had little impact on the forecast.

One way to significantly reduce the effects of clouds is to use microwave data. Using the Nimbus-E Microwave Sounder (NEMS) on Nimbus-5, Staelin *et al.* [7] demonstrated the capability of microwave sensors to sense atmospheric temperatures within and below clouds. Unfortunately, the vertical resolution achievable in the troposphere from the microwave region is inferior to that achievable in the 4.3-$\mu$m $CO_2$ band, and it is difficult to build microwave instruments with hundreds of temperature sounding channels. In addition, microwave emissivity is strongly frequency and surface dependent, such that even with the best models the residual emissivity uncertainty makes the "microwave-only" solution less attractive.

The alternative to cloud filtering is "cloud-clearing." Smith [8] proposed the $N^*$ parameter for IR cloud clearing and demonstrated the technique using the Infrared Temperature Profile Radiometer (ITPR) on the Nimbus-5 satellite. Chahine [9], [10] proposed a physical basis for cloud-clearing IR radiances by analytically combining IR sounder data and 54-GHz band microwave sounder data. McMillin and Dean [11] tested a variant of the $N^*$ method using data from the operational TOVS (HIRS/MSU).

The information content of the 19 HIRS and four MSU bands is inadequate to simultaneously yield an accurate temperature profile, moisture profile, surface temperature, and wavelength-dependent emissivity *and* eliminate cloud contamination effects. The replacement of the MSU with the 15-channel AMSU-A and the addition of the five-channel AMSU-B with NOAA15 did not resolve this basic problem. In 1977, Kaplan *et al.* [12] showed that a major improvement in vertical resolution and accuracy could be achieved by increasing the spectral resolution $\lambda/\Delta\lambda = 75$ to $\lambda/\Delta\lambda = 1200$ and by using many more sounding channels, including the R-branch of the 4.2-$\mu$m $CO_2$ band. This increased information content, available with much higher spectral resolution IR data, was out of reach for an operational IR sounder using the technology of the late 1970s. It took another ten years, until the late 1980s, before breakthroughs in IR detector and cooler technology made such an instrument practical.

The World Meteorological Organization (WMO) predicted in 1987 [13] that, by the mid-1990s, data assimilation would reach the stage where the accuracy of model-derived atmospheric temperature fields would exceed that obtained from the operational satellite soundings based on HIRS and MSU. Additional improvements in numerical weather prediction would require improvement in the accuracy of atmospheric temperature profiles to better than 1 K, with 1-km vertical layers (referred to as the "1 K/1 km" requirement) and humidity soundings with 10% accuracy in 2-km layers in the troposphere, both globally, with 100-km horizontal sampling. The required accuracy is routinely achieved by radiosondes. To establish the feasibility of the WMO requirements, an extensive data-simulation and retrieval-algorithm development effort was combined with a technology assessment to establish instrument design and measurement capabilities. In 1989, D. Q. Wark, then the Senior Scientist at NOAA's National Environmental Satellite Data and Information Service (NESDIS), proposed a set of measurement requirements for an "Inter-agency Sounder," which was accepted by a team of scientists from NOAA and NASA. The measurement requirements included detailed specifications of spectral coverage, sensitivity, resolution, calibration accuracy and stability, and spatial-response characteristics. The ability of this sounder to work in combination with the microwave sounder was key to achieving "1 K/1 km" globally under clear and cloudy conditions.

TABLE I
AIRS TEAM SCIENCE TEAM

| | |
|---|---|
| Hartmut H. Aumann | Spatial and Temporal Extent of Sea Surface Temperature Abnormalities and Climate Correlations |
| Moustafa T. Chahine(1) | Radiative Interactions in Cloudy Atmospheres |
| Alain P. Chedin | Improved Initialization Inversion |
| Catherine Gautier | Global Surface Radiation Budget Computations |
| Henry Fleming (2) | Retrieval Algorithm Development for AIRS |
| John LeMarshall | Validation of AIRS Data Impact on Mesoscale Analysis and Prediction |
| Larry McMillin | Validation and Tuning of AIRS Measurements |
| Ralph Petersen (3) | Evaluation of AIRS Data for Global and Regional Weather Prediction Allocations |
| Hank Revercomb | Climate Applications of AIRS |
| Rolando Rizzi | Validation of the 3-Step Cloud Filtering Method |
| Philip W. Rosenkranz | Algorithms development for microwave retrievals |
| William L. Smith | AIRS Algorithm Development using HIS Data |
| David Staelin | Recursive Estimation of Geophysical Products with AIRS/AMSU data |
| Larrabee Strow | AIRS Radiance Validation and Constituent Abundance Retrieval |
| Joel Susskind | Determination of Surface and Atmospheric Parameters from AIRS |

(1) AIRS Science Team Leader
(2) Replaced by Mitch Goldberg, NOAA/NESDIS
(3) Replaced by Eugenia Kalnay, then NOAA/NCEP, now University of Maryland.

Based on proposals (Table I) submitted by the members of the team, the then Associate Administrator for Space Science and Applications, L. A. Fisk, in a letter dated January 18, 1991, appointed the AIRS Science Team members to become integral partners in the development of the AIRS facility instrument for the Earth Observing System (EOS), including the AIRS spectrometer, the AMSU-A, and the AMSU-B, with M. Chahine as the AIRS Facility Team Leader. The "Inter-agency Sounder" measurement requirements became the basis of the AIRS design. Aumann and Pagano [14] described the 1993 instrument concept, which ultimately was implemented with relatively few modifications. AIRS, along with the AMSU microwave sounder, was to form an advanced sounding system under clear and cloudy conditions.

The AIRS spectrometer was designed, fabricated, and tested by Loral Infrared Imaging Systems in Lexington, MA, which was acquired first by Lockheed Martin and then British Aerospace Systems, with overall project management by the Jet Propulsion Laboratory (JPL). A copy of the AMSU-A1 and AMSU-A2 was procured by the Goddard Space Flight Center (GSFC) from AeroJet in Azusa, CA. A copy of the AMSU-B, without the 89-GHz channel, was procured by the

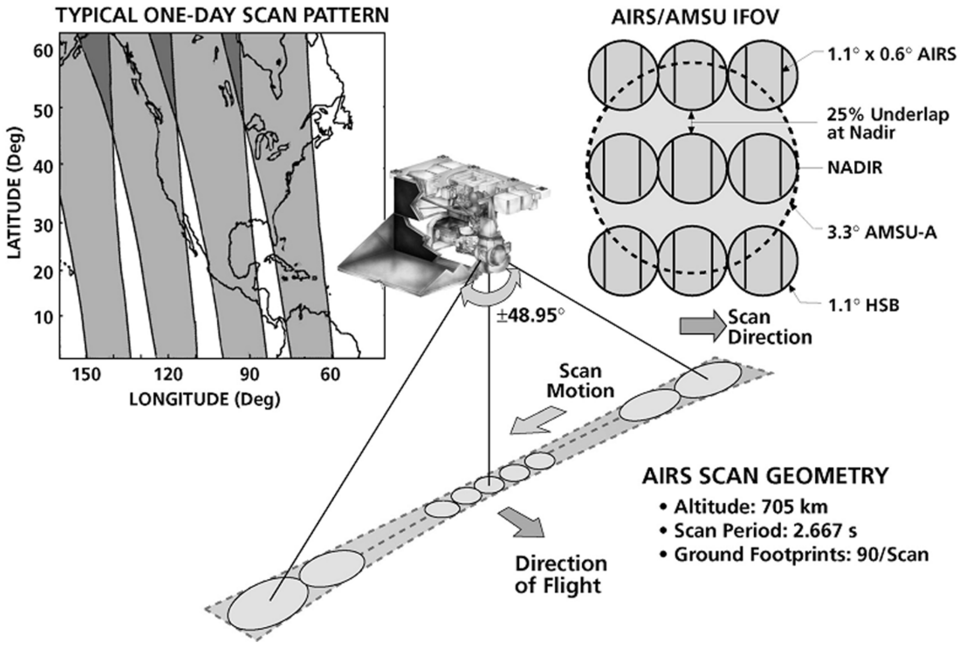


Fig. 1. Relative alignment of the AIRS/AMSU/HSB footprints is key to achieving radiosonde accuracy retrievals.

Brazilian Space Agency (INPE) from Matra Marconi Space (U.K.) and named HSB. The AIRS Science Team members have been integrally involved in the development of the AIRS spectrometer, its calibration, the development of the algorithms to convert radiances to the geophysical sounding products, and the development of the data processing system to make the data available to the scientific community and the operational weather forecasting centers.

## II. AIRS Science Objectives

The AIRS spectrometer is designed to operate in synchronism with the microwave instruments AMSU-A1, AMSU-A2, and HSB. The simultaneous use of the data from the three instruments provides both new and improved measurements of cloud properties, atmospheric temperature and humidity, and land and ocean skin temperatures, with the accuracy, resolution, and coverage required by numerical weather prediction and climate models.

Among the important datasets that AIRS will contribute to climate studies are as follows:

- atmospheric temperature profiles;
- sea-surface temperature;
- land-surface temperature and emissivity;
- relative humidity profiles and total precipitable water vapor;
- fractional cloud cover;
- cloud spectral IR emissivity;
- cloud-top pressure and temperature;
- total ozone burden of the atmosphere;
- column abundances of minor atmospheric gases such as $CO_2$, $CH_4$, CO, and $N_2O$;
- outgoing longwave radiation and longwave cloud radiative forcing;
- precipitation rate.

Alignment and synchronization of the "AIRS Instrument Suite" are key to the ability to achieve 1-K/1-km retrieval accuracy in the presence of clouds. The scan geometries of AIRS and HSB, both with 1.1° footprints, relative to the AMSU, with a 3.3° footprint, are illustrated in Fig. 1. The on-orbit verification of this special alignment is discussed in [15].

The AIRS/AMSU/HSB data will be used to improve numerical weather predictions and to support climate-related studies. These include the evaluation of the potential correlation between the speed of the hydrological cycle, cirrus clouds, and greenhouse gas abundance with global warming. Also of interest to climate are the global day/night measurements of ozone, CO, and $CO_2$ profiles possible with AIRS data.

### A. Improving Numerical Weather Prediction

The data from satellite sounding systems are used to augment the operational radiosondes (about 4000 are launched every day) in the global definition of the initial conditions for the General Circulation Models (GCM) used by the Numerical Weather Prediction (NWP) centers around the world. There are two ways to assimilate data into a GCM: direct assimilation and retrieval assimilation. For direct assimilation, calculated radiances, based on the state of the atmosphere as defined by the GCM analysis and the instrument characteristics, are directly compared to the calibrated radiances measured by an instrument, the level 1b product in the case of AIRS.

The state of the atmosphere in the GCM is adjusted to achieve agreement within the noise. This process works currently only with radiances from cloud-free fields of view; all but about 5% of the data have to be rejected as cloud-contaminated [4]. The potential impact of AIRS data on forecast accuracy would, thus, be limited to the small fraction of cloud-free data. The high spectral resolution of AIRS data suggests a potential alternative to rejecting all data from cloud-contaminated footprints, which will be tested with AIRS data by ECWMF: soundings are made to the cloud tops, and only the data affected by clouds are rejected. The alternatives to rejecting cloudy data are to either assimilate "cloud-cleared" radiances or to assimilate temperature and moisture profiles (Level 2 products) obtained from cloud-cleared data, similar to the current assimilation of conventional radiosonde and land and ocean surface-temperature reports. Because the data from AIRS/AMUS/HSB are expected to produce radiosonde-quality soundings in the presence of significant cloud cover, perhaps as much as 80% of the AIRS data should be usable to help define the initial state of the GCM. Since the error in the forecast doubles every two days that a forecast is extended, the radiosonde quality of global AIRS data in the presence of many cloud types should lead to significant advances in the reliability of the three- to five-day forecast.

### B. Study of Processes That Affect the Climate

Ultimately, the earth's climate depends on the radiative output of the sun and the balance between the portion of the shortwave radiation absorbed from the sun and the longwave radiation reemitted into space from the earth's surface, clouds, and atmosphere. However, the earth's climate is a complex system with many components and feedback processes that operate on different characteristic time scales. The slow components, with characteristic time scales of the order of decades and longer, involve the deep oceans and permanent and semipermanent ice and snow covers. The fast components, with time constants of days to months, encompass the atmosphere, upper ocean layers, and include the biosphere as well as air–land and air–sea interactions and clouds. Atmospheric and surface measurements from AIRS will be able to provide data regarding these faster interactions with unprecedented accuracy.

The study of the global hydrologic cycle, with a characteristic time of about two weeks, is an example of one of the faster processes that can be studied using AIRS/AMSU/HSB data. AIRS will measure the major components of these driving forces, including the thermal structure of the surface and atmosphere, the amount and height of clouds, outgoing longwave IR radiation, the distribution of atmospheric water vapor, and precipitation. Particularly important is the unique ability of AIRS to measure water vapor in the upper troposphere between 300 and 100 mbar. Since conventional radiosondes provide no usable water vapor information at pressures below 300 mbar, corresponding to an altitude of about 12 km, the GCMs tend to be too dry [16]. Cirrus clouds in the upper troposphere trap more energy than they reradiate, thus producing a net warming effect. The spectral signature of cirrus clouds can be detected directly by AIRS. The measurements of the water cycle and the upper tropospheric water amount will be key to assessing changes indicative of or precursors to climate change.

Another example of processes related to climate amenable to study with AIRS data is measurement of the amount and the effects of increased greenhouse gases. The most important greenhouse gas is water vapor, followed by carbon dioxide and methane. The ability to provide simultaneous observations of the earth's atmospheric temperature, ocean surface temperature, and land surface temperature, as well as humidity, clouds, albedo, and distribution of greenhouse gases, will enable AIRS to provide a single consistent dataset with which to observe the effects of increased greenhouse gases.

TABLE II
AIRS DATA PRODUCTS

| | Product Name | Accuracy Absolute :: Relative | Data Volume [Gbytes/day] |
|---|---|---|---|
| Level 1b | Radiance (IR) cloudy | 3% (190 K-330 K) :: 0.2 K at 250 K | 29 |
| | Radiance (IR) cloud cleared | 3% (190 K-330 K) :: 0.3 K at 250 K | 3.1 |
| | Radiance (AMSU-A) | 1.5 K:: 0.5 K | 0.075 |
| | Radiance (HSB) | 1.K:: 0.6 K | 0.334 |
| | Radiances (VIS/NIR) | | 4.2 |
| Level 2 | Temperature Profile T(p) | 1 K rms in 1 km layers below 100 mb | 1.1 |
| | Humidity Profile q(p) | 20% required, 10% goal::10% in 2 km layers below 100 mb | (2) |
| | Precipitable water [mm] | 5%::3% | (2) |
| | Surface Skin Temperature | 1 K:0.5 K | (2) |
| | Cloud Top Height | 0.5 km::0.25 K | (2) |
| | Cloud fraction | 10%:5% | (2) |
| | Cloud Liquid water content | 20% | (2) |
| | Ozone total column | 20% | (2) |

(1) Product specifications from the 1999 EOS Reference Handbook. For up-to-date information on product readiness see http://airstream.jpl.nasa.gov. For file sizes, formats and for ordering data see http://daac.gsfc.nasa.gov/atmodyn/airs/

(2) All level 2 products for one granule are in one HDF file, with 240 granules/day.

Table II lists the data products obtainable from the algorithm developed by the science team members. It leverages the IR sounding channels and microwave sounding channels to obtain the highest accuracy geophysical products. Global coverage is twice per day. Calibrated radiances (also referred to as Level 1b products) will be obtained at the instrument footprint size 13.5, 40, and 13.5, for AIRS, AMSU, and HSB, respectively. Retrieved geophysical products, also referred to as Level 2 products, including cloud-cleared radiances, are based on the combined AIRS/AMSU/HSB 40-km scale.

The AIRS Team is actively collaborating with NWP centers to ensure that the full impact of AIRS is realized in improving weather forecasting. End-to-end simulations of AIRS/AMSU/HSB data have been used to fully test the Product Generation System and corresponding algorithms and to prepare for the scientific exploitation of the AIRS data after launch [17]. In the sections that follow, we provide a brief overview of the AIRS, AMSU, and HSB instruments, calibration, and data processing. A series of articles by AIRS Science Team members in this special issue of TGARS describes details of the radiometric, spectral, and spatial calibration, and the various algorithms for the retrieval of the geophysical parameters and the data processing systems. The data processing system at JPL focuses on algorithm development and data-product validation. The GSFC DAAC supports routine data processing, archiving, and distribution. The NOAA/NESDIS computer system is optimized to support near-real-time data distribution to the medium-range weather forecasting centers.

## III. AIRS Instrument

The AIRS instrument, shown in Fig. 2 during final inspection, provides spectral coverage in the 3.74–4.61-$\mu$m, 6.20–8.22-$\mu$m, and 8.8–15.4-$\mu$m infrared wavebands at a nominal spectral resolution of $\lambda/\Delta\lambda = 1200$. A diffraction grating disperses the radiation from the scene onto 17 linear arrays of HgCdTe detectors on the focal plane. The layout of the focal plane is shown in Fig. 3. The focal plane is mounted on an 8.4 mm $\times$ 37 mm ceramic substrate. It contains all detector arrays and readout electronics. Each detector array has dimension of $N \times 2$, where $N$ ranges from 94 and 192 elements. Two rows (A and B) provide redundancy of the readout electronics and bias power supplies.

The focal plane is cooled to 60 K by a Stirling/pulse tube cryocooler. The IR spectrometer is cooled to 155 K by a two-stage passive radiative cooler. This temperature is controlled to within 0.1 K of the setpoint by a choke heater. The time constant of the spectrometer is approximately 23 hours. Cooling of the detectors and the optics is necessary to achieve the required instrument sensitivity. Spatial coverage and views of cold space and hot calibration targets are provided by a scan mirror. The mirror makes a full revolution every 2.67 s. The scan mirror is radiatively coupled to the spectrometer and operates at a temperature of 250 K. This temperature is recorded in the telemetry and is a parameter in the radiometric calibration equation [18].

The AIRS instrument also includes four visible/near-IR (Vis/NIR) channels between 0.40 and 0.94 $\mu$m, with a 2.3-km FOV. The four spectral bands are defined by filters. Two of the channels emulate the AVHRR visible channels. The Vis/NIR detectors operate at the 293-K ambient temperature range of the instrument housing. Each AIRS IR footprint is mapped into an 8 $\times$ 9 pattern of Vis/NIR footprints. Because the IR channels and the Vis/NIR channels share the scan mirror, the spatial relationship between the IR and Vis/NIR is fixed. The spatial relationship between the Vis/NIR and the IR spectrometer will be established empirically in orbit at the 1-km level using coastline crossings. The primary function of the Vis/NIR channels is for the diagnostics of cloud in the IR FOV. Details are discussed in [19].

Design redundancy in the major subsystems, including the Stirling coolers and electronics, has been employed for an expected seven-year on-orbit lifetime.

Signals from both the IR spectrometer and the Vis/NIR photometer are passed through onboard signal and data processing electronics, which perform functions of radiation circumvention, ground-programmable gain adjustment and offset subtraction, signal integration, and output formatting and buffering to the high-rate science data bus. In addition, the AIRS instrument contains command and control electronics whose functions include communications with the satellite platform, instrument redundancy reconfiguration, the generation of timing and control signals necessary for instrument operation, and collection of instrument engineering and housekeeping data. Table III summarizes high-level AIRS parameters. Morse *et al.* [20] gave a more detailed description of the AIRS instrument and testing program. Pagano *et al.* [18] presented the results of AIRS prelaunch performance testing.

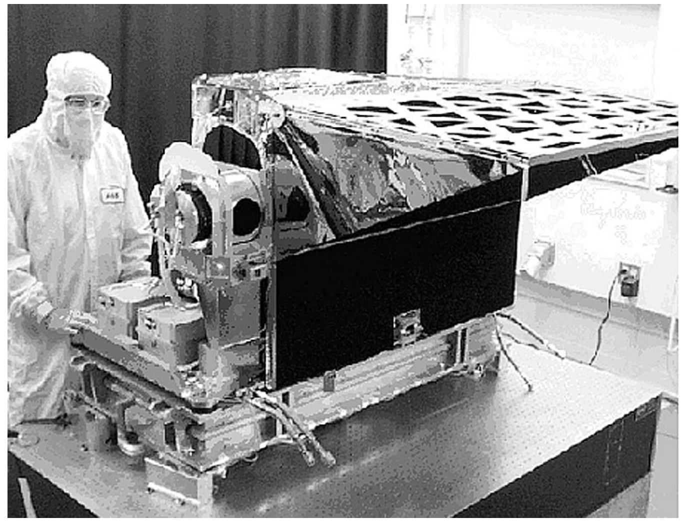

Fig. 2. AIRS during final inspection at BAE in the fall of 1999.

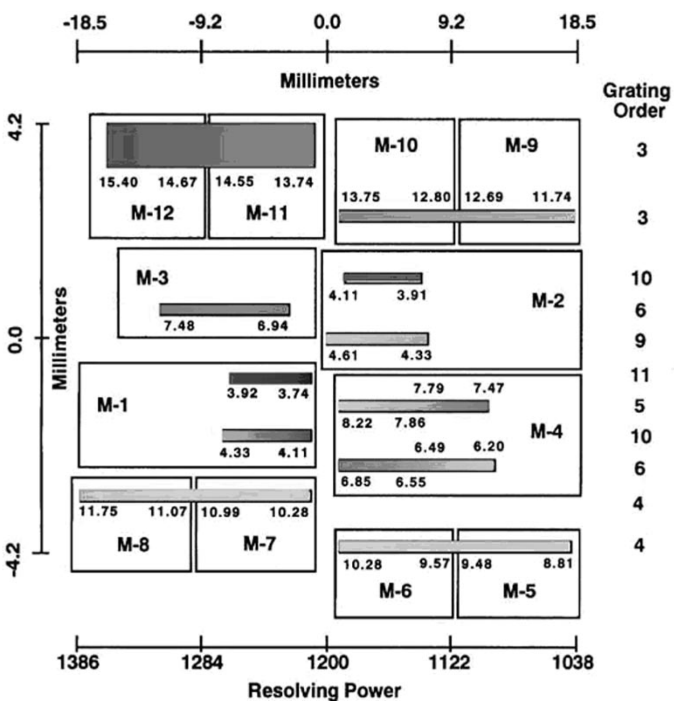


Fig. 3. AIRS focal plane contains 17 detector arrays and their readout electronics on a ceramic substrate. The two arrays labeled M4 consist of two arrays each, which are butted together.

The prelaunch and in-flight calibration of AIRS is critical to the mission success. Details of the AIRS radiometric, spectral, and spatial calibration are discussed in subsequent papers [21]–[24]. AIRS superclear window channels, selected to minimize absorption by atmospheric lines, will be used to globally validate the radiometric calibration. This process will initially include the use of sea surface temperature models provided by NOAA/NCEP. Ultimately, the long-term validation and monitoring of the radiometric calibration accuracy required for climate studies will exclusively use surface marine reports [25].

TABLE III
HIGH-LEVEL AIRS PARAMETERS

| | |
|---|---|
| Size | Stowed: 116.5 × 80 × 95.3 cm<br>Earth shade deployed: 116.5 × 158.7 × 95.3 cm |
| Mass | 177 kg |
| Power | 220 Watt |
| Data Rate | 1.27 Mbits per second |
| Spectral Range | IR: 3.74 – 15.4 μm<br>2378 channel with λ/Δλ =1200 resolution<br>VIS/NIR: 0.4 – 1.1 μm with 4 channels |
| Aperture | IR: 10 cm<br>VIS/NIR: 0.2 to 1 cm |
| Instrument Field of View | IR: 1.1 degree (13.5 km at nadir from 705 km altitude)<br>VIS/NIR: 0.2 degree (2.3 km from 705 km altitude) |
| Swath Width | 99 degree (1650 km from 705 km orbit altitude) |
| Scan Sampling | IR: 90 × 1 × 1.1 degree<br>VIS/NIR: 720 × 8 × 0.2 degree |
| Pointing Accuracy | IR and VIS/NIR 0.1 degree (2 sigma) |
| Thermal Control | IR detectors: active cooler at 60 K<br>Spectrometer: Passive Radiator at 150 K<br>Electronics: Ambient |
| Prime Contractor | British Aerospace SYSTEMS (formerly Lockheed Martin Infrared Imaging Systems division) |
| Procurement, Operations and Data Processing Software | Jet Propulsion Laboratory |

TABLE IV
HIGH-LEVEL MICROWAVE INSTRUMENT PARAMETERS

| Instrument | AMSU A1 | AMSU A2 | HSB |
|---|---|---|---|
| Size | 72 x 34 x 59 cm | 73 x 61 x86 cm | 70 x 65 x 46 cm |
| Mass | 49 kg | 42 kg | 51 kg |
| Power | 77 watt | 24 watt | 56 watt |
| Data Rate | 1.5Kbits/second | 0.5Kbits/second | 4.2Kbits/second |
| Spectral Range | 50-90GHz | 23-32 GHz | 150 – 190 GHz |
| Channels | 13 | 2 | 4 |
| Aperture | 15 cm (two) | 30 cm (one) | 18.75 cm (one) |
| Instrument Field of View | 3.3 degree (40.5 km at nadir from 705km) | 3.3 degree (40.5 km at nadir from 705 km) | 1.1 degree (13.5 km at nadir from 705 km) |
| Swath Width | 100 degree (1690 km from 705 km) | 100 degree (1690 km from 705 km) | 99 degree (1650 km from 705 km) |
| Scan Sampling | 30 x 3.33 degrees | 30 x 3.33 degrees | 90 x 1.1 degrees |
| Pointing Accuracy | 0.2 degrees | 0.2 degrees | 0.1 degrees |
| Thermal Control | None (ambient) | None (ambient) | None (ambient) |
| Prime Contractor | Northrop Grumann (previously Aerojet) | Northrop Grumann (previously Aerojet) | Astrium, UK (Matra Marconi Space, UK) |
| Procurement | NASA/GSFC | NASA/GSFC | INPE (Brazil) |
| Operation and Data Processing Software | Jet Propulsion Laboratory | Jet Propulsion Laboratory | Jet Propulsion Laboratory |

## IV. AMSU AND HSB INSTRUMENTS

The ability of the AIRS/AMSU/HSB sounder system to obtain accurate temperature and moisture profiles in the presence of clouds is based on the combined analysis of AIRS infrared and AMSU microwave data. AMSU-A is comprised of two separate sensor units, AMSU-A1 and AMSU-A2, with coaligned, synchronized, and equal-size field of views. The AMSU-A footprint is three times wider than the AIRS footprint and covers a cluster of nine AIRS footprints. Fig. 1 shows the relative alignment of these instruments. Data from one AMSU footprint and nine AIRS footprints are used to create a single "cloud-cleared" infrared spectrum. The HSB is essentially a copy of the AMSU-B minus the 89-GHz channel. The high-level microwave instrument parameters are listed in Table IV. Because AMSU and AMSU-B instruments have been in orbit since 1998, the calibration software is relatively mature. Details for instrument prelaunch calibration, alignment, and synchronization can be found in [26].

## V. AIRS/AMSU/HSB PRODUCT GENERATION SOFTWARE

The AIRS Product Generation Software (PGS) has seven major modules: calibration, microwave retrieval, cloud clearing, initial IR retrieval, physical retrieval, bias correction, and radiative transfer calculations. The output are the products listed in Table II.

1) Level 1b software is used to convert the Level 1a (raw data numbers from the instruments) to calibrated radiances. Details can be found in the Level 1b Algorithm Theoretical Basis Documents for the IR spectrometer [27], for the Vis/NIR [28], and for the microwave instruments [29]. The software uses the internal calibration sources and space views for the radiometric calibration. The upwelling spectral radiances are used for the AIRS spectral calibration. In addition, the Level 1b software generates quality assessment (QA) indicators that are used to monitor the health of the AIRS instrument and trend system performance.
2) *Microwave retrieval:* The microwave calibrated radiances are used to generate the initial estimate of the temperature and moisture profile. Details of the algorithm are given in [30]. Key to the algorithm is the "Rapid Forward Model for AMSU/HSB Channels," which is described in [31]. Microwave data are not affected by most clouds; they are, however, affected by precipitation and uncertainty in surface emissivity. The "at-launch" algorithm generates a precipitation flag to alert subsequent users of the data and includes an initial precipitation-rate estimate.
3) *Cloud clearing:* Selected IR and microwave channels are used to create the "cloud-cleared" IR radiance product. The algorithm combines the $3 \times 3$ pattern of AIRS data that overlay a single AMSU footprint into a single cloud-cleared spectrum on the AMSU 40-km footprint scale. The precipitation flag generated by the microwave algorithm is used to identify data where the microwave radiances are perturbed by precipitation and are not usable for cloud clearing. Details of the cloud-clearing algorithm are described in [32]. Retrievals of all geophysical products use the "cloud-cleared" radiance product as input.

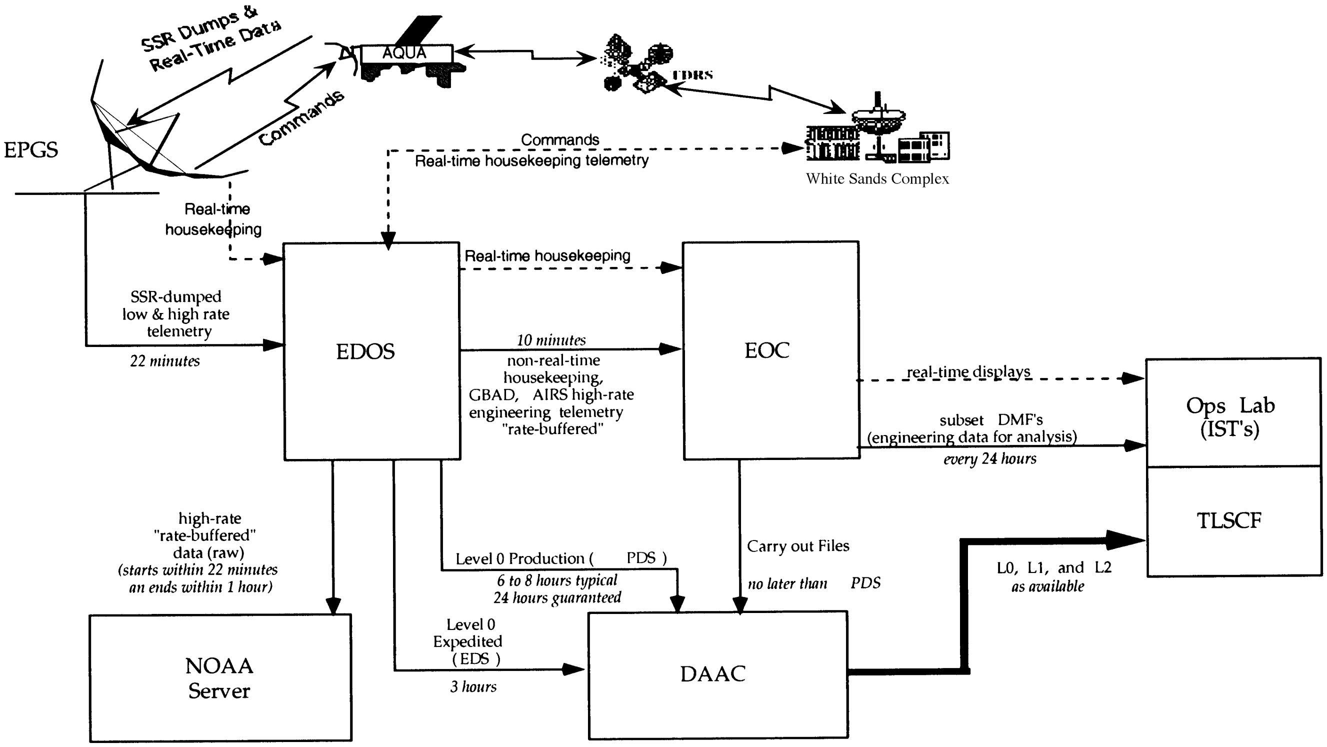


Fig. 4. Dataflow from the EOS Aqua accommodates the near-real-time data requirement of weather services.

4) *First IR retrieval:* The first IR retrieval of temperature and moisture profiles as function of pressure, $T(p)$ and $q(p)$, uses physical regression. Goldberg *et al.* [5] provide details.
5) *Final IR retrieval:* The initial solution for the temperature and moisture profiles is used to initialize the iterative physical retrieval described in [32]. In addition to temperature and moisture profiles, the software solves for IR and microwave surface emissivity as a function of frequency, total ozone, cloud fraction, and cloud top height for up to two cloud layers and IR cloud emissivity.
6) *Bias estimation module and tuning:* Convergence of the physical retrieval solution is based essentially on a chi-squared test of (observed − calculated). The chi-squared test assumes that any bias in (observed − calculated) in a globally representative sample of data is well below the noise level. If this assumption is not valid, the chi-squared test has to be written as $\Sigma_i(\text{observed}_i - \text{calculated}_i - \text{bias}_i)^2/\text{noise}_i^2$. The inclusion of the bias term is referred to as "tuning." Bias and and noise of each channel are estimated from the analysis of (observed − calculated) for cloud-free cases where the truth is reliably known either from routine radiosonde launches (RAOB) or from validation data obtained during the Aqua pass over special validation sites [33]. Special observation sites include the Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) site in Oklahoma, the north slope of Alaska, and similar sites in Germany, France, the South Pacific, and Brazil. The result of the analysis of clear truth data is a regression-based bias equation for each channel, which may be zero or as simple as a constant for some channels. Some channels may not be "tunable." This is particularly true for the upper tropospheric water channels due to the dry bias in the RAOBs.
7) *Radiative transfer module:* Key to the ability to accurately calculate the radiances that would be observed with a given $T(p)$, $q(p)$ is a very fast radiative transfer calculation algorithm (RTA). The RTA is accessed as a subroutine by the modules related to the data processing. The radiative transfer algorithm development for the IR channels and its validation is described in [34]; the microwave RTA is described in [31].

The noise term in the chi-squared test is due to a combination of instrument noise, spatial and temporal mismatch between the radiosonde and the AIRS observations, and uncertainty in the forward algorithm and the bias term. The AIRS instrument noise, which is routinely estimated by the level 1b software using cold-space-view data [21], defines the lower limit to the noise. The uncertainty of the forward algorithm calculation is expected to be less than the instrument noise. The spatial and temporal mismatch between the AIRS observations and the ground truth is minimized using the special validation sites.

Algorithms for the retrieval of minor gases (other than ozone), CO, $CO_2$, cirrus, surface wind speed, and others are being developed as "research products." Software for these products is not part of the initial "at-launch" PGS, but will be included in PGS upgrades after proper validation starting about one year after launch. Two of these experimental algorithms—precipitation and mesoscale retrievals—are of particular interest.

1) The "at-launch" microwave retrieval algorithm produces a precipitation flag and a preliminary precipitation rate product that was tuned for mid-latitudes (Continental United States), as discussed in [35]. This precipitation estimate appears to respond well to both rain and snow

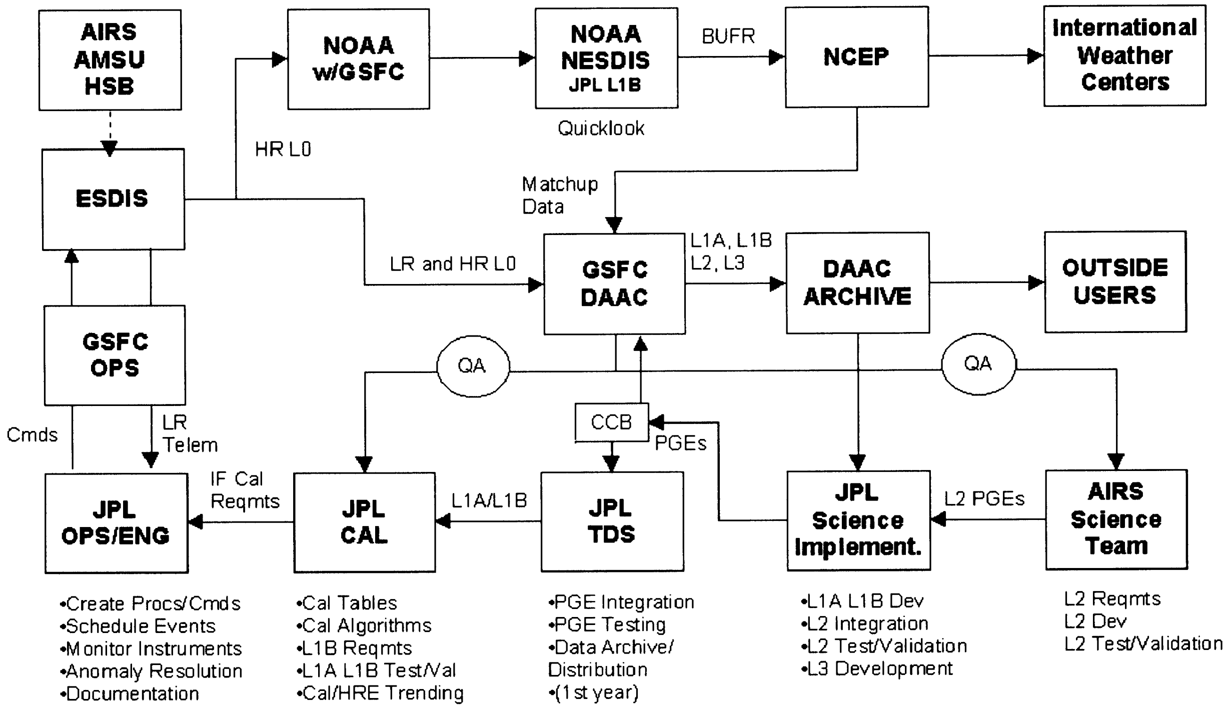


Fig. 5. Interagency connections for instrument operations and data processing.

over both land and sea; because it primarily utilizes opaque frequencies, it is much less sensitive to surface conditions than are prior methods utilizing microwave window channels.

2) The AIRS/AMSU/HSB retrievals are based on cloud-cleared radiances, which are generated on AMSU footprint centers, i.e., with 40-km characteristic scale. Conceptually, the radiance measured by the MODIS sounding channels in 1 km or larger holes in the clouds in AIRS 13.5-km footprints might be usable for cloud clearing. This would allow $T(p)$, $q(p)$ retrieval on a 15-km AIRS footprint scale. This product could be very useful to feed mesoscale forecast models. In case of an AMSU failure, the use of MODIS data for cloud clearing of the AIRS data has to be considered as potential backup.

## VI. Dataflow, Science Data Processing, and Data Release

The AIRS dataflow and data processing system were designed to support the near-real-time data access requirements of the weather forecasting centers and the more archival process and climate research objectives of NASA. This requires close interaction between the AIRS Science Team and four organizations: the Earth Data Operations System (EDOS), NOAA/NESDIS, DAAC at GSFC, and the Team Leader Science Computing Facility (TLSCF) at JPL. The dataflow from the EOS Aqua spacecraft is shown in Fig. 4. The responsibilities of these organizations are defined in detailed Interface Control Documents (ICD).

Passes of the EOS Aqua over a ground receiving station occur for every orbit (about every 100 min). Data from a ground station overpass are received within 22 min at EDOS and passed from there to the NOAA/NESDIS server and the GSFC/DAAC as high-rate buffered data.

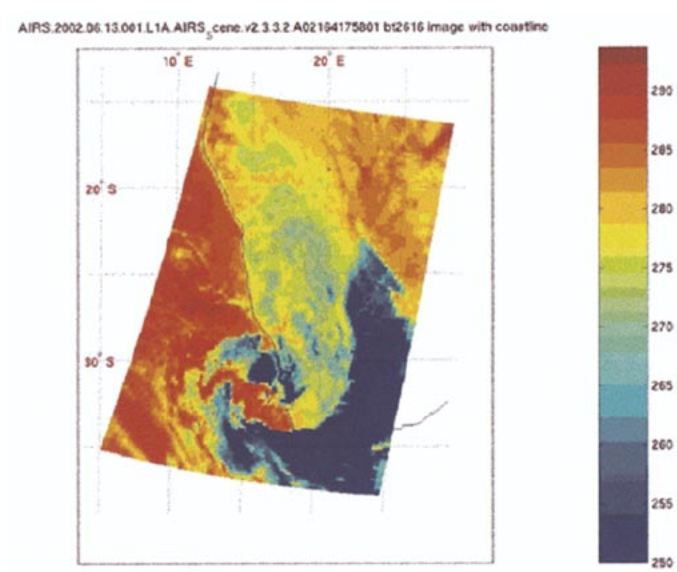


Fig. 6. Image in the 2616-cm$^{-1}$ window channel of the first-light data granule from the AIRS IR spectrometer obtained within minutes after the instrument was activated on the morning of June 13, 2002. A full spectrum is obtained for each of the 12 150 footprints in one granule.

At NOAA/NESDIS, the Level 0 data are converted to Level 1b and are quality-controlled using software supplied by the JPL TLSCF. The data are then thinned from 2378 channels to key sounding channels (about 300) at the center of every second AMSU-A footprint and distributed to the numerical weather forecasting centers using the BUFR format within three hours after the data are received [5].

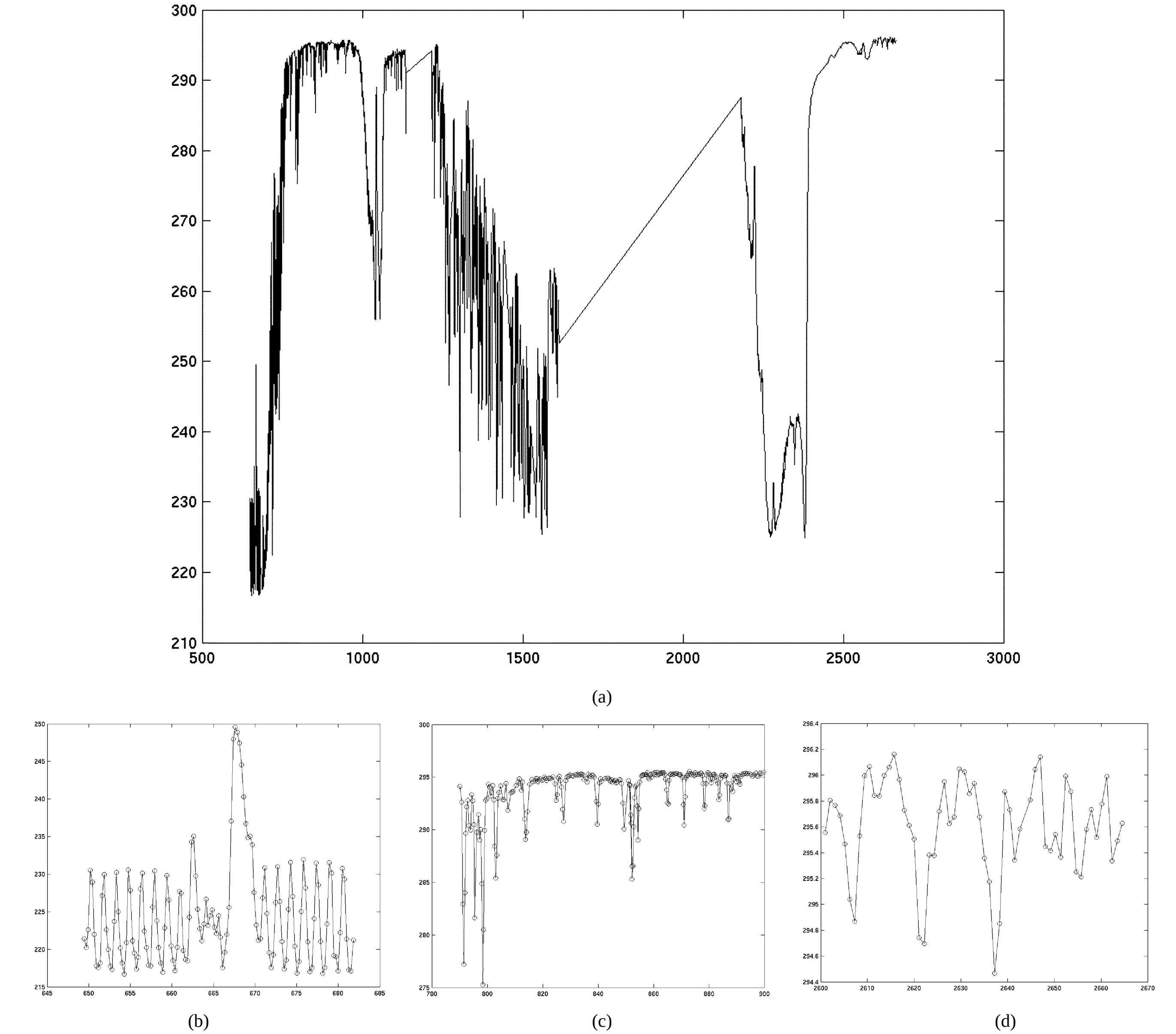


Fig. 7. (a) Upwelling spectrum in brightness temperature units of one clear ocean footprint between 640 and 2680 cm$^{-1}$. (b)–(d) zooms in on the spectrum of upper tropospheric $CO_2$ lines between 640 and 680 cm$^{-1}$, weak water lines between 785 and 880 cm$^{-1}$, and the 2616 cm$^{-1}$ superwindow channel between the weak water lines in the 2590–2670-cm$^{-1}$ region of the spectrum. AIRS characterizes the state of the atmosphere with 3 000 000 spectra each day.

The GSFC/DAAC eliminates multiple copies of the data and converts them to Level 1b and Level 2 data products using the PGS supplied by the TLSCF.

Level 1b products at NOAA and the DAAC are identical. All products are archived at the DAAC and made available to the science user community. The PGS is based on algorithms developed by AIRS Science Team members and documented in the Algorithm Theoretical Basis Documents. Fig. 5 illustrates the connections between the Science Team and these Centers. It also shows the operations link from the JPL operations/engineering team through Earth Science Data Information System to the AIRS/AMSU/HSB instruments.

The Science Team is responsible for the spot validation of Level 1b and Level 2 products and algorithm and software upgrades as soon as the real AIRS/AMSU/HSB data become available. The development and upgrading of the PGS and the routine validation of the data products is done at the TLSCF. A description of the architecture and capabilities of the AIRS science data processing system is provided in [36]. Samples of first-light data processed at the TLSCF will be made available via the GSFC DAAC to the general science user community by launch + four months.

Evaluation of AIRS radiances by NASA, NOAA, ECMWF, and other international forecasting centers is expected to start at launch plus-five months This effort will focus on the evaluation of the statistical properties of (calculated − observed). This will be followed by the experimental assimilation of cloud-free AIRS radiances. Ultimately, for operational assimilation, this is expected to expand to the assimilation all AIRS radiances to the cloud-top height, the assimilation of cloud-cleared radiances, and the assimilation of temperature and moisture profiles (Level 2 products) based on cloud-cleared radiances.

To maximize the usefulness of the AIRS data products to science investigations and archival use, routine validation of the data, i.e., documentation of their absolute and relative accuracy, is the responsibility of the TLSCF. The overall concept is described in the AIRS Data Product Validation Plan, which is summarized in [33]. Algorithm and software updates by the AIRS Science Team as a result of the validation activities by launch plus-12 months will be incorporated into the operational data processing software at the GSFC DAAC. At launch plus-12 months AIRS data products will become available routinely through the GSFC/DAAC. Data products can be requested from the GSFC DAAC on a per-granule basis, where one granule is 6 min of data, i.e., 240 granules/day. The last column in Table II shows the volume of data in gigabytes/day required to store the data products in the EOS Hierarchial Data Format (EOS HDF) at the GSFC DAAC. There are four HDF files for calibrated radiances, one HDF file for cloud-cleared IR radiances and one for all Level 2 products. The calibrated radiances add up to 34 GB/day; Level 2 retrievals can be stored in only 1.1 GB/ day. While this appears to be a significant amount of data compression, alternative data compression and/or decimation schemes are under evaluation to optimize data utilization.

The validation task ultimately has to demonstrate that the AIRS Level 2 products globally meet the "radiosonde accuracy" stated in Table II. Global validation of all Level 2 products at this level might not be feasible by launch plus–12 months due to the sparseness of truth data. Software refinement, Level 2 product upgrades, new product validation, and routine Level 2 product quality monitoring continue throughout the expected seven-year mission life of the EOS Aqua.

AIRS, AMSU, and HSB were launched successfully on May 4, 2002 on the EOS Aqua spacecraft into a 705-km high circular sun-synchronous 1:30 P.M. orbit. First-light data from AIRS were received on June 13, 2000. Fig. 6 shows the first-light image from AIRS, taken near the coast of West Africa at 1:30 UTC on June 13, 2002, minutes after the AIRS IR spectrometer was activated. The image shows the brightness temperatures for the 2616-cm$^{-1}$ window channel, one of the 2378 IR channels measured by AIRS, for 6 min of data, corresponding to one data granule. The image covers an area of approximately 1500 $\times$ 1500 miles with 12 150 footprints.

The top panel of Fig. 7 shows the full AIRS spectrum for a cloud-free ocean footprint. The key $CO_2$ sounding regions at 700 cm$^{-1}$ and 2400 cm$^{-1}$, the water sounding area between 1200 and 1650 cm$^{-1}$, and the ozone feature near 1000 cm$^{-1}$ are immediately recognized. Only when expanding the frequency axis, as shown in the lower panel of Fig. 7, can the wealth of information provided by each spectral channel (circles) be appreciated. The calibration phase for AIRS was completed after 90 days in orbit. Analysis of early data, with focus on July 20, 2002, by the AIRS Science Team and members of the major numerical weather forecasting centers, confirms excellent radiometric performance and spectral stability [37]–[40]. The complete Level 1b dataset from AIRS/AMSU/HSB for July 20, 2002 is available as sample data from the GSFC DAAC. The routine transfer of Level 1b data in BUFR format to the NWP centers started on October 10, 2002. Routine release of Level 1b data from the GSFC/DAAC to general science investigators is expected to start at about launch plus-ten months, i.e., about March 2003.

## VII. Summary

AIRS, AMSU, and HSB form an integrated cross-track-scanning temperature and humidity sounding system on the EOS Aqua spacecraft. In addition to supporting NASA's interest in process study and climate research, AIRS is the first hyperspectral IR radiometer designed to support NOAA/NCEP's operational requirements for numerical weather forecasting during its expected seven-year lifetime. AIRS, together with the AMSU and HSB microwave radiometers, will achieve global retrieval accuracy better than 1 K/1 km in the lower troposphere under clear and partly cloudy conditions. Based on the excellent radiometric and spectral performance demonstrated by AIRS during the prelaunch testing (now confirmed during on-orbit testing), we expect the full assimilation of AIRS data into the forecast to result in significant forecast improvement.

## Acknowledgment

With the development of AIRS going back 25 years, numerous individuals have been involved, and there are more names than can be acknowledged in this paper. D. Q. Wark (NOAA/NESDIS), who passed away on July 30, 2002, was able to provide the critical memory continuity of "lessons learned" starting from the very beginning of the NOAA operational sounders. R. Kakar, NASA program scientist, was a key supported of AIRS at NASA Headquarters from the start of the progrm. The AIRS Team at BAE Systems under the leadership of J. Bates and P. Morse, with C. Miller and P. O'Sullivan, and the JPL team under the leadership of F. O'Callaghan and A. Karnik, along with the Operations Team led by D. Elliott, need to be prominently acknowledged. The Calibration Team under the leadership of T. Pagano at JPL, with the tireless support from K. Overoye and M. Weiler at BAE, provided the first-class prelaunch calibration that is key to first-class retrievals. Not to be forgotten are the contributions of the late L. Kaplan (University of Chicago and later JPL), the late H. Fleming (NOAA/NESDIS), and the late R. Haskins (JPL) to the success of AIRS. A true team spirit exists on the AIRS Program, and each player has had a vital role in getting us where we are today.

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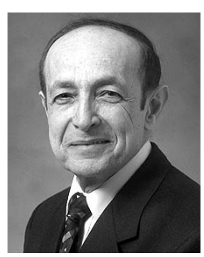

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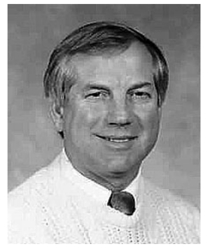

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He is currently a Senior Scientist at the NASA Langley Research Center Atmospheric Sciences Competancy, Hampton VA, where he leads scientific research programs dealing with problems of the earth's atmosphere. Prior to joining NASA in 1997, he was a Principal Investigator of several satellite instrument programs for the National Oceanic and Atmospheric Administration, Washington, DC (1966–1984) and Professor of atmospheric and oceanic sciences at the University of Wisconsin, Madison (1984–1997), where he also directed the Cooperative Institute for Satellite Studies. He is a member of the AIRS Science Team and is an active satellite and airborne experimentalist. He is the Principal Scientist for the Geostationary Imaging Fourier Transform Spectrometer, scheduled to fly on NASA's Earth Observing-3 mission planned for launch in 2005. He is also the Principal Investigator of the National Polar-orbiting Operational Environmental Satellite System Aircraft Sounding Testbed Interferometer, which flies aboard the NASA ER-2 and the Northrop-Grumman Proteus aircraft.

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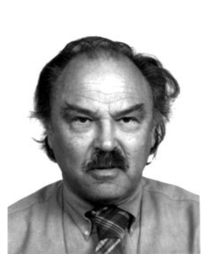

**Joel Susskind** was born in Brooklyn, NY, on April 9, 1944. He received the A.B. degree from Columbia University, New York, in 1964 and the Ph.D. degree in physical chemistry from the University of California, Berkeley, in 1968, where he did research in experimental and theoretical microwave gas phase spectroscopy. He conducted Postdoctoral research in high-resolution IR gas phase spectroscopy with the Chemistry Department, University of Minnesota, MN, from 1968 to 1970 and with the Physics Department, Florida State University, Tallahassee, from 1970 to 1972.

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