AIRS/AMSU/HSB Validation

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***Abstract*—The Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit/Humidity Sounder for Brazil (AIRS/AMSU/HSB) instrument suite onboard Aqua observes infrared and microwave radiances twice daily over most of the planet. AIRS offers unprecedented radiometric accuracy and signal to noise throughout the thermal infrared. Observations from the combined suite of AIRS, AMSU, and HSB are processed into retrievals of atmospheric parameters such as temperature, water vapor, and trace gases under all but the cloudiest conditions. A more limited retrieval set based on the microwave radiances is obtained under heavy cloud cover. Before measurements and retrievals from AIRS/AMSU/HSB instruments can be fully utilized they must be compared with the best possible *in situ* and other ancillary "truth" observations. Validation is the process of estimating the measurement and retrieval uncertainties through comparison with a set of correlative data of known uncertainties. The ultimate goal of the validation effort is retrieved product uncertainties constrained to those of radiosondes: tropospheric rms uncertainties of 1.0 °C over a 1-km layer for temperature, and 10% over 2-km layers for water vapor. This paper describes the data sources and approaches to be used for validation of the AIRS/AMSU/HSB instrument suite, including validation of the forward models necessary for calculating observed radiances, validation of the observed radiances themselves, and validation of products retrieved from the observed radiances. Constraint of the AIRS product uncertainties to within the claimed specification of 1 K/1 km over well-instrumented regions is feasible within 12 months of launch, but global validation of all AIRS/AMSU/HSB products may require considerably more time due to the novelty and complexity of this dataset and the sparsity of some types of correlative observations.**

***Index Terms*—Atmospheric measurements, infrared spectroscopy, inverse problems, microwave radiometry, remote sensing, terrestrial atmosphere.**

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I. Introduction

THE ATMOSPHERIC Infrared Sounder/Advanced Microwave Sounding Unit/Humidity Sounder for Brazil (AIRS/AMSU/HSB) instrument suite observes radiation leaving the planet in the infrared, the near infrared, and microwave spectral regions [1]–[3]. After calibration, these observations (Level 1B radiances) are converted to geophysical quantities (Level 2)—including temperature, water vapor, and cloud and surface properties—through a set of retrieval algorithms [4], [5]. Validation is the process of ascribing uncertainties to these directly observed radiances and retrieved quantities through comparison with correlative observations. The goal of the AIRS validation process is to demonstrate that the measurement and retrieval uncertainties meet or exceeds the specifications of the AIRS/AMSU/HSB Level 1B and Level 2 products shown in Table I [6]. A plan for AIRS/AMSU/HSB validation was developed two years prior to launch [7]. This paper describes the current status of AIRS/AMSU/HSB validation activities, including procedures for assessing product uncertainties, the sources of "truth" used for these procedures, the sampling and error characteristics of those datasets, and the planned schedule of product uncertainty estimation.

Extensive model- and climatology-based simulations [11] have shown the retrieval software capable of meeting the requirements in Table I. Nevertheless, system performance can be rigorously established only through comparison with other observations. Also, the simulations suggest that uncertainties will vary geographically and with atmospheric state. Descriptions of AIRS/AMSU/HSB validation analyses will be described in a series of additional publications. These will present the results of the analyses of the datasets described below, including formal error budgets. They will also present error estimates conditional on surface and atmospheric state, solar angle, seasonality, cloud cover, satellite view angle, and other sources of error variability. Examples of validation analyses using datasets available prior to Aqua launch may be found in accompanying articles [9], [12], [38].

Summarizing, the Introduction explains the concepts behind validation, especially the potential sources of uncertainty. Section II describes the data from operational meteorological experiments used for AIRS/AMSU/HSB validation, and Section III discusses the experiments devoted specifically to AIRS/AMSU/HSB validation. Section IV summarizes the

TABLE I
ACCURACY SPECIFICATIONS OF AIRS/AMSU/HSB RADIANCE (LEVEL 1B) AND RETRIEVED (LEVEL 2) PRODUCTS

Radiance Product Name	**Absolute Accuracy**	**Relative Accuracy**
Radiance (AIRS Infrared)	3%, for brightness temperatures of 190 to 330 K	0.2K at 250 K brightness temperature
Radiance (AIRS Vis/NIR)	10%	1%
Radiance (AMSU-A)	1.5K	0.5K
Radiance (HSB)	1 K	0.6K
Radiance (AIRS IR cloud-cleared)	3%, for brightness temperatures of 190 to 330 K	0.2K at 250 K brightness temperature
Retrieved Product Name	**Absolute Accuracy**	**Relative Accuracy**
Temperature Profile	1K root-mean-square	None.
Humidity Profile	20% required, 10% goal	10%
Precipitable water	5%	3%
Surface Skin Temperature	1K	0.5K
Cloud Top Height	0.5 km	0.25 km
Cloud fraction	10%	5%
Cloud Liquid water content	20%	None.
Ozone total column	20%	None.

validation data sources, including the expected number of samples usable for validation and their associated uncertainties. Section V gives a schedule for release of validated products, and a summary is presented in Section VI.

The validation process is divided into radiance validation and retrieval validation. Radiance validation includes validating the algorithms used to compute radiances given a complete description of the atmospheric and surface state—also called forward model validation. Direct radiance validation involves comparison of satellite-measured radiances with temporally and spatially coincident radiance measurements of the same field of view (FOV) from another well-calibrated instrument. Due to differing observation geometries and large natural variability, such direct comparisons are notoriously difficult. Moreover, the satellite instruments have noise characteristics comparable to many *in situ* radiance observations systems. AIRS/AMSU/HSB calibrated radiances are validated primarily by comparison with radiances generated using a forward radiative transfer calculation; direct radiance comparisons are possible only for a limited number of aircraft field campaigns. The forward radiance calculation requires knowledge of all the quantities that contribute to the radiance field, including surface properties, atmospheric temperatures, water vapor, trace gases, and clouds. The use of such forward model calculations implies the forward model itself is also being validated in this process. Because the entire retrieval process [4] relies on the forward model [9], validating the forward model is the first step in validating retrieved quantities.

The closely related but distinct activity of *tuning* is the removal of systematic errors in AIRS/AMSU/HSB radiances through regression on modeled forward radiance using *in situ* cloud-free observations. (Retrieved quantities are not tuned.) Because it is founded on forward radiance modeling, tuning will utilize many of the same datasets and procedures as radiance validation. Since tuning relies on forward model calculations, it too requires the most accurate forward model.

Intermediate to the directly observed AIRS/AMSU/HSB radiances and the retrieved geophysical products are the cloud-cleared AIRS radiances, i.e., radiances AIRS would detect if no clouds were present in the FOV (see [4] and [5] for a discussion). Cloud-cleared radiances are most accurate over clear ocean and are least accurate over partially cloudy land because of scene inhomogeneities. Because retrieved products are generated from cloud-cleared radiances, correlative "truth" datasets associated with clear-sky ocean are an early priority.

The validation of retrieved quantities can be achieved through direct comparison with *in situ* observations. For example, retrieved temperatures can be compared with temperatures observed directly by radiosonde or aircraft or indirectly by other remote sensing instruments. This process is superficially simpler than radiance validation, requiring only temporal and spatial coincidence or stable conditions. Nevertheless, such temporal and spatial coincidences are difficult to achieve in practice, and sufficiently stable conditions are rarely encountered. Moreover, the retrieval of one quantity is often affected by errors in another. (For example, clouds will contribute significantly to radiance in the ozone spectral lines, so both quantities should be observed simultaneous to reliably validate ozone.) For these reasons, the AIRS validation effort places a premium on synergistic observations including as many relevant parameters as possible.

A. Sources of Uncertainty

Uncertainties in the AIRS/AMSU/HSB observations originate from several sources. Radiance errors arise from noise processes within the instruments themselves and from imperfect calibration [8], but particularly from cloud contamination or residuals from the cloud-clearing process.

The errors in retrieved products have several sources. Uncertainties in the radiances used in the retrieval are one source of retrieval errors. Another error source is limitations of the forward model used in the retrieval software [9]. (Some systematic biases that may be discovered during forward model validation could be explained by errors in the calibration process. Other errors due to poorly understood spectroscopy or flaws in the initial forward model are being corrected by updating the forward model itself.) Incomplete truth data, such as limited observations of skin temperature and emissivity, or limited temperatures soundings above 50 hPa (a typical upper altitude for weather balloons), are another source of uncertainty. Yet another error source is related to the resolution of the satellite observing system. This null-space error [10] represents underresolved structure in the observed atmosphere. Consider, for example, a layer of water vapor hundreds of meters deep. While physically realistic, this layer is too thin to be resolved by the broad weighting functions of the AIRS/AMSU/HSB instruments. This inability to resolve fine-scale structure must be reflected in the error estimates of retrieved products. Similar to null-space error is computational noise [4]: uncertainties introduced by modeling a continuous system with discrete numerical elements. Simulations have shown [11] that null-space errors and computation noise can combine to give retrieval uncertainties roughly half as large as the specifications in Table I.

An important source of uncertainty in the AIRS products is the errors in the data used to validate those products. The AIRS/AMSU/HSB instrument suite is designed to provide a tropospheric retrieval uncertainty of 1.0 K over a 1-km layer for temperature, and 10% over 2-km layers for water vapor. These approach or surpass the combined errors of many *in situ* measurements. Due to the high cost, limited number, and restricted geographical distribution of the most accurate "truth" measurements, AIRS must make use of more conventional measurements, such as standard radiosondes, to obtain a large enough number of comparisons for statistical significance. The error characteristics of all these validation datasets must be known.

All error processes occur in the presence of the large, natural variability of the geophysical system being observed. Natural variability can introduce apparent error in many ways, especially through nonsimultaneous or spatially disjoint observations by the instruments being compared. Some of the effects of natural variability are only subtly distinct from null-space errors. Separating natural variability due to noncoincident sampling—"mismatch error"—from the other error processes described above is one of the great challenges of validating satellite datasets.

II. Routine Data for AIRS Validation

This section describes validation data being routinely collected by conventional operational observing systems. These include forecast model assimilations, radiosondes, aircraft reports, global positioning system (GPS) total water vapor, ozone measurements, rocketsondes, buoy data, hourly surface observations, and other remote sensing observations. Radiosondes are a special case in that they are typically launched once or twice daily from a large number of sites worldwide and are often collocated with other data types to provide a more complete specification of the atmospheric state. For example, the hourly surface observations spanning the time between a radiosonde and a satellite measurement can help characterize the diurnal variability (though Aqua's 1:30 local time puts it nearly atop the peak and trough of the diurnal cycle). These surface observations are used to remove the changes in the atmospheric state resulting from time and space difference between satellite and radiosonde. In addition to specifying the atmospheric state more completely, the additional data are used for radiosonde data quality control. The errors in the correlative data can thus be better understood when multiple sources of truth exist for a single parameter. This is important for an instrument with the expected accuracy of the AIRS measurements.

As mentioned above, the nearly complete state of the atmosphere must be known to calculate radiances. To do so requires the use of auxiliary data to supplement the radiosonde reports. Measurements of the ocean surface temperature are used to define the temperature of the radiating surface [12]. Aircraft data, where available, can be used to supplement radiosonde upper tropospheric water vapor measurements known to be inaccurate. Limb sounding data from other satellite instruments can be used for the middle atmosphere. Because other passive vertical sounders have retrieval error characteristics similar to those of AIRS, their use for validation is limited to determining consistency. There are also a limited number of rocketsonde observations. Retrievals of total precipitable water from the ground-based GPS receivers are compared to the radiosonde values. If a difference is found, the radiosonde profile will either be scaled to match or rejected. Hourly surface observations are used to adjust for time and space differences between the radiosonde and the satellite.

The radiosonde data will also be used to develop tuning coefficients, or bias adjustments, for the AIRS/AMSU/HSB radiances.

Routine data available for the validation include the conventional radiosonde network, ground-based GPS measurements of total water vapor, the hourly surface observations, the commercial aircraft data, ozone measurements, and limb sounding data. Each of these is discussed in Section II-A.

A. Comparison With Forecast Model Assimilations

Forecast model assimilation data products can be compared globally with the AIRS/AMSU/HSB products. As discussed in [11], these assimilation products are interpolated to the locations of the satellite observations. Because these simulations completely mimic the structure and content of the AIRS/AMSU HSB products, a comparison between the two is straightforward.

Although this approach yields large datasets for comparison, it cannot give significant results at the resolution of individual retrievals because inconsistent cloud fields introduced uncertainties significantly greater than those in Table I. Instead, comparison with forecast models can reveal large-scale biases between model and AIRS observations ("sanity checks"). Over smaller regions where both model and satellite data indicate

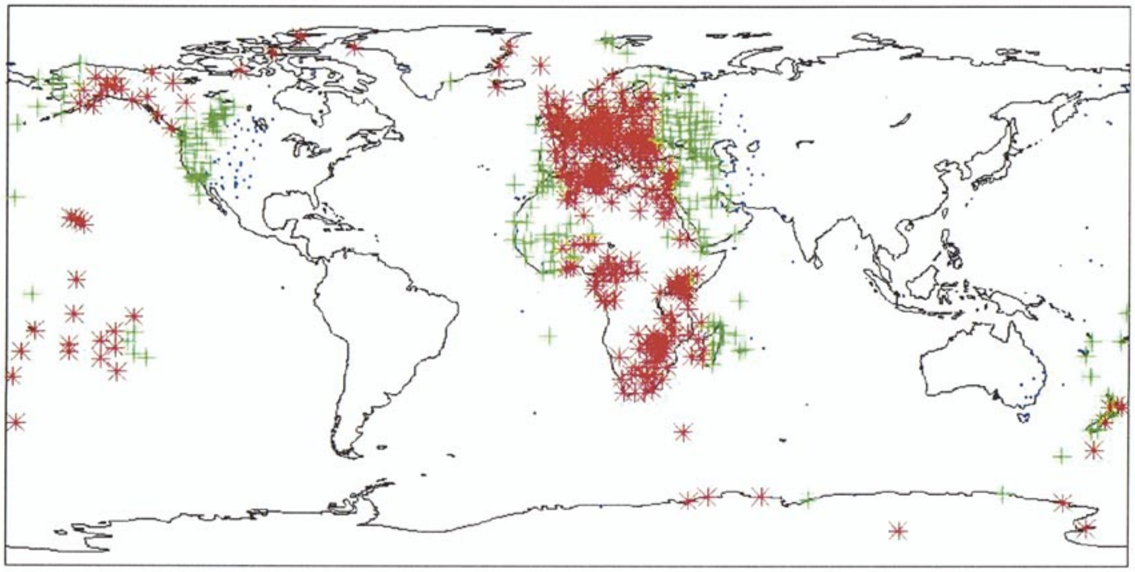

Fig. 1. Locations of CARDS operational radiosondes matching AIRS/AMSU/HSB observations within one hour and 100 km (red crosses), two hours and 200 km (green crosses), and three hours and 300 km (blue dots) of an orbit near 12 Z for simulated data on December 15, 2000. The sun-synchronous early afternoon/early morning Aqua orbit skews radiosonde sampling to those launched over Europe at 00 and 12 UTC.

cloud-free conditions, computed radiances from assimilation models can readily be compared to AIRS/AMSU/HSB measured radiances.

Early results show agreement to within 0.5 K in brightness temperature between observed and computed surface window channel infrared radiances. This comparison utilized radiances computed using sea surface temperatures in forecast model assimilations and was performed over cloud-free parts of the Mediterranean Sea—one of the best-observed bodies of water in the world—during the first month of AIRS observations.

B. Large Sample Datasets

Due to their daily worldwide release, radiosondes are the major atmospheric profiling instrument available for satellite validation. Furthermore, their use in large numbers and over many years means their error characteristics are well known. Most radiosondes are launched at 00 UTC and 1200 UTC to match the prediction cycles of the major forecasting centers. The Aqua orbit places it over radiosonde-sparse regions at these times, limiting the number of usable radiosondes to a small fraction of the total number of sondes launched daily. (Some sites also launch at 0600 Z and 1800 Z, and arrangements have been made for special launches at the time of the Aqua overpass.) A major shortcoming of the global radiosonde system is large variability in measurement quality between nations, reflecting socioeconomic differences. This leads to significant geographic differences in radiosonde coverage and quality. Nevertheless, radiosondes provide the most readily available robust measurements of the atmospheric state. A map depicting radiosonde observations matched to the satellite sounding locations is shown in Fig. 1. Radiosondes provide measurements up to 10–5 hPa, although many do not reach these altitudes.

Radiosondes report the temperature of a sensing element, not the true atmospheric temperature [13], [14]. The radiosondes utilized by the AIRS/AMSU/HSB project are corrected for this and other well-understood effects [15], [16]. Nevertheless, the radiosonde observations may contain unknown, systematic errors. Also, the corrections for some radiosonde types are unobtainable for proprietary or other reasons (most radiosondes are produced by one manufacturer, so this error is reduced). Consequently, a mix of radiosondes biased with respect to each other will introduce an apparent random error when compared with satellite observations. The National Oceanic and Atmospheric Administration's National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) currently utilizes observations from operational TIROS Operational Vertical Sounder and Geostationary Operational Environmental Satellite instruments to reduce these biases. Similarly, biases in total water vapor are reduced with observations from the GPS network.

The measurement characteristics of radiosondes are well understood, and their uncertainties are comparable to or better than the specified uncertainties on the AIRS/AMSU/HSB retrievals: 1 K in a 1-km layer for tropospheric temperatures and 10% in a 2-km layer for lower tropospheric moisture. Operational radiosondes will therefore be most useful for validation of tropospheric temperature and lower tropospheric moisture, as well as the parameterization of these in the forward model calculations. Radiosondes are also very important in tuning systematic radiance biases. Although radiosondes are accurate, significant errors may be introduced by spatial and temporal mismatch with AIRS/AMSU/HSB retrievals. The current match-up system based on simulations [11] uses matching criteria of 100 km and three hours. These yield about 250 daily match-ups, with temperature bias and variance of about 1° each in the lower troposphere. (Note that this is a comparison between simulated atmosphere and observations, however.) Tighter matching criteria may be used later, but with concomitant reduction in the number of matches (see also Table II).

TABLE II
EXPECTED NUMBER OF MATCH-UPS AND ERROR CHARACTERISTICS OF OPERATIONAL DATASETS

Operational Data Sets	**Number of match-ups; mismatch errors**	**Relevant quantities and expected correlative data uncertainties**
Model Assimilations [11]	Perfect match to satellite observations through interpolation	*All quantities*; large uncertainties under most conditions from inconsistent cloud fields. Expect global biases near zero.
Operational Radiosondes [16]	~250 daily based on simulation with 300 km-1 hr window; significant mismatch errors	*Tropospheric temperature*: 0.5 to 1.5 K *Lower Tropospheric Humidity*: ~10% Expect zero global bias for tropospheric temperature and lower tropospheric humidity
ACARS and MOZAIC aircraft observations [20, 21, 22]	Hundreds daily (mostly over land); minimal mismatch errors	*Tropospheric temperature*: <1 K in 0.5 km layers *Tropospheric water vapor*: 2-5 %, increasing with height.
Land Surface Sites	Hundreds daily; minimal mismatch errors	*Surface air temperature*: ~0.5 K or larger due to null-space errors from scene complexity
Combination of above for forward modeling [9]	Hundreds Daily; significant mismatch errors	*Forward model and cloud-cleared radiance*: Preliminary result: ~0.5 K brightness temperature for clear scenes
Surface Marine Observations [12, 26]	Hundreds daily; a few clear spots daily; minimal mismatch errors; discrepancies between bulk and skin temperatures.	*Ocean skin temperature*: ~0.3 K at night, much larger during daytime due to bulk / skin temperature differences *Forward model and clear sky radiance*: ~1 K noise equivalent radiance

The AIRS/AMSU/HSB suite is capable of retrieving moisture at high altitudes, where operational radiosonde moisture measurements are very unreliable. As described below, a number of specialized radiosondes capable of making accurate upper tropospheric humidity measurements are being launched for AIRS/AMSU/HSB validation. Also, some validation sites will make upper tropospheric water vapor measurements using lidar systems. An additional source of total water vapor is the GPS total water vapor measurement [17].

An important implication of the above discussion is that the AIRS/AMSU/HSB remote sensing system, with its high radiometric accuracy and precision, has the potential to become a transfer standard for radiosondes and other heterogeneous, globally deployed observing systems. Geopolitical inconsistencies in measurement by radiosondes, as discussed above, are one shortcoming of radiosonde observations. In addition, middle and upper tropospheric sonde water vapor measurements have consistent dry biases [18], [32]. Attempts have been made to adjust upper level radiosonde humidity measurements [19], [33]. Realizing the AIRS/AMSU/HSB observing system's potential for reconciling radiosonde observations will be an important activity in the upcoming years.

C. Observations From Instrumented Commercial Aircraft

A program using sensors on commercial aircraft to measure water vapor and temperature is described elsewhere [20]–[22]. The program for United States carriers is called Airline Communications Addressing and Reporting System (ACARS), and the one for European carriers is called Measurement of Ozone by Airbus In-Service Aircraft (MOZAIC). These measurements can be used in three ways. First, takeoffs and landings provide profiles from the surface to cruising altitudes of 7–12 km, typically over 100–200-km horizontal scales. Second, most aircraft fly in well-defined flight corridors providing routine measurements along the same path at different times. Moreover, many of these corridors cross each other at different altitudes, providing some profile information over limited horizontal regions. Third, some aircraft measurements will coincide with radiosondes. In addition to direct validation, these coincident measurements can be used to cross-validate the radiosondes. See Table II for a discussion of error and sample size of the aircraft observations.

D. Surface Marine Observations

The validation of the Level 2 sea surface temperature (SST) is based on measurements acquired from several sources, including drifting and fixed buoys, ship radiometric observations, SST from the Advanced Very High Resolution Radiometer (AVHRR), and SST from the Aqua MODIS instrument. The validation data sources are described in [12], and examples are provided there of the accuracies that can be expected from each of these. The most accurate of the validation sources is the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) [23], a Fourier-transform infrared spectroradiometer mounted on a ship to measure the emission spectra from the sea surface and atmosphere. This instrument has been used to successfully validate MODIS SST measurements [24]. Because of the limited geographic coverage of the M-AERI measurements, data comparisons will also rely on less accurate measurements from drifting and fixed buoys. Past studies using data from the Along-Track Scanning Radiometer (ATSR) demonstrate satellite SST measurements can be validated against drifting and fixed buoys to within an uncertainty of about 0.27 K [25], [26]. In [27], the AVHRR Pathfinder products are compared with drifting buoys to show a global uncertainty of 0.02 ± 0.5 K. Comparisons of AIRS SST to MODIS- and AVHRR-derived SST provide an additional method for identifying regional and temporal biases in the product.

III. Special Observations for AIRS Validation

In addition to the datasets from operational observing systems discussed above, several dedicated experiments have been undertaken in the validation of AIRS/AMSU/HSB products. The resulting observations have two advantages over larger operational datasets described above. First, these observations can be timed to be coincident with the satellite observations, reducing the contribution of atmospheric variability to the uncertainties. Second, the noise characteristics of these observations are better understood and usually superior to those of the operational datasets. Despite these advantages, the dedicated observations are limited in number, so will provide a statistically limited picture of satellite uncertainties.

A. Measurements From Dedicated Observing Sites

Temperature and water vapor profiles constructed from data acquired at Atmospheric Radiation Measurement (ARM) sites are being used for validation of the AIRS/AMSU/HSB-retrieved profiles under both clear and cloudy sky conditions. This includes the three main ARM sites: the Southern Great Plains (SGP) site in north-central Oklahoma, the North Slope of Alaska (NSA) site near Barrow, Alaska, and the Tropical Western Pacific (TWP) site on the island of Nauru.[1] The primary goal of the ARM sites is to provide data for development of improved representations of atmospheric radiation and clouds in global climate models [28], but these heavily instrumented ground sites are also well suited to satellite validation applications.

The ARM site atmospheric state best estimate validation product draws on the wealth of data from routine ARM operations, from dedicated radiosonde launches coincident with Aqua overpasses of the sites, and data from other sources including geostationary satellite, surface networks, and numerical models. The dedicated radiosondes are included to capture the high variability of water vapor in space and time. Dedicated radiosondes were launched from the ARM sites coincident with Aqua overpasses for a three-month period starting roughly 120 days after launch. Two sondes are launched per overpass, roughly 45 and 5 min prior to each acceptable overpass to provide coincident sampling of the atmosphere at multiple altitudes. (Acceptable overpasses are those with zenith angles from the ARM site to the satellite of less than 30°.) The best estimate product is also being generated for high zenith angle overpasses, but without the information from dedicated sondes. Current plans are for an additional three-month period of dedicated sonde launches once a year for the life of AIRS.

For temperature profiles, Vaisala radiosondes [29] are the primary data source. Atmospheric Emitted Radiance Interferometer (AERI) retrieval fields [30] acquired every 8 min are used to interpolate the Vaisala profiles to the overpass time and to quantify small-scale variability (AERI-retrieved quantities are limited to pressures beneath 700 hPa, however). Geostationary satellite retrievals and/or numerical model analyses are then used to characterize the large-scale horizontal gradients within the AMSU footprint and to modify the best estimate profile based on the gradients and the location of the ARM site within the AMSU footprint. The absolute accuracy of the best estimate profile is checked by comparison to the high-quality *in situ* sensors, including Surface Meteorological Observation Systems, other ground meteorological stations, and tower sensors.

[1]See http://www.arm.gov.

For the water vapor profiles, a similar approach is taken, but before interpolation to the overpass time, the radiosonde water vapor profiles are first multiplied by an altitude-independent scale factor. Applying this scale factor constrains the radiosonde-integrated column water vapor amounts to those of a collocated ARM microwave radiometer, a technique adopted by ARM to remove calibration errors [31]. GPS total water vapor measurements have been shown [17] to be accurate compared to the microwave radiometer and are used similarly. In addition to AERI retrieval fields, Raman lidar profiles [32] help characterize small-scale variability. Comparisons with nighttime Raman lidar profiles can be used to assess the accuracy of the radiosondes to altitudes of about 12 km.

The uncertainty of the ARM best estimate is considerably better than the satellite specifications (Table I), but the number of match-ups is a few hundred total, very limited compared to operational radiosondes (Tables II and III). Plans are currently underway to further improve the ARM upper level humidity observations using the procedure described in [33].

In addition to the ARM observations, international collaborators in Australia, Brazil, and Europe are contributing to the AIRS/AMSU/HSB validation effort. Radiosondes are launched at every Aqua overpass from Toulouse, France and Garmisch/Zugspitze, Germany. The Brazilian government is launching dedicated radiosondes from Bauru in Sao Paulo State during Aqua overpasses. The Australian Bureau of Meteorology launches dedicated RS80 sondes from several sites, as well as ozonesondes from Melbourne and Macquarie Island. Many of these sites included a GPS receiver or microwave radiometer [32] for correct normalization of the sonde water vapor, The Brazilian observations at Bauru are supplemented with those from a precipitation radar for the validation of the microwave-derived rainfall estimate [38].

B. AIRS/AMSU/HSB Validation Team Experiments

The EOS Validation Program supports several investigators providing dedicated observations for validation of the AIRS/AMSU/HSB instrument suite. These investigators bring to the AIRS/AMSU/HSB project extensive experience in obtaining and interpreting field observation. Many of their experiments have been deployed in the first several months after Aqua launch, with the intention of characterizing the atmosphere sufficiently to model the upwelling radiances for forward model and radiance validation [9]. Moreover, several experiments are deployed from oceanic sites providing nearly constant background emissivity, significantly simplifying the forward radiance calculation. The data from these sites are delivered to the AIRS Science Team and stored with the matched AIRS/AMSU/HSB datasets maintained at the Jet Propulsion Laboratory (JPL) and at NOAA/NESDIS. Modeled radiances are compared with radiances observed at the spacecraft, to furnish estimates of the uncertainties in the observed radiances

TABLE III
EXPECTED NUMBER OF MATCH-UPS AND ERROR CHARACTERISTICS OF DEDICATED VALIDATION EXPERIMENTS

Investigator; Experiment	**Number of overpasses (first year total)**	**Correlative measurements and associated uncertainties**
AIRS Science Team; ARM and similar instrumented sites [28, 31, 32]	180 dedicated sondes, launched two per overpass, at each of 3 locations during 3 month period	*Tropospheric temperature*: 0.2 K absolute; 0.5 K reproducibility *Lower tropospheric humidity*: 5% absolute *Upper tropospheric humidity*: 15% absolute All profiles with ~100 m resolution.
Vis/NIR team; Vis/NIR validation [3, 54]	~10 well-characterized targets Hundreds at ARM SGP, Santa Barbara	*Vis/NIR radiance*: <5% *Cloud fraction*: <10%
Barnes; humidity lidar and ozonesondes	Lidar: 15 nights Ozonesondes: at least 7	*Temperature (from radiosondes)*: 0.2-1.5 K, increasing with height. *Humidity 4 to 16 km at 300 m resolution*: 5-15%, increasing with height. *Ozone*: 5% profiles, 5 % total
Bennartz; Baltic radars [34-38]	Continuous observations, with rain ~10% of time	Resolution of rain elements roughly 2 km in diameter
McMillan; instrumented ocean platform [23, 29, 30, 39, 41]	96 radiosondes	*Downwelling and ocean upwelling spectra*: <0.1 K *Sea surface temperature*: ~0.1 K *Temperature*: 0.2-1.5 K, increasing with height. *Lower tropospheric humidity*: 5% absolute *Upper tropospheric humidity*: 15% absolute *GPS total precipitable water vapor*: 1 mm *Ozone*: 5% profiles, 5 % total
Minnett; instrumented ships [23, 30]	~50 radiosondes	*Ocean upwelling spectra*: <0.1 K *Sea surface temperature*: ~0.1 K *Temperature*: 0.2-1.5 K, increasing with height. *Lower tropospheric humidity*: 5% absolute *Upper tropospheric humidity*: 15% absolute *GPS total precipitable water vapor*: 1 mm
Newchurch; ozonesondes and Dobson network [44, 45]	20 ozonesondes 20 standard sondes Hundreds of Dobson observations	*Temperature*: 0.2-1.5 K, increasing with height. *Lower tropospheric humidity*: 5% absolute *Upper tropospheric humidity*: 15% absolute *Ozone*: 5% profiles, 2 % total
Schmidlin; dedicated sondes [13, 14, 45]	~100 ozonesondes ~50 chilled-mirror hygrometers	*Temperature*: 0.2-1.5 K, increasing with height. *Lower tropospheric humidity*: 5% absolute *Upper tropospheric humidity (standard*

and to enable forward model validation. After radiance and forward model validation is complete, AIRS/AMSU/HSB-retrieved product validation will commence through comparison with directly measured *in situ* and remotely sensed "truth" quantities. These experiments are briefly described below. Table III lists the AIRS/AMSU/HSB quantities these experiments help validate, the number of sample each provides, and their expected uncertainties.

R. M. Atlas of the Data Assimilation Office, National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) provided comparisons of AIRS-retrieved temperatures, water vapor, and ozone with fields generated in a global general circulation model assimilation analysis. Both the AIRS retrieval algorithms and the assimilation analysis contain implicit estimates of uncertainties. This study will also address forecast improvements due to the AIRS data.

J. E. Barnes of the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) provides observations of middle and upper tropospheric water vapor obtained by lidar from the top of Mauna Loa, HI. The Mauna Loa Observatory sits above most of the lower tropospheric water vapor and experiences relatively cloud-free conditions much of the time, especially compared to other tropical and subtropical sites. The lidar provides two-hour average nighttime profiles of water vapor, as well as associated profiles of observational error from the ground near 4 km to about 15 km. (Temperatures are from operational radiosondes launched from Hilo by the National Weather Service at 12 Z.) Balloons launched from Hilo by H. Vömel, as described below, will take ozone measurements. Additional observations can be coordinated with AIRS-dedicated Hilo radiosonde launches to maximize information from measurements around Mauna Loa, with an emphasis on upper tropospheric humidity.

R. Bennartz of the University of Kansas provides precipitation radar data matched to the AMSU/HSB resolution to validate the precipitation screening/retrieval based on AMSU/HSB. The validation approach utilizes data from networks of precipitation radars and is described in detail elsewhere [34], [35]. Due to the strong contrast in surface emissivity, precipitation validation

TABLE III
(Continued) EXPECTED NUMBER OF MATCH-UPS AND ERROR CHARACTERISTICS OF DEDICATED VALIDATION EXPERIMENTS

	~100 standard sondes	*sondes*): 15% absolute *Humidity (chilled-mirror hygrometers)*: 2-10%, surface to ~10 hPa. *Ozone*: 5% profiles, 5 % total
Vömel; dedicated sondes [44, 47]	15 humidity sondes 15 ozonesondes 180 radiosondes	*Temperature*: 0.2-1.5 K, increasing with height. *Lower tropospheric humidity*: 5% absolute Upper tropospheric humidity (standard sondes): 15% absolute *Upper tropospheric humidity (chilled-miror hygrometer)*: <10% *Ozone*: 5% profiles, 5 % total
Walden; Antarctic observations [17, 23, 48]	Four to six daily overpasses during one month operations; total of 30 radiosondes	*Upwelling and downwelling spectra*: <0.1 K *Temperature*: 0.2-1.5 K, increasing with height. *Tropospheric Humidity*: ~15% *GPS total precipitable water vapor*: 1 mm .
Whiteman; Raman lidar [30, 49, 51, 51]	Lidar, radiosonde and GPS measurements during ~25 overpasses.	*Water vapor mixing ratio, surface to 12 km*: 2-25% random error increasing with height. *Temperature*: 0.25 K up to 70 mbarr *Total precipitable water vapor*: 1 mm.
Yoe; GPS receivers [17]	Hundreds daily	*Total precipitable water vapor*: 1 mm.

has to be done separately for observations taken over land and water surfaces [36]. The pointing accuracy of the instruments is determined by maximizing the correlation between satellite observations and high-resolution land/sea-masks convolved to the spatial resolution of the sensors [36], [37]. Cross-validation between the AMSU/HSB and the AMSR-E Level 1 brightness temperatures will also be performed. Although AMSU and HSB absolute calibration is difficult to verify, demonstration of small relative deviations between the two instruments will make it statistically less likely that either sensor suffers from a large absolute calibration error. This activity is similar to that described in [38], whose authors are collaborators in this analysis.

W. W. McMillan of the University of Maryland—Baltimore County (UMBC) leads the AIRS Baltimore Bomem AERI (BBAERI) Ocean Validation Experiment (ABOVE) [39] deploying a suite of instruments to the United States Coast Guard Chesapeake Light lighthouse platform 25 km due east of Virginia Beach, VA. The BBAERI observes upwelling sea surface and downwelling sky infrared spectra every 10 min. SST, tropospheric temperature and moisture profiles, and column trace gas abundances, including carbon monoxide and ozone, are retrieved from the spectra [30], [40], as discussed above for the ARM sites. Co-Investigator R. Hoff (UMBC) has deployed the Elastic Lidar Facility (ELF) instrument to provide aerosol profiles and cloud-base/thickness information from near the surface to the tropopause [41], [42]. Radiosondes have been launched during most Aqua overpasses. Initial ABOVE deployment proceeded between about 90 and 150 days after launch for forward model validation. Subsequent deployments of two to four weeks will occur up to three times yearly for the second and third years for continued forward model and product validation, including cloud-clearing. Chesapeake Light is a fully instrumented NOAA National Data Buoy Center site including a GPS receiver for total precipitable water vapor, as well as being the primary ocean validation site for the Cloud and the Earth's Radiant Energy System instruments on Aqua and its sister satellite Terra.[2]

P. J. Minnett of the University of Miami measures spectrally resolved radiances and retrieved skin surface temperatures, surface winds, temperature and humidity profiles, column water vapor, and rainfall from instrument packages deployed on research vessels and a commercial cruise ship, the *Explorer of the Seas* [43] that follows regular routes in the Caribbean out of Miami, FL. Other research voyages include the Canadian Arctic and the western Mediterranean, both in autumn 2002, and a trans-Pacific voyage leaving Seattle in November and arriving in Sydney in December 2002. The instrument packages include infrared M-AERI spectrometers [23], anemometers, thermometers in both air and water, a microwave radiometer to measure total atmospheric water vapor and to renormalize the radiosonde humidity profiles, rain gauges, and radiosonde launch equipment.

M. J. Newchurch of the University of Alabama, Huntsville is providing measurements of ozone, water vapor, and temperature from a set of dedicated ozonesondes launched from Huntsville [44], [45]. These ozonesondes observe to altitudes as high as the middle stratosphere. Other instruments on the balloons carrying the ozonesondes provide information about the temperature and water vapor profile. These observations are being used to verify the AIRS ozone retrieval and constrain the ozone for forward modeling. In addition to these dedicated sondes, ozone observations from the global Dobson network are being compiled and compared with the satellite retrievals [46].

F. J. Schmidlin of the NASA GSFC Wallops Flight Facility is providing measurements of temperature, water vapor, and ozone from a set of dedicated ozonesondes and hygrometers (all with associated thermometers) launched from several sites

[2]See http://eospso.gsfc.nasa.gov/validation/valpage.html for a discussion of EOS validation activities

to characterize ozone and water vapor variability [13], [14], [45]. The temperature measurements are made with a three-sensor approach that can eliminate radiation errors. Balloons are being launched from Wallops Island, VA; Andros Island, the Bahamas; Natal, in Brazil; Ascension Island, in the South Atlantic Ocean; and Kiruna, Sweden.

H. Vömel of the University of Colorado provides measurements of water vapor and temperature from balloon-borne ozone sensors and frost-point hygrometers [47] launched from several sites in the continental United States, San Cristobal in the Galapagos Islands, and Hilo, HI. The hygrometers are sensitive enough to detect the very low humidity values found in the upper troposphere and stratosphere. The Hilo observations are coordinated with those by Barnes from the CMDL Mauna Loa lidar. The Galapagos experience high cirrus clouds much less frequently than other tropical sites, and those clouds present are often low stratus with cloud-top altitudes of roughly 1000 m. The station in the Galapagos will also launch dedicated radiosondes timed to satellite overpasses. Measurements from island sites are of particular interest, especially in the first several months after launch.

V. P. Walden of the University of Idaho measures upwelling and downwelling infrared radiance spectra, total precipitable water, and profiles of temperature and humidity from instruments deployed at Dome Concordia, 74.5 S by 123 E at an altitude of 3280 m above sea level on the Antarctic Plateau. These instruments include an AERI infrared spectrometer similar to that used by Minnett [23] but using calibration targets at lower temperature (Polar AERI), plus a GPS receiver [17] and Vaisala RS80 radiosondes. Upwelling radiances are also sampled over an extended area using a narrowband infrared radiometer calibrated against the Polar AERI. Compared to other land-based observations sites, Antarctica has several advantages [48], including cloud-free conditions roughly half the time—very clear by any standard—a nearly constant background surface emissivity, water vapor amounts comparable to those in the upper troposphere, and frequent Aqua overpasses.

D. N. Whiteman of the NASA GSFC measures water vapor mixing ratio profiles, as well as cirrus cloud properties such as boundaries, optical depths, extinction-to-backscatter ratios, and diffraction equivalent particle radii using the Scanning Raman Lidar (SRL) [49]. Total precipitable water measurements are provided by collocated SuomiNet GPS [50], while radiosondes are used to measure atmospheric temperature and pressure. These measurements are made at NASA GSFC and at UMBC, where they are augmented by infrared spectra from Co-Investigator W. W. McMillan's BBAERI. Clouds are a persistent, complicating factor in the AIRS/AMSU/HSB retrieval, particularly in the tropics, where they are present a large percentage of the time. Thick clouds are clearly discernable in the satellite retrieval system, but high, thin cirrus clouds are present in as many as half of the observations taken by AIRS and can be difficult to detect. Previous research [51] has shown that undetected cirrus clouds can be a significant error source in satellite retrievals of water vapor. The Raman lidar can be used to detect the presence of very thin cirrus clouds while simultaneously quantifying the profile of water vapor for use in validating AIRS retrievals in the presence of cirrus clouds.

J. G. Yoe of NESDIS provides measurements of integrated water vapor from a network of 50 GPS receivers distributed across the United States. The coverage will later be extended to other regions. The GPS network provides nearly continuous measurements of total precipitable water vapor at each receiver under most nonprecipitating atmosphere conditions. This experiment provides a large high-quality set of observations for total column precipitable water vapor [17].

The locations of some of the dedicated AIRS/AMSU/HSB validation sites are shown in Fig. 2.

C. Aircraft Campaigns

Observations from aircraft flown beneath the Aqua spacecraft can help constrain measurement uncertainties of directly observed and retrieved satellite quantities.

Aircraft radiance observations are particularly useful in the validation of the cloud-cleared radiances: the AIRS/AMSU/HSB retrieved estimate of the radiance emitted by the cloud free part of the FOV. Here, aircraft observations from regions known to be clear are compared with simultaneous, collocated retrieved cloud-cleared radiances. Microwave radiances at frequencies little affected by clouds can be directly compared, particularly over ocean. Dedicated aircraft campaigns also often provide *in situ* observations of several retrieved quantities, including temperature and water vapor from dropsondes or dedicated radiosondes, cloudiness from lidars, and a suite of retrieved quantities from infrared spectrometers.[3] Clouds and complex surface features are observed in great spectral and spatial detail from aircraft. These observations are particularly useful for the study of the effect of land surface emissivity variability on the satellite retrievals.

The primary instruments for AIRS radiance validation are the Scanning High-Resolution Interferometer Sounder (S-HIS) [52] and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Aircraft Sounding Testbed (NAST) [53]. NAST consists of separate microwave and infrared instruments, NAST-I and NAST-M, respectively, carried aboard the ER-2 and Proteus high-altitude aircraft. Several campaigns are planned to compare AIRS/AMSU/HSB products with these aircraft observations. The CRYSTAL-FACE experiment to study cirrus cloud properties over Florida included several underflights of the Aqua spacecraft. Other campaigns include overflights of the ARM SGP site and the Gulf of Mexico for Aqua validation in November 2002. Aqua validation flights of NAST and S-HIS will be conducted from Hawaii in February 2003, and Kiruna, Sweden in August 2003. A Southern Hemisphere validation campaign is currently being planned for February 2004.

D. Validation of AIRS Visible and Near-Infrared Observations

The AIRS instrument carries four visible and near-infrared (Vis/NIR) channels at wavelengths from roughly 0.4–1.0 μm and at high spatial resolution relative to the infrared footprint: 2.3 versus 15 km at nadir; see [3]. As discussed there, Vis/NIR

[3]See http://cloud1.arc.nasa.gov/crystalface/index.html for a description of CRYSTAL-FACE, The Cirrus Regional Study of Tropical Anvils and Cirrus Layers—Florida Area Cirrus Experiment, as well as for an overview of a recent campaign.

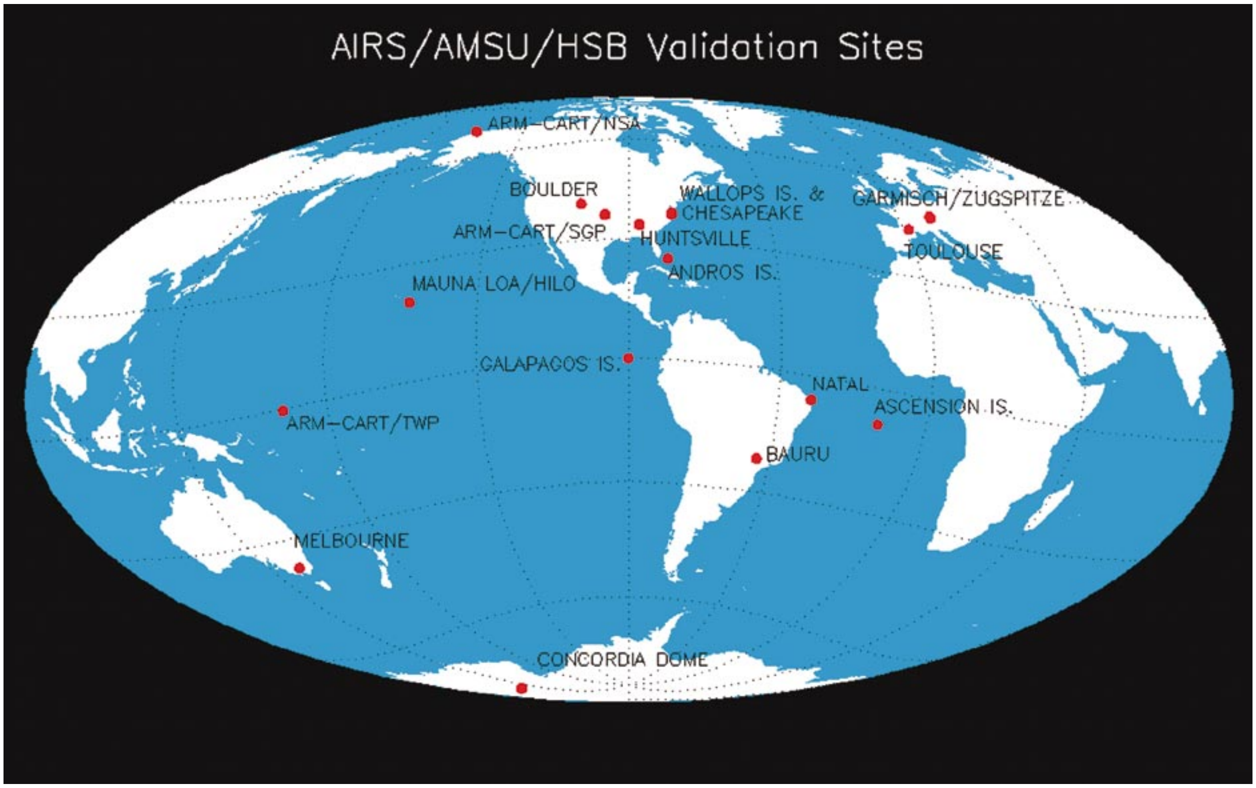

Fig. 2. Locations of sites providing dedicated observations for validation of AIRS/AMSU/HSB data.

data are used by the AIRS team to investigate the effect of subfield variability on the errors in Level 2 products, and as an aid in recognizing low clouds. The two primary Vis/NIR products subject to validation are radiances and cloud quantities. Validation of these products is discussed fully in [3], but a summary is provided here for completeness.

Level 1B Vis/NIR radiances are being validated over well-characterized ground targets under clear-sky conditions, using a forward model to calculate top-of-atmosphere radiances given *in situ* observations of solar flux at the surface, surface reflectivity, and atmospheric water vapor and aerosol loading. These activities are carried out in close collaboration with the MODIS and MISR calibration teams, who are using similar measurements to validate their instruments. The Moderate Resolution Imaging Spectroradiometer (MODIS) was flown on both the Terra and Aqua spacecraft. The Multi-angle Imaging SpectroRadiometer (MISR) was flown on Terra. The MODIS team estimates that this approach yields radiance accuracies of better than 5% [54].[4]

The Vis/NIR cloud detection results are being validated primarily over the Great Plains ARM-CART site, using lidar and solar flux radiometer measurements to detect clouds. The University of California, Santa Barbara is also a validation site where human observers and radiometers are utilized to identify clouds. This coastal site is particularly useful because low-level marine stratus clouds are common; recognition of this type of cloud is one of the key tasks of the Vis/NIR system. Also, statistical comparisons of the AIRS Vis/NIR cloud amount are being made to International Satellite Clod Climatology the Project (ISCCP) and Advanced Very High Resolution Radiometer (AVHRR) data.

[4]See http://eospso.gsfc.nasa.gov/validation/valpage.html for overviews of other Earth Observing System (EOS) instrument validation activities.

IV. Sample Sizes and Error Characteristics of the Correlative Datasets

Table III summarizes the number of match-ups between correlative data and the AIRS/AMSU/HSB observations and retrieval, as well as the error characteristics of the datasets being used for AIRS validation.

V. Schedule of Validation Activities

The goal of the AIRS/AMSU/HSB validation effort is global characterization of the uncertainties of the products listed in Table I through comparison with *in situ* observations. The uncertainties specified in Table I are being attained at different times for different products. For example, temperature uncertainties will likely be known before those for humidity. (Temperature is easily observed *in situ*, yielding more observations for comparison than humidity, and temperature varies more smoothly in both space and time, giving it smaller mismatch errors.) The error characterization of some quantities is particularly challenging. For example, upwelling radiance from land is the product of skin temperature and skin emissivity, two quantities notoriously difficult to observe, particularly over the 45-km scale of the AMSU footprints. Moreover, land surface temperature has a diurnal cycle with amplitude of up to 50 K. Surface temperature error characterization will therefore follow that of most other quantities and is dependent primarily on aircraft observations.

For these and similar reasons, error estimation will follow the schedule outlined below, with some products lagging well behind others. The following description of the validation phases is a synopsis of part of the AIRS Validation Plan [7]. Note that many datasets have been acquired during Phase B (see below), when the majority of dedicated observations are obtained to expedite instrument spectral and radiometric characterization, though their full analysis will likely not be completed until later phases.

Phase A: Initial Instrument Commissioning (Timing: AIRS/AMSU/HSB Stable + Two Months): This phase focuses on 1) the prevalidation confirmation of AIRS online blackbody behavior and 2) AIRS/AMSU/HSB instrument boresight coalignment at coastal crossings [55].

Phase B: Basic Field Validation (Timing: AIRS/AMSU/HSB Stable + Two Weeks to Four Months): This phase emphasizes clear-sky, calm ocean conditions. Correlative datasets include SST from buoys, radiosonde observations of temperature and water vapor, and AIRS Vis/NIR cloud masks. This phase addresses water vapor contribution in AIRS infrared window regions, microwave-only retrievals over a range of conditions, and infrared retrieval under conditions of simple surfaces and no clouds. Analyses include regressing AIRS window region brightness temperatures against SST and humidity and comparing radiosonde observations with microwave-only retrievals and with infrared retrievals under the simplest geophysical conditions.

Phase C: Cloud-Clearing Validation (Timing: AIRS/AMSU/HSB Stable + Three to Seven Months): This phase addresses cloudy sky conditions over calm ocean, with emphasis on cloud clearing and cloud fraction retrievals. The datasets used during this aspect of validation include SST, AIRS Vis/NIR cloud masks, radiosonde observations, and aircraft-observed spectra. Retrieved cloud fraction is compared with the Vis/NIR cloud mask, and cloud-cleared radiance is compared with observed radiance in nearby cloud-free AIRS footprints. Infrared and microwave retrievals are compared with radiosonde profiles. This activity depends upon well-validated microwave retrievals and partial completion of Phase B.

Phase D: Retrieved T, q Validation (Timing: AIRS/AMSU/HSB Stable + Five to 11 Months): This phase addresses the infrared retrieval during cloudy skies over both ocean and land. The necessary correlative datasets include surface temperatures and emissivities over one or several AMSU footprints (e.g., the ARM SGP site), AIRS Vis/NIR cloud mask, and radiosonde observations of temperature and water vapor. Any additional cloud information available, such as from ARM instruments, is also utilized. This activity will confirm tropospheric temperature and humidity retrieval by AIRS/AMSU/HSB processing software over a wide range of cloud and surface conditions but at a limited number of sites.

Phase E: Extended Validation (Timing: AIRS/AMSU/HSB Stable + Eight to 24 Months): This phase provides the final estimates of AIRS/AMSU/HSB standard product uncertainties and begins to validate some of the AIRS research products. It addresses 1) the full retrieval under general surface and cloud conditions and 2) instrument or retrieval trends over monthly to yearly time scales. Correlative datasets include large numbers of surface, temperature, water vapor, cloud state, and ozone observations. These data are acquired under a wide range of geophysical conditions. Cross comparisons with retrieved surface temperatures, cloud properties, and water vapor loading from other Aqua instruments are also made.

VI. Summary

The AIRS/AMSU/HSB instrument suite and associated processing software provides a large, self-consistent set of surface and atmospheric products. Each of these products has associated uncertainty specifications (see Table I). The validation effort is responsible for constraining these uncertainties using correlative observations.

AIRS/AMSU/HSB validation activities utilize a wide range of operational datasets to determine the uncertainties on the observed and retrieved satellite products. Routine validation involves comparison with these operational datasets, including observations from assimilation models, operational radiosondes, meteorological surface instruments, instrumented commercial aircraft, and surface marine buoys. The operational datasets include a large number of observations, so are most useful for bounds checking and statistical comparisons.

Observations from instruments dedicated to AIRS/AMSU/HSB product validation are also utilized. The AIRS Validation Team provides some of these observations. These experiments include instrumented balloons for measuring temperature, ozone and water vapor, lidars for observing clouds and water vapor, spectrometers for *in situ* radiance observations, GPS measurements of total water vapor, and radars for detecting rainfall. Though limited in number, these observations are individually of higher scientific utility than similar operational observations because of better noise characteristics and an emphasis on simultaneity and colocation with satellite observations. The direct comparison with these dedicated observations complements the statistical comparisons made with the operational datasets.

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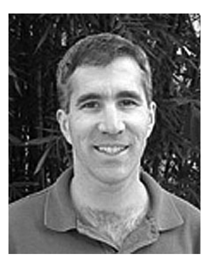

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Robert Atlas, photograph and biography not available at the time of publication.

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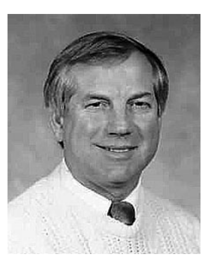
Sisong Zhou, photograph and biography not available at the time of publication.

HanJung Ding, photograph and biography not available at the time of publication.



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