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# Development of Processing System of the Direct-broadcast Data from the Atmospheric Infrared Sounder (AIRS) on Aqua Satellite

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**Abstract :** We present a processing system for the Atmospheric Infrared Sounder (AIRS) sounding suite onboard Aqua satellite. With its unprecedented 2378 channels in IR bands, AIRS aims at achieving the sounding accuracy of radiosonde (1 K in 1-km layer for temperature and 10% in 2-km layer for humidity). The core of the processor is the International MODIS/AIRS Processing Package (IMAPP) that performs the geometric and radiometric correction for generation of Level 1 brightness temperature and Level 2 geophysical parameters retrieval. The processor can produce automatically from received raw data to Level 2 geophysical parameters. As we process the direct-broadcast data almost for the first time among the AIRS direct-broadcast community, a special attention is paid to understand and verify the Level 2 products. This processor includes sub-systems, that is, the near real time validation system which made the comparison results with in-situ measurement data, and standard digital information system which carry out the data format conversion into GRIdded Binary II (GRIB II) standard format to promote active data communication between meteorological societies. This processing system is planned to encourage the application of geophysical parameters observed by AIRS to research the aqua cycle in the Korean peninsula.

Key Words : AIRS sounding suite, Aqua, direct broadcast, validation, Grib II format conversion.

## 1. Introduction

Aqua, launched in May 2002, is a major satellite mission of the Earth Observing System (EOS), an international program centered at the U.S. National Aeronautics and Space Administration (NASA; Parkinson 2003). The mission goal of Aqua is to monitor the water cycle of the Earth with a view to examining the indication of 0.4% increase in the rate of precipitation and evaporation. AQUA is a sister satellite with TERRA and its orbit differs by 12 hours with TERRA's.

The Atmospheric Infrared Sounder (AIRS) system is made up of three of the six Aqua instruments -

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AIRS itself, which is an infrared sounder with an unprecedented 2378 spectral channels, complemented with a 4-channel visible/near-infrared imaging module; the Advanced Microwave Sounding Unit-A (AMSU-A) system, which is a 15-channel microwave temperature sounder; and the Humidity Sounder for Brazil (HSB), which is a passive 4-channel radiometer to obtain data on humidity profiles. Among these, the AIRS is an innovative sensor that has 2378 spectral channels in three bands: 3.74 $\mu$m to 4.61 $\mu$m, 6.20 $\mu$m to 8.22 $\mu$m, and 8.8 $\mu$m to 15.4 $\mu$m with the spectral resolution of $\lambda/\Delta\lambda$ = 1200. AIRS was designed to meet the retrieval of meteorological parameters. With this unprecedented spectral resolution, AIRS aims at matching the sounding accuracy of radiosonde (1 K in 1-km layer for temperature and 10% in 2-km layer for humidity). To assist the AIRS, the AMSU-A and the HSB operate in microwave bands for temperature and moisture sounding. AIRS/AMSU/HSB forms a sounding suite on Aqua. The HSB is not valid now.

The data from all sensors on Aqua are direct-broadcasted to local users, meaning that whoever with an X-band antenna system may receive the data with no restriction and charge. Such direct-broadcast (DB) policy enables the near-real time processing of the data within a couple of hours. This point helps to improve weather forecasting.

In this article, we present the AIRS preprocessing system to obtain brightness temperature (Level 1b) and geophysical parameters (Level 2) from AIRS DB data. Then we transformed the Level 2 products with HDF-EOS (Hierarchical Data Format-Earth Observing System) into GRIB II (GRIdded Binery II) format. Finally, we will establish the near real time validation system which can compare with data measured by the in-situ measurement instruments, such as radio-sondes and buoys. The system can observe the atmospheric temperature in the troposphere with accuracies of 1 K over 1 km-thick layers under both clear and cloudy conditions, while the accuracy of the derived moisture profiles will exceed that obtained by radiosondes. In addition, the system will provide additional data on land and ocean surface temperature and surface emissivity, cloud properties, and ozone burden of the atmosphere. This makes the primary observing system to study the global water and energy cycles, climate variation and trends, and the response of the climate system to increased greenhouse gases

## 2. AIRS Processing System

The key parameters and their specifications of AIRS Level 1b and Level 2 are summarized in Table 1 and Figure 1. Aqua orbit is designed to have local passing time of 1:30 pm and to augment Terra's observation at 1:30 am. The footprints of the instruments are collocated to achieve 1-K/1-km retrieval accuracy in cloudy conditions such that there are three AIRS/HSB pixels per AMSU (Figure 1). Also one AIRS IR pixel corresponds to 8 × 9 AIRS visible/NIR pixels, because AIRS has an additional instrument in visible and NIR bands for daytime cloud clearing, as shown in Figure 1(Aumann *et al.* 2003).

In Figure 2, the whole processing systems are shown and this system consists of three sub-systems; Level 2 products generation system (L2PGS), standard digital information system (SDIS), near real time validation system (NRVS), and one web based demonstration system actually. Only L2PGS, SDIS, NRVS, and their products are described are presented in this chapter. All these processes, including the Level 2 generation system, are fully automated after being triggered by an incoming Level 0 data. It takes about 3 hours to finish the whole processes on a 3GHz Linux machine.

The IMAPP (International MODIS/AIRS

Table 1. AIRS Level 1 (a) and Level 2 (b) core products specifications (Fetzer *et al.*, 2003).

(a)

| Level 1b Products | Accuracy Absolute::Relative | Temporal Resolution | Horizontal Res. Coverage | Vertical Res. Coverage |
|---|---|---|---|---|
| Radiance AIRS [(1)]IR | 3% (190K-330K) :: 0.2K at 250K | 2/day (d/n) | 15 km:: Global | NA |
| Radiance AIRS [(2)]VIS_NIR | 10% :: 1% | 2/day (d/n) | 2.7 km: Global | NA |
| Radiance AMSU-A | 1.5K :: 0.5K | 2/day (d/n) | 50 km :: Global | NA |
| Radiance AIRS Cloud_cleared | 3% (190K-330K) :: 0.3K at 250K | 2/day (d/n) | 50 km :: Global | NA |

[(1)] IR: InfraRed, [(2)] VIS_NIR: VISual and Near InfraRed.

(b)

| Level 2 Product Name | Accuracy Absolute :: Relative | Temporal Resolution | Horizontal Resolution :: Coverage | Vertical Resolution :: Coverage |
|---|---|---|---|---|
| Temperature Profile T(p) | 1K rms | 2/day (d/n) | 50 km :: Global | 1 km :: surface to 100mb |
| Humidity Profile q(p) | 20% required, 10% goal ::10% | 2/day (d/n) | 50 km :: Global | 2 km :: surface to 100mb |
| Surface Skin Temperature | 1K :: 0.5K | 2/day (d/n) | 50 km :: Global | NA |
| Precipitable water [mm] | 5% :: 3% | 2/day (d/n) | 50 km :: Global | column :: troposphere |
| Cloud properties | NA | 2/day (d/n) | 50 km :: Global | surface :: 100mb |
| Ozone total column | 20% | 2/day (d/n) | 50 km :: Global | NA |

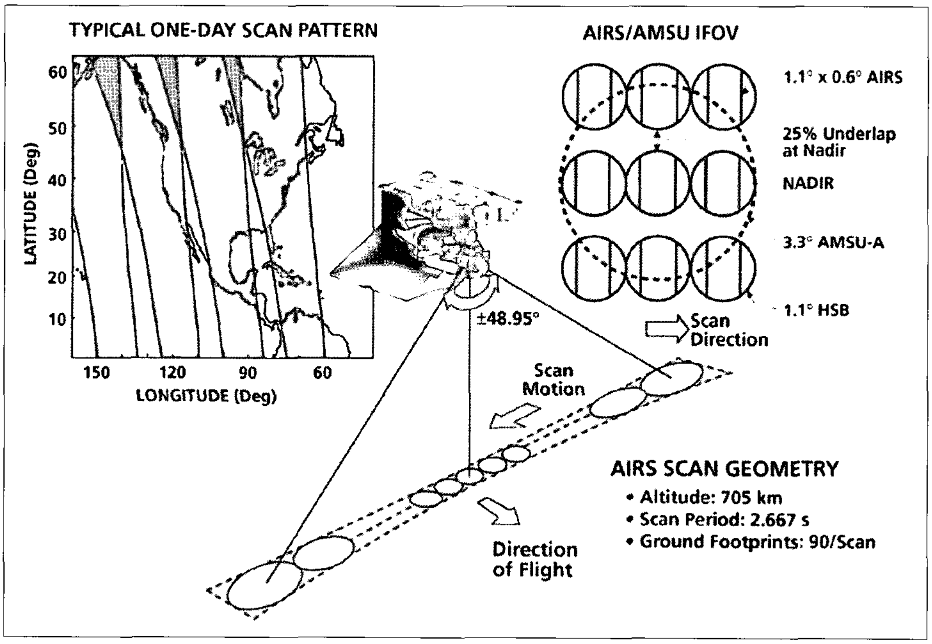



Fig. 1. Geometry of AIRS/AMSU/HSB cross-track imaging (center) with a picture of a swath (left) and the footprint configuration of the three instruments (right). Courtesy of Jet Propulsion Laboratory (JPL).

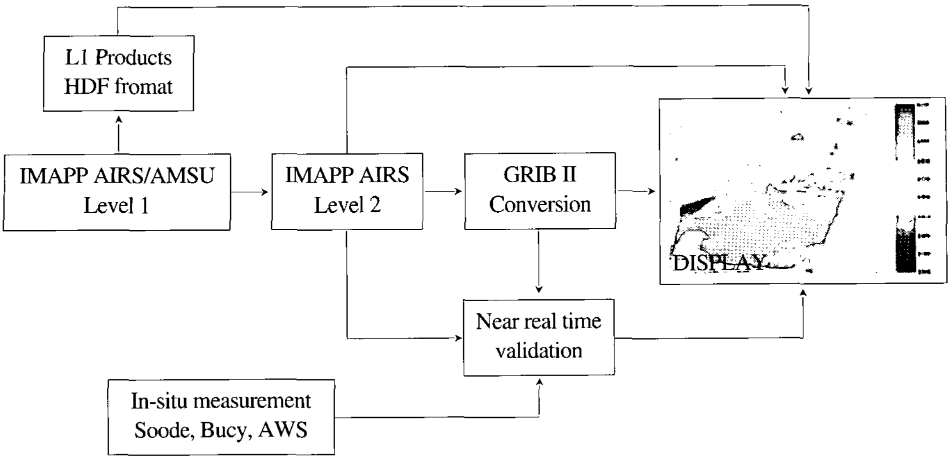



Fig. 2. Block diagram of the AIRS processing software (consisting of IMAPP and successive processers). Validation results with AWS measurement data are omitted in this paper, for they are prepared for comparison of precipitation using AQUA AMSR-E (Advanced Microwave Scanning Radiometer - EOS) data.

processing package) was used for the generation of AIRS products, which is distributed from the operational EOS processing software developed at NASA GSFC (Gaddard Space Flight Center) and JPL (Jet Propulsion Laboratory), and modified to be compatible with direct broadcast data.

### 1) AIRS Radiance Products

AIRS requires two types of calibration: radiometric and spectral. The radiometric calibration is one of the most important parts of AIRS preprocessing, because it determines the accuracy of radiance of 2378 channels. Both AIRS and AMSU employ onboard calibrators that provide the cold and warm references for non-linear calibration of raw observation counts (Pagano *et al.* 2003; Lambrigtsen 2003). Radiometric calibration utilizes the cold sky view (CSV) and the warm onboard blackbody calibrator (OBC), and their calibration data determine the radiance through observations view. Calibration coefficients are computed every scan using onboard calibrator measurements. The spectral calibration aims at ascertaining that spectral response function (SRF) keeps accurate and stable. A spectral calibration position is obtained by matching the upwelling spectra both measured and modeled. By arranging the focal plane assembly (FPA) and IR spectrometer assembly systematically and by adjusting the spectral grating model using in-orbit data, the center frequency of the IR spectra is determined within 1% error thus meeting the requirement (Gaiser *et al.* 2003). For AIRS, Level 1 product generation system (L1PGS) converts raw observation counts in the Level 0 data into radiance values in the units of mW $m^{-2}$ $sr^{-1}$ cm, and into brightness temperature for AMSU. This also performs geolocation, i.e., assigning latitude and longitude values to each pixel.

Spurious data exist in the AIRS radiance as shown in Figure 3 (a). Two types of information are available for filtering the bad data, one is a channel characteristic report and another is quality flag information report. The channel characteristic report defines which channel is operating correctly or not. The report is updated irregularly but every half a year or so. The quality flag report contains the information on noise level, moon contamination and detector mode. The filtered AIRS radiance is converted into brightness temperature ($T_b$) by using the Planck

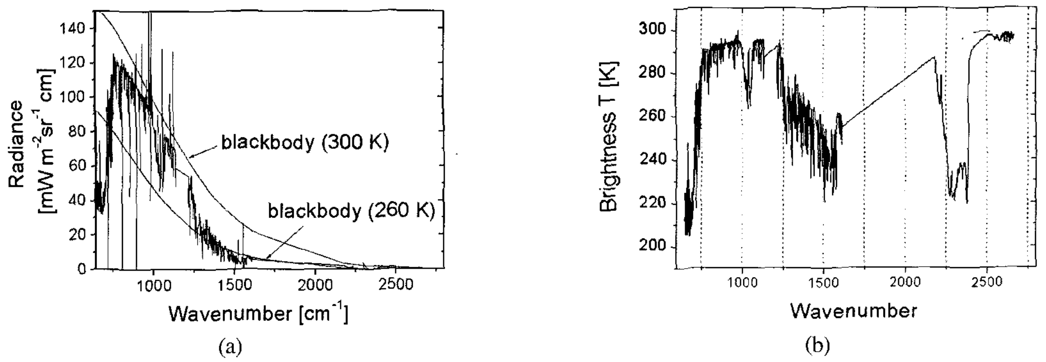
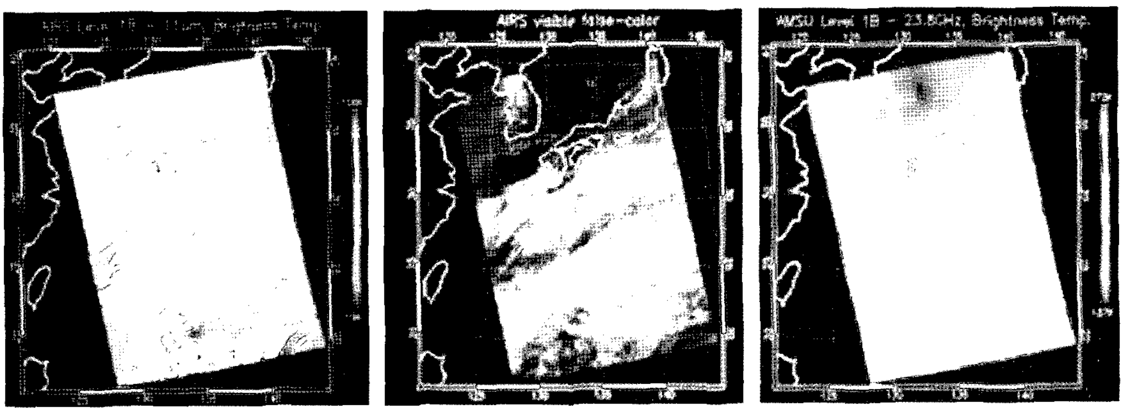



Fig. 3. Radiance (a) and brightness temperature after filtering spurious data (b) for AIRS level 1b at a point (Chilvaldo; 34.48′ N, 125.47′ E) and at a time (0417 (UTC) on 25 Febuary 2004).

function (in the Figure 3). The retrieved $T_b$ is successfully shown over the spectral region in the Figure 3 (b). This region includes the important temperature sounding regions in the 4.2 and 15 $\mu$m $CO_2$ bands, water vapor sounding in the 6.3 $\mu$m water band and ozone sounding in the 9.6 $\mu$m region. AIRS takes advantage of the ability to sound between absorption lines and its temperature dependence in the high-J lines in the 4.18 $\mu$m $CO_2$ band (to sharpen the weighting functions due to its enhanced resolution), addition to a sufficiently large number of 15 $\mu$m infrared channels, because high J-lines in the region, (in which the $CO_2$ absorption coefficient increases rapidly with increasing temperature,) provide the highest possible lower tropospheric vertical resolution of any part of the infrared spectrum. Figure 4 shows an example of AIRS/AMSU $T_b$ images. The scene is about 70% cloudy. Since AMSU channel 1, 23Ghz, is transparent to clouds, no cloud imprint is apparent.

## 2) AIRS Level 2 Products

The AIRS standard retrieval product consists of retrieved estimates of cloud and surface properties, plus profiles of retrieved temperature, water vapor, and ozone, and a flag indicating the presence of cloud



(0417 (UTC) on 25 Feb. 2004.)

Fig. 4. From left to right: Browse images of AIRS 11$\mu$m channel, VIS channel, AMSU 23 GHz channel from the KMA (Korea Meteorological Administration) DB data.

ice or water. Estimates of the errors associated with these quantities are also part of the standard product. The goal of accuracy is presented in table 1.

The profile vertical resolution is 28 points total between 1000 mb and 0.02 mb. In the table 1, the accuracy and resolution requirements of AIRS standard products are specified. The standard product contains quality assessment flags in addition to retrieved quantities. The standard product will be generated by L2PGS (Level 2 product generation system) at all locations where atmospheric soundings are taken. An AIRS granule has been set as 6 minutes of data. This will normally correspond to approximately 1/15 of an orbit but exactly 45 scanlines of AMSU-A data or 135 scanlines of AIRS and HSB data. The surface pressure (PsurfStd) is derived from the forecast sea level surface pressure and the topography provided by the digital elevation model (DEM) (Aumann *et al.* 2001):

$$\text{PsurfStd} = P_f \times \left[1 - g^{(h-h_f)}/c_p T_s\right]^{7/2} \qquad (1)$$

Where $P_f$ is the forecast sea level surface pressure; $h_f$ is the altitude from the DEM; hf is the forecast altitude; $T_s$ is the forecast surface temperature; $c_p$ is the gas constant; g is the gravitational constant. The fixed pressure grid for the AIRS Level 2 standard product, pressStd, contains 28 levels defined congruent with the World Meteorological Organization (WMO) standard pressure levels.

The standard product has surface skin temperature (K), Surface air temperature (K), air temperature (K), water vapor mass mixing ratio (gm/kg, dry air), water vapor saturation mass mixing ratio (gm/kg, dry air), total water (kg/m$^2$), ozone volume mixing ratio (micromoles/mole), total ozone (Dobson units), IR surface emissivities, IR surface reflectivities, microwave surface brightness temperature, microwave emissivity at 50.3 GHz, total cloud water (kg/m$^2$), cloud top temperature (K), cloud top pressure (mb), cloud fraction (0.0 - 1.0), geopotential heights (m above mean sea level), and geopotential height of surface (m above mean sea level).

Since every IMAPP product is divided into a granule unit, inevitably products with partial granules (whose length is less than 6 minutes) are often obtained. Resultantly, the radiance difference between this product and EOS DAAC (Distributed Active Archive Center) standard product arises because of radiance calibration difference by the incomplete granule length (Kim *et al.* 2003). For an example of difference between two products, the mean and standard deviation (SD) differences are less than 0.1 K and 0.2 K, respectively for two air temperature data in the scene of September 2, 2004.

Figure 5 shows AIRS Temperature images in the height of 500 and 850 hPa, and on the surface skin after AIRS temperature retrieval. Figure 6 shows an example of AIRS temperature profile data in Paekryong-island (38.0° N, 124.6° E). Blue line is measurement data by radiosonde, black line is measurement data by AIRS. This figure demonstrates that two temperature profiles agree well.

### 3) Near Real time Validation system (NRVS)

The EOS validation program has supported several investigators providing dedicated observations for AIRS validation. 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 1. AIRS operational validation program includes 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 (Hagen and Minnett. 2003). This section describes near real time validation system (NRVS)

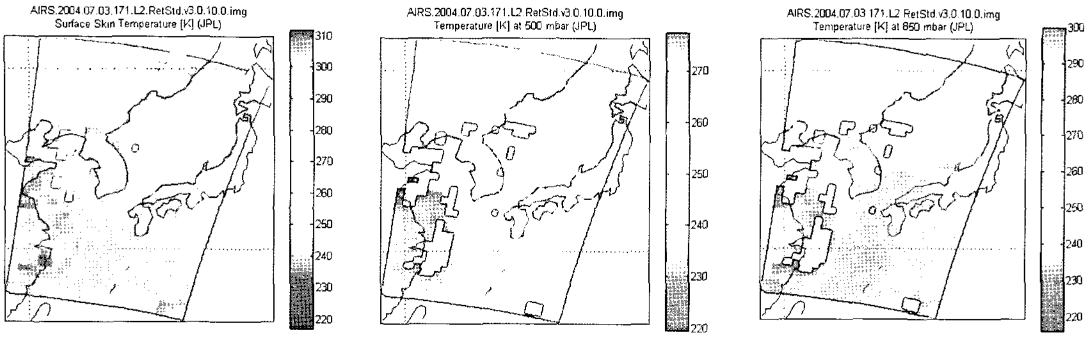



Fig. 5. Examples of successful geophysical (AIRS Level 2) retrievals. From left to right: AIRS browse images of temperature at 500 and 850 hPa, and surface skin temperature, third of July, 2004.

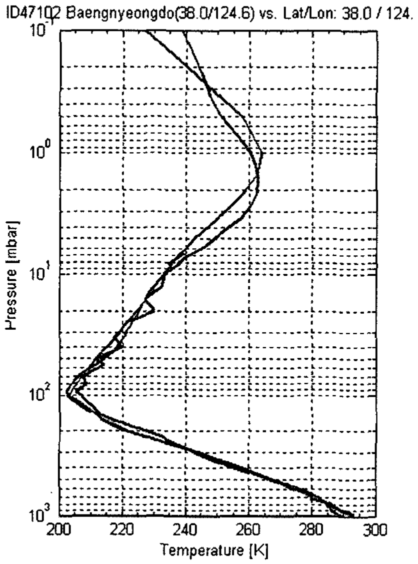



Fig. 6. Temperature profile data in Paekryong-island (38.0° N, 124.6° E). Blue line: measurement data by Radiosonde; Black line: measurement data by AIRS (Red line is a result retrieved by other algorithm and not discussed here.).

and presents some validation results. The NRVS to validate the AIRS retrieval accuracy produces comparison results with radiosonde and buoy observation data, and it includes bias and RMSEs as a part of the result. This NRVS enables one to compare and monitor at near real time the results measured by the two different measurement systems, AIRS and in-situ. Looking into a processing manner of the NRVS, firstly only available parameters are extracted from the meteorological data and sorted with reference to its geographical location. To allocate the meteorological (in-situ) data point to the AIRS level-2 pixels, all in-situ meteorological data is relocated to the 5 × 5 km grid which is based on the Lambert conformal conic projection. Comparison parameters and collocation condition are presented in Table 2.

The primary source of real-time in-situ observations is radiosondes which are acquired from six different observation stations (Paekryong-island, Sokcho, Osan, Pohang, Gwangju, and Cheju) in the Korean peninsula. In spite of their daily release, radiosondes are the major atmospheric profiling instrument available for satellite validation. They are routinely launched two (or four) times (0, (6), 12, (18) UTC) a day and measures various meteorological parameters such as pressure, height, temperature, dew point temperature, and relative humidity. Since the measurement characteristics of radiosondes are well understood and their uncertainties are comparable to or better than the specified uncertainties on the AIRS retrievals, they are used as ground truth data for this study. Two specific validation results from Gwangju, Pohang, Sokcho and Osan are represented in Figure 7 and 8. Figure 7 (a) and (b) and (c). show the vertical temperature profiles of the radiosondes and the AIRS data and their statistical results such as BIAS, RMSE,

Table 2. Validation parameters and their conditions in NRVS.

| Geophysical parameters | In-situ observati on system | Comparison site | Collocation(reference to the corresponding site) | |
|---|---|---|---|---|
| | | | Spatial Distance Horizontal :: vertical | Temporal Distance |
| Temperature profile | Radio sonde | 6 sites; (Paekryong and Cheju island, Sokcho, Kwangju, Osan, and Pohang) | ± 0.5° AIRS pixel average (Singh *et al.* 2002) :: interpolation between two levels | within ±2 hours |
| Water vapor profile | | | | |
| Sea surface temperature | [1]Moored buoy | 5 sites; (Dukjuk, Chilbal, Gujae and Gumun islands, and Donghae sea) | Corresponding AIRS pixel::NA | within ±1 hours |

[1] At present, the validation results using Moored buoyes are not presented in this paper, because all of the Moored buoy observation do not have such a good condition to validate according to the scientific review (Donlon *et al.* 2002), however, with the drift buoyes meaningful validation results are expected.

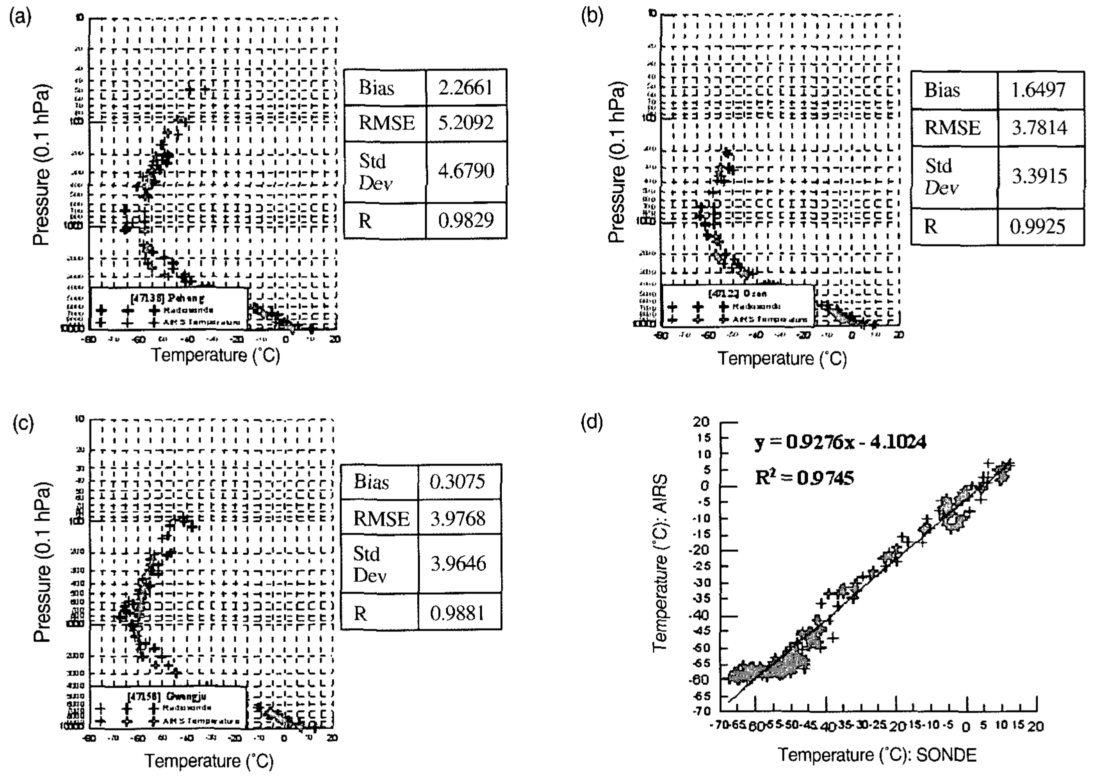



Fig. 7. Statistical results of the atmospheric temperature profiles of the radiosondes (blue) and the AIRS data (red) at the sites of (a) Pohang, (b) Osan, and (c) Gwangju, Nov. 16, 2004 and (d) scattering plot and linear regression relation between sondes and the AIRS data.

and correlation coefficient. Figure 7 (d) presents the scattering plot between two the different observations. Higher value of $R^2$ for atmospheric temperature expresses the outstanding matching between two observation systems, while large offset of -4.1 °C says that it requires a calibration procedure like a zero drift correction. Despite of this offset, it shows the possibility that the AIRS can replace sonde measurement for temperature profile as an input data of the weather prediction model. In Figure 8, statistical results of the atmospheric humidity profiles of the radiosondes (blue) and the AIRS data (red) at the sites of (a) Sokcho, (b) Pohang, and (c) Gwangju, Nov. 16 2004 and scattering plot (d) between sondes and AIRS data appear. The comparison results look generally worse than that of temperature. The correlation coefficient is comparable to the previous results which show relative RMS percent of 0~50 % (Fetzer *et al.* 2005). The temperature difference more than 1 K appears at lower troposphere 800-1000 hPa because of cloud clearing error, and this trend is similar to the previous study(Hagen and Minnett 2003). Here, only preliminary validation results are demonstrated now, when this validation system is used in the forthcoming study, improvement may be expected though the measured data is localized and the number of data is not enough to execute statistical treatment compared to the operationally investigated validation program. In order to be done so, it needs that the systematic errors of each measurement system are speculated and corrected in advance.

### 4) Standards Digital Information System (SDIS)

This section describes the Standard digital information system (SDIS), one of sub-systems in this processing system. The goal of SDIS is to improve user's application to his study by packing them in a

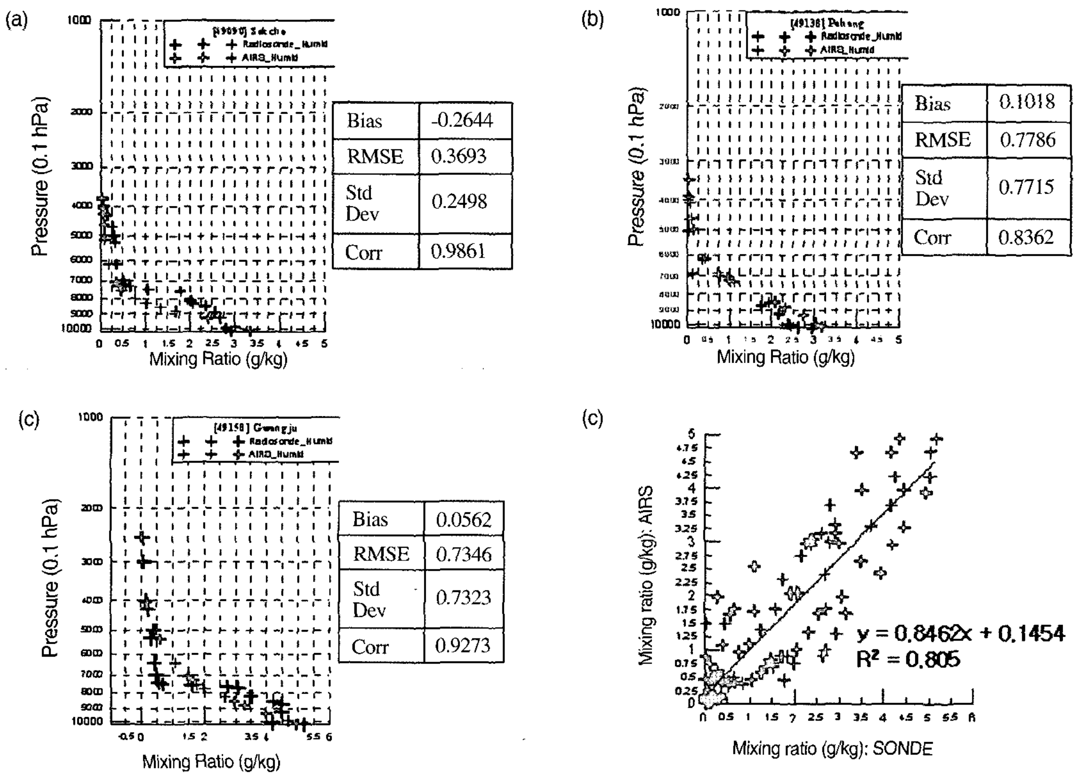



Fig. 8. Statistical results of the atmospheric humidity profiles of the radiosondes (blue) and the AIRS data (red) at the sites of (a) Sokcho, (b) Pohang, and (c) Gwangju, Nov. 16, 2004 and (d) scattering plot and linear regression relation between sondes and AIRS data.

friendly format. This goal is achieved by connecting the AIRS data consisted of a granule after a satellite pass and by converting the output file format into GRIB II which is universally used for data communication in the meteorological society. One scene (or data) of AIRS is different from the type of geostationary satellite, for example GOES series. DB data are confined only while a satellite is within the sight of a ground station, because AQUA travels in a near-polar low-Earth orbit. DB data covers generally the three granules (a granule is defined 6-minute long, because the data size is very big due to unprecedented huge number of channel). So we connected 3 granules acquired during one pass according to the time series, for user to conveniently use. Again, HDF-EOS (NASA standard format) output products are converted to GRIB II format. GRIB II is approved by the World Meteorological Organization (WMO) Commission for Basic Systems (CBS) Extraordinary Meeting Number VIII (1985), because it is an efficient and compact vehicle for transmitting large volumes of gridded data to automated centers over high-speed telecommunication lines using modern protocols. GRIB II can equally well serve as a data storage format, generating the same efficiencies relative to information storage and retrieval devices. Each pixel in the granule is reorganized into constant size grid, and a grid is achieved by Lambert conformal map projection which is recommended by the KMA. User makes his choice of grid size for his application in the range of 5~55 km. This reorganized pixel is considered to be used as a tool for the comparison between in-site and AIRS data. Figure 9 shows the results produced by SDIS for the retrieval products SST (Sea Surface Temperature).

## 3. Summary

We have performed the processing of AIRS data to

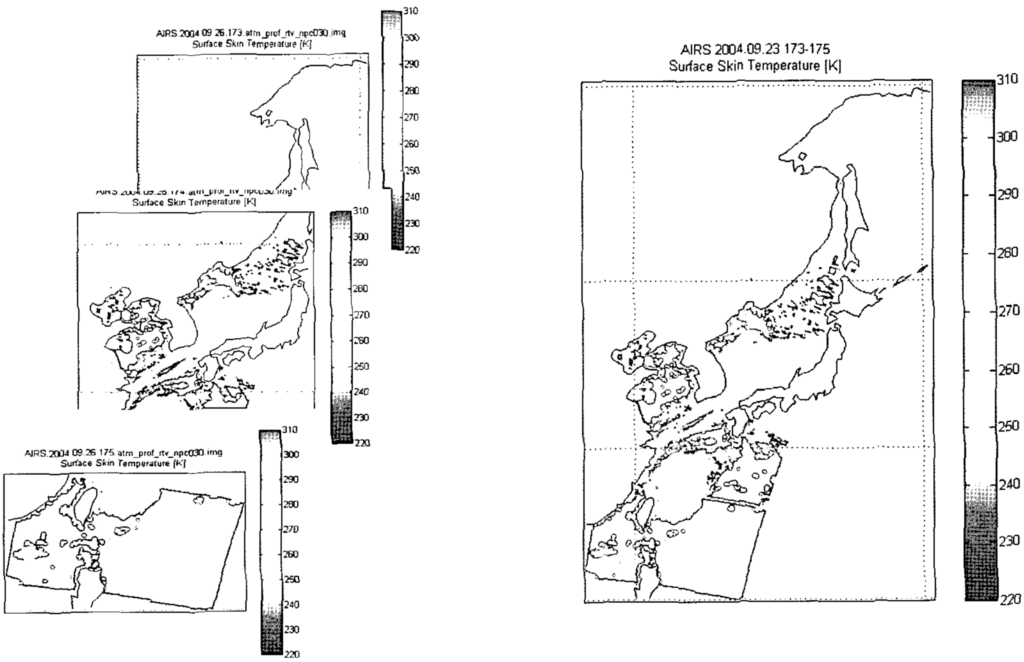



Fig. 9. (a) shows the original pictures produced by L2PGS and (b) is after data connection and mapping to the Lambert conformal map projection for GRIB II file format conversion. Granules were produced 26th of September, 2004 and their number is 173~175 (a) and after one data (b).

generate L2 (L2PGS) and format converted data (SDID) and validation (NRVS) from KMA's direct-broadcast (DB) data. The goal of the AIRS suite is to provide temperature and moisture sounding data with accuracy by radiosonde observation data for the weather prediction. AIRS Level 2 data from DB matches perfectly with the EOS DAAC standard product for a full granule. Level 2 product generated is EOS standard format, HDF-EOS format. For a broad application, the level 2 data are converted into GRIB II format through Lambert conformal map projection. To validate the AIRS products, meteorological in-situ data are prepared for comparison and the results are summarized statistically in the result report in the NRVS. This processing system is expected to encourage the application of AIRS products to research the AQUA cycle in the Korean peninsula.

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