Validation of Satellite AIRS Retrievals with Aircraft NAST-I Soundings and Dropsondes – Implications for Future Satellite Sounding Capabilities

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ABSTRACT

The airborne NPOESS Aircraft Sounding Test-bed Interferometer (NAST-I) has flown on numerous flights under the Aqua satellite in order to validate AIRS radiance measurements and profile retrievals. The NAST-I is an excellent AIRS airborne validation tool since it possesses relatively high spectral and spatial resolution as well as relatively low radiance measurement noise, especially after the data are spatially averaged to the footprint size of the AIRS sensor. The results of these airborne missions have shown that the AIRS calibration validates well against airborne interferometer radiance measurements[1]. Here, it is shown that the retrievals obtained using the same retrieval algorithm are in general agreement, although the airborne NAST-I result possesses higher vertical resolution as a consequence of it's higher spectral resolution and lower "effective" radiance noise level. The "effective" radiance noise level is a function of the single spectral sample radiance measurement noise, the number of spectral channels used for the retrieval, and the number of spatial samples averaged to produce the final profile result. For the NAST-I aircraft instrument, the effective radiance noise level is extremely small, particularly after reducing the horizontal linear resolution to that of the satellite AIRS instrument (i.e., ~14 km for AIRS as opposed to ~2 km for NAST-I), and as a result its relatively large spectral range and high spectral resolution (i.e., NAST-I possess nearly four times the number of spectral channels as does the AIRS). It is shown here that spatial averaging of the AIRS data, which decreases the noise level of the radiances used for the retrieval, improves the vertical resolution of the profile results.

1. Introduction

A new era of higher vertical resolution atmospheric temperature and moisture profile retrievals from satellite radiance measurements has begun in an attempt to improve weather and climate monitoring and forecasts. The higher vertical profile resolution is to be achieved by a one to two order of magnitude enhancement of the spectral resolution and coverage, dependent upon spectral location[2, 3]. Improved Instrument Line Shape (ILS) (i.e., spectral position) knowledge, and a lower spectral radiance noise over that characteristic of the current operational sounding spectrometers (Smith, et. al., 1979, 1991) also contribute to the improved vertical resolution. The approach is soon to be implemented using high precision Fourier Transform Spectrometers (FTS) on both European (METOP) and US (NPOESS) operational polar satellites beginning in 2005. Imaging spectrometers are under development for the future generation of operational geostationary spacecraft, the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) being an experimental prototype to be in orbit during the latter part of this decade[4].

The first airborne tests of the high vertical resolution sounding concept began with the advent of the High resolution Interferometer Sounder (HIS) [5,6] flown on NASA's the high altitude ER-2 aircraft from 1985 to 1998. The success of the HIS led to a spaceborne demonstration of concept instrument, the Atmospheric Infrared Sounder (AIRS), a cryogenic cross-dispersed grating spectrometer[7], launched on the NASA Aqua satellite on 20 May 2002. In order to validate the AIRS and the operational instruments to follow, two improved airborne FTS instruments were developed, the Scanning HIS (S-HIS) and the NPOESS Airborne Sounding Testbed-Interferometer (NAST-I)) which are a cross-track scanning Michelson Interferometer follow-on to the original nadir-only viewing HIS. Both the S-HIS and the NAST-I were developed to collect controlled sets of very high quality spectral radiance and retrieved atmospheric profile reference data as needed to validate the spacecraft radiance measurements and derived geophysical products. Beyond Aqua, the airborne FTS validation approach will be applied to the Aura and NPP research satellites and the Meteorological European Terrestrial Operational Polar satellite (METOP) and the National Polar Orbiting Environmental Satellite System (NPOESS) operational satellites.

This paper focuses on the use of the NAST-I for the validation of the Aqua AIRS profile retrieval capability. (The use of S-HIS for the validation of AIRS radiance measurement accuracy has been addressed in these proceedings by Revercomb[2]. In order to conduct an objective assessment, the AIRS and NAST retrievals are produced using exactly the same retrieval algorithm. The forward radiative transfer model used for the AIRS retrievals is the SARTA[8], based on the GENLEN line-by-line model, whereas that used for the NAST retrievals is the OSS model[9], based on LBLRTM. No adjustment of the radiances (i.e., radiance tuning) is made, on the basis of comparisons between observed and calculated radiances, to account for forward radiative transfer model errors. The results show that the retrievals from the NAST-I radiances possess higher vertical resolution than those produce from AIRS radiances. This was expected due to the higher spectral resolution, broader spectral coverage, and thus lower effective noise achieved by NAST-I. Thus, NAST-I is a very good AIRS product validation tool. It is also shown that the vertical resolution of the AIRS retrievals is improved by 3 x 3 footprint averaging of the data which reduces the spectrally random noise level of the radiances used for the retrieval by a factor of 3.

2. The NPOESS Aircraft Sounder Testbed – Interferometer (NAST-I)

The NPOESS Airborne Sounding Testbed-Interferometer (NAST-I) [8,9] was developed to be flown on high altitude aircraft to provide experimental observations needed to finalize the specifications and to test proposed designs and data processing algorithms for the Cross-track Infrared Sounder (CrIS) to fly on the National Polar-orbiting Operational Environmental Satellite System (NPOESS). NAST-I is a Michelson Fourier Transform Spectrometer with high spectral resolution (0.25cm^{-1}) and high spatial resolution (0.13 km linear resolution per km of aircraft flight altitude at nadir). The NAST-I spatially scans cross-track to the aircraft motion +/- 48.2 degrees, thereby providing a 2.3 km ground track swath width per km of aircraft flight altitude. The radiometric noise is about 0.3 K, spectrum-to-spectrum, dependent upon spectral region and scene temperature. The spectral precision is generally better than 0.25 K, spectral point to spectral point, within a given radiance spectrum.

As shown in figure 1, the NAST-I has a spectral range of 3.6 - 16.1 µm, without gaps, and covers the spectral ranges and resolutions of all planned advanced high spectral resolution infrared spectrometers to fly on polar orbiting and geostationary weather satellites, including the EOS-AIRS, METOP-IASI, the NPP/NPOESS-CrIS, and the EO3-GIFTS. Thus, the NAST-I data can be used to simulate the radiometric observations to be achieved from these advanced sounding instruments. Moreover, the forward radiative transfer models and product retrieval algorithms planned for these satellite systems can be validated prior to launch. Finally the NAST-I can be used for the fundamental purpose of post-launch calibration and validation of products for the advanced satellite sounding systems.

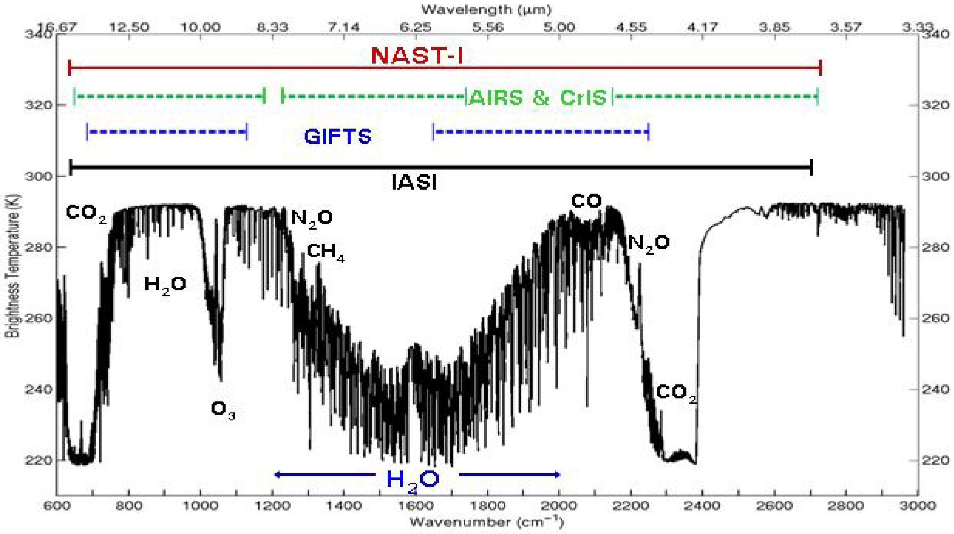


Figure 1: The NAST-I spectral coverage compared to that of advanced satellite sounders.

The NAST-I instrument design is based on reflective optics, KBr beam splitter compensator and separate integral detector/cooler assemblies operating at 65K. A heated and an ambient cold blackbody sources are viewed in each scan to provide absolute radiometric calibration at the level of 0.25 K. Dynamic alignment of the interferometer optics, a pressurized N2 enclosure and wire coil shock mounts are used to minimize the environmental effects of aircraft flight. The instrument processor/controller is based on a Pentium CPU with real time digital signal processing. A ring laser gyro/GPS navigation sensor is used to earth locate the data.

The NAST-I spatially scans the Earth and atmosphere from an aircraft, such as the high-altitude NASA ER-2 research airplane or the Northrop-Grumman Proteus aircraft. From an aircraft altitude of 20 km, 2.6 km spatial resolution is achieved, thereby providing three-dimensional hyper spectral images of radiance and derived geophysical products (figure 2).

The NAST-I aircraft interferometer instrument is capable of spatially mapping atmospheric temperature and moisture with a very high horizontal resolution (~1-3 km, depending on altitude and scan angle). The basic NAST-I product is a two-dimensional “image” of spectral radiance, for any spectral channel within the 3.5 to 16.5 micron range of the instrument (figure 2). The derived products include cloud and surface radiative and physical properties (e.g., spectral emissivity and temperature, cloud-top pressure and optical depth) and a three-dimensional representation of the temperature, water vapor, and the concentration of other radiatively active trace gases (e.g., O_3, CO, CH_4, and N_2O) of the atmosphere. NAST-I provides a vertical resolution of 1–2 kilometers for atmospheric temperature and water vapor, so that distinct layers are observed, the number depending upon aircraft altitude. Thus, as the aircraft passes over the Earth, NAST-I scans an area at the Earth’s surface collecting data on the properties of the Earth’s surface and atmosphere beneath the aircraft. The wide variety of surface and atmospheric sounding and cloud products support scientific studies as well as provide a means to validate both forward model and inverse algorithms to be used for future spacecraft high spectral resolution sounding instruments.

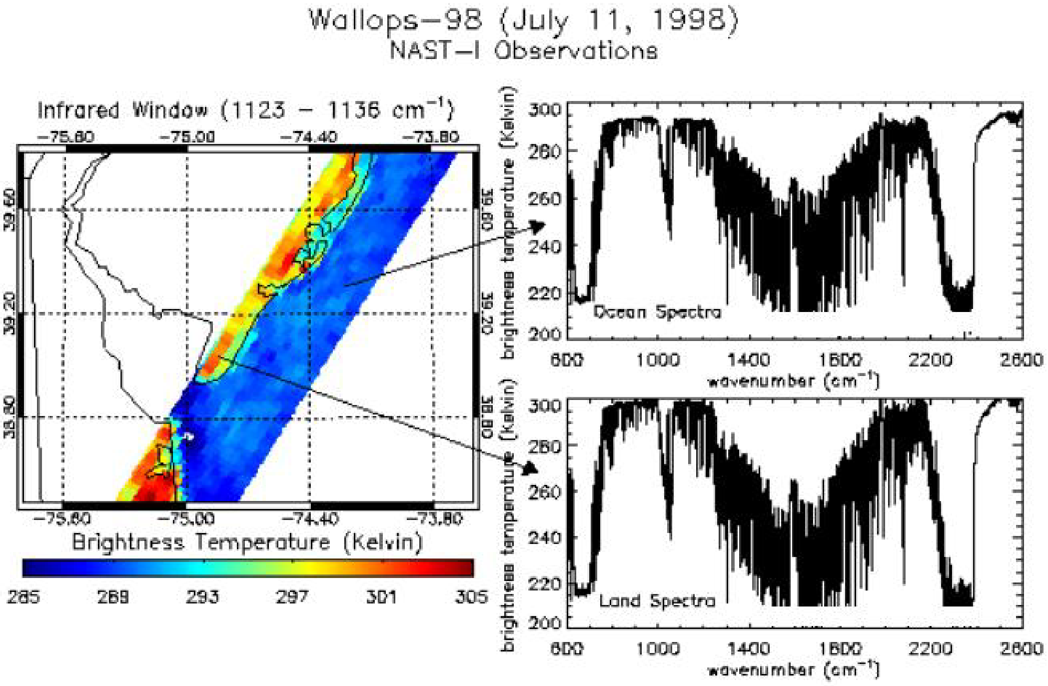


Figure 2: NAST-I Observations along the Atlantic coast of Virginia on July 11,1998.

3. Sounding Retrieval Approach

Temperature and moisture sounding capability of the NAST-I high spectral resolution infrared sounder, has been tested during numerous field programs. The retrieval results are obtained using the eigenvector regression retrieval method as applied to high spectral resolution interferometer data[12, 13]. In this technique, a training sample of historical radiosonde data is used to simulate radiance spectra for the NAST-I instrument. In the simulation, the radiosonde temperature and humidity structure is used to diagnose the cloud top level. For the spectral radiance calculations, each radiosonde, which possesses cloud, is treated as both a clear sky and as an opaque cloud condition profile. The opaque sky condition profile is created by representing the radiosonde temperature and moisture profile below the cloud as isothermal, at cloud top temperature, and saturated. This profile adjustment enables the retrieval system to obtain a clear sky equivalent, from a radiative transfer point of view, temperature and moisture profile regardless of the cloud condition. If the sky is cloud free, then the correct atmospheric profile will be obtained from aircraft level down to the earth's surface. If an opaque cloud exists, the correct atmospheric profiles will be retrieved down to cloud top with an isothermal, at cloud top temperature, and saturated profile being retrieved below the cloud top down to the earth's surface. If a semi-transparent or broken cloud cover exists, then the correct profile will be retrieved down to the cloud top level; below the cloud a temperature profile intermediate to the true profile and the cloud top temperature, and a less than saturated water vapor condition, will be retrieved, the proportion of isothermal and saturation structure being dependent on the cloud opacity and fraction (see figure 3). The surface emissivity spectrum for each radiosonde profile is randomly selected from a set of laboratory measured emissivity spectra for a wide variety of surface types[14]. Trace gas species, such as ozone and carbon monoxide are specified using a statistical representation based on correlations of these gases with temperature and humidity conditions specified by the radiosonde data[15].

Eigenvectors are computed and regression equations which relate the eigenvector amplitudes to the radiosonde temperature and water vapor values, surface temperature, and the coefficients of an eigenvector representation of the surface emissivity spectra[16], used in the radiance simulation, are derived, assuming a variable number of eigenvectors for the representation of the spectral radiance information. Appropriate random instrumental noise is then added to the simulated radiance data set and retrievals are performed for all cases as a function of the number of eigenvectors. The optimal number of eigenvectors is then selected as that number which minimizes the RMS retrieval error for the historical radiosonde data set. This number generally ranges between 15 and 50, for NAST-I, depending upon the variance associated with the particular data set used (higher natural variance requires a larger number of eigenvectors to represent the information content of the radiance spectra). The regression equations for the optimal set are then applied to real NAST-I radiance measurements, which are corrected for reflected solar radiation contributions. The reflected solar contribution correction is based on a reflected solar spectrum calculated for a model surface and atmospheric condition, similar to that being observed, and the radiances observed in the 4.0 and 9.0-micron window regions of the spectrum[10]. Since all the radiative transfer calculations and eigenvector decomposition analysis are done “off-line” to the actual data processing, the algorithm is extremely fast when applied to real data

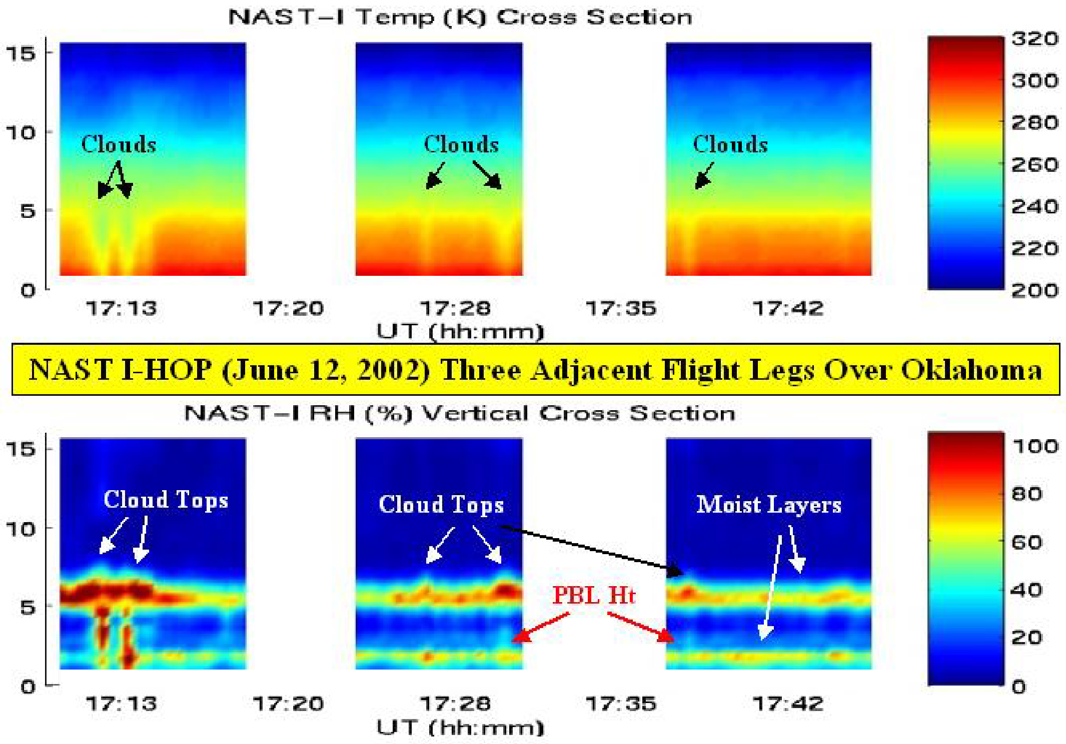


Figure 3: Typical temperature and moisture retrievals observed by NAST-I during the I-HOP field experiment conducted over Kansas and Oklahoma. One can see from that the temperature tends toward the isothermal (top panel) and the moisture saturated (bottom panel) below the cloud, the degree of which depends on the cloud opacity.

4. Validation of AIRS Retrievals with NAST-I Retrievals

The Atmospheric Infrared Sounder (AIRS) on the NASA Aqua spacecraft launched on 20 May 2002 is a cryogenic cross-dispersed grating spectrometer[7]. It employs 7 different orders of dispersion to map the spectrum onto 12 detector modules with a total of 15 linear arrays. The AIRS instrument is the first spaceborne spectrometer designed to meet the 1-K/1-km sounding accuracy objective by measuring the infrared spectrum quasi-continuously from 3.7 to 15.4 microns with high spectral resolution ($\nu/\delta\nu = 1200/1$). The sensitivity requirements, expressed as Noise Equivalent Differential Temperature (NEdT), referred to a 250-K target-temperature ranges, from 0.1 K in the 4.2-µm lower tropospheric sounding wavelengths to 0.5 K in the 15-µm upper tropospheric and stratospheric sounding spectral region. Spatial coverage and views of cold space and hot calibration targets are provided by a 360-degree rotation of the scan mirror every 2.67 seconds. Table 1, below, summarizes the AIRS measurement characteristics.

Table 1. AIRS Measurement Characteristics

Data Rate	1.27 Mbits per second
Spectral Range	IR: 3.74 – 4.61 µm, 6.20-8.22 µm, 8.80-15.4 µm (2378 spectral channels) VIS/NIR: 0.4 – 1.1 microns
Spectral Resolution ($\nu/\delta\nu$)	1200 (0.5 – 2.25 cm^{-1})
Field of View	IR: 1.1 degree (13.5 km at nadir from 705 km altitude) 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 x 1 x 1.1 degree VIS/NIR: 720 x 8 x 0.2 degree
Scan Period	2.67 seconds

Figure 4 shows the spectral channels of the NAST-I and the AIRS used for the atmospheric sounding retrievals. There are approximately three times as many NAST channels as there are AIRS channels (i.e., 4425 compared to 1594 spectral channels for NAST-I and AIRS, respectively) used for the retrievals as a result of the higher spectral resolution of the NAST.

Figure 5 shows the Aqua underpass leg of the NASA ER-2 for which sounding comparisons were performed. There were also four dropsondes released from the NOAA Gulfstream 4 (G-4) aircraft along the flight track directly under the Aqua satellite, one each at the Northern and Southern ends, and two in the middle portion of the eastern leg of the flight loop shown. The ER-2 NAST, Aqua AIRS, and G-4 dropsonde observations were all within a few minutes of each other.

Figure 6 shows the footprints of the Aqua AIRS sounding instrument and those of the NAST-I for the data used for the sounding intercomparison. One can see from the images for the window spectral region (870 – 900 cm^{-1}) that there was some low cumulus cloud across the middle of the ER-2 flight leg used for the intercomparison. One can also see the spatial resolution differences between the NAST-I and the Aqua AIRS brightness temperature observations, the NAST-I possessing almost 40 times higher area resolution than the AIRS (nominally, 2.5 vs. 15 km linear resolution). The very high spatial resolution of the NAST-I is important for isolating clear sky observations needed for obtaining accurate soundings to the Earth’s surface for validating the lower resolution satellite retrievals.

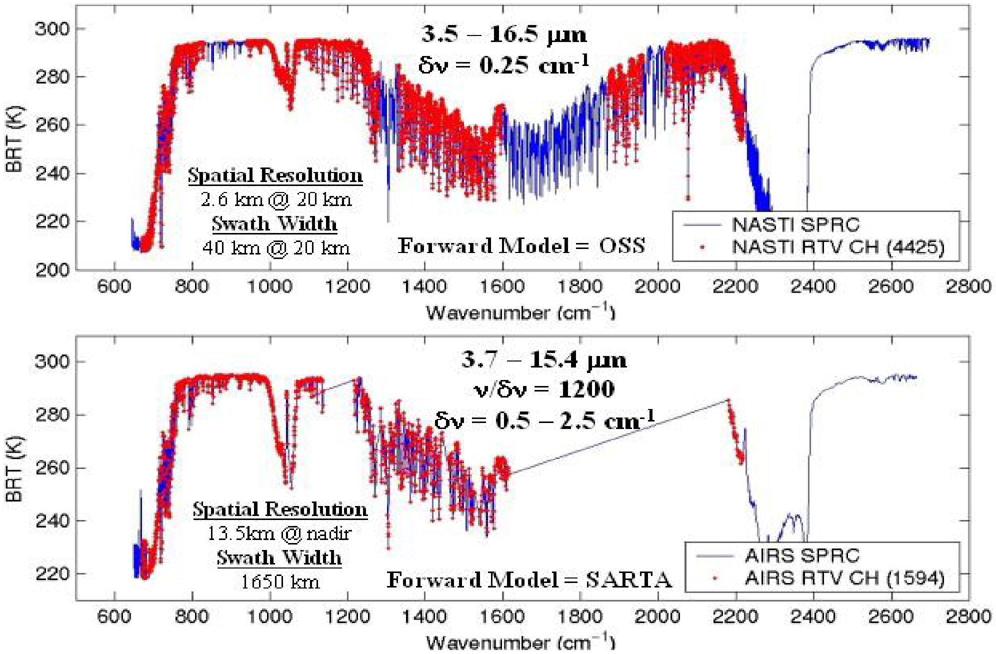


Figure 4: Spectral channels (red dots) used for the sounding retrievals are shown here.

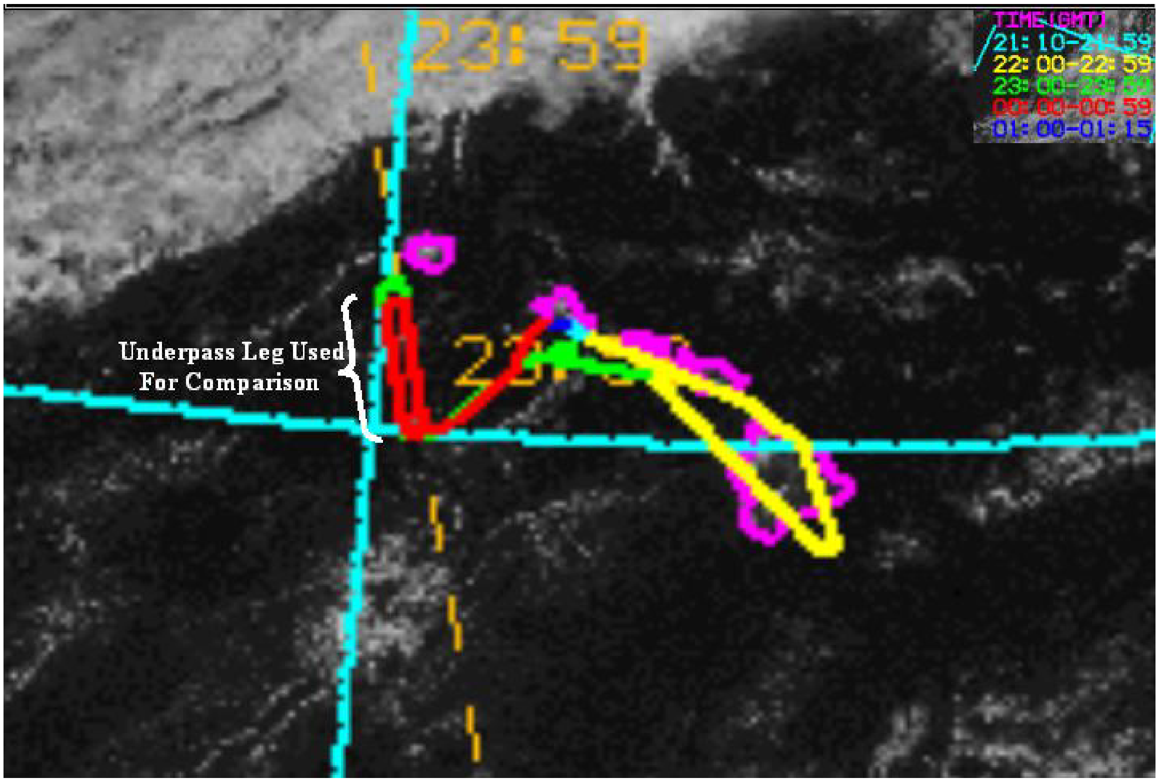


Figure 5. The NASA ER-2 flight tracks on March 3, 2003 in the vicinity of the Hawaiian islands. The flight track used for the comparison of NAST-I and dropsonde soundings with the Aqua AIRS retrievals are shown (the dashed brown line is the Aqua orbital track).

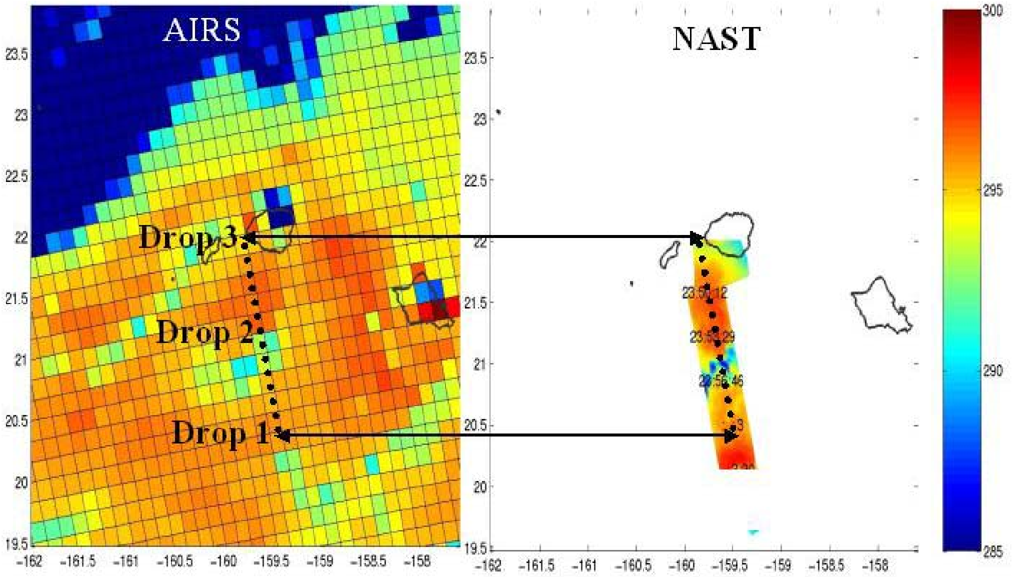
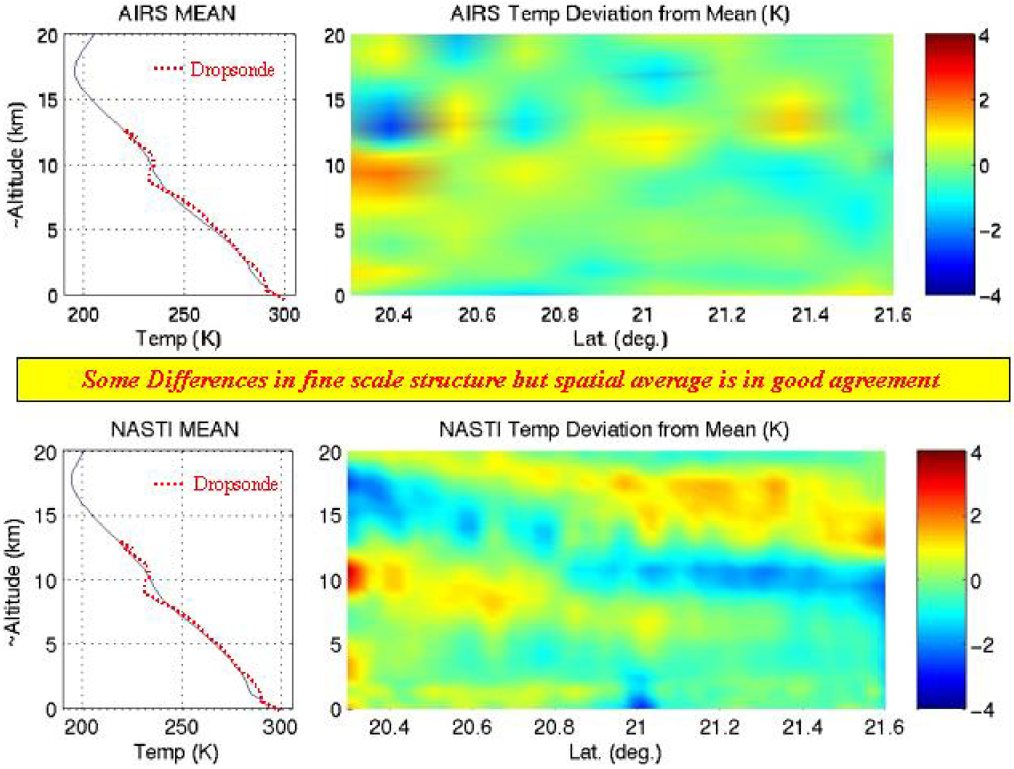


Figure 6. Brightness temperature (870 – 900 cm^{-1}) images showing the footprints of the AIRS and NAST-I radiance data used for sounding intercomparisons shown in figure 7.

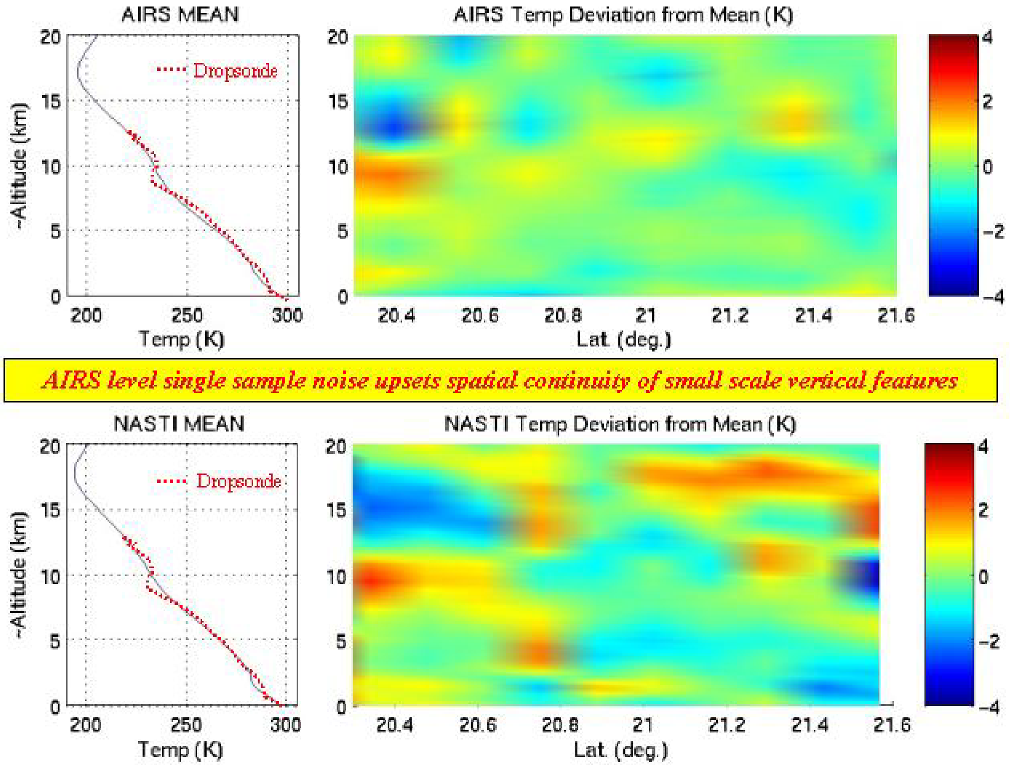


Some Differences in fine scale structure but spatial average is in good agreement

Figure 7. Cross-sections of full spatial resolution AIRS and NAST-I retrievals along the flight tracks shown in figures 5 and 6. The color panels illustrate the temperature anomaly from the mean profiles shown on the left of each cross-section. The average of the dropsonde measurements along the flight tracks are shown by the red dots superimposed on the soundings.

Figure 7 shows the comparison between the temperature profiles obtained from the full spatial resolution Aqua AIRS (~ 15 km) and ER-2 NAST-I (~2.5 km) measurements along the orbital track of the Aqua. The cross-sections are illustrated in terms of the deviation of the profiles from their mean along the track. The mean profiles are shown to the left of each cross-section image. The spatial average of the dropsonde measurements along the track are superimposed upon the AIRS and NAST-I mean profiles to provide validation of the absolute values of the temperature retrieval results. As shown from the cross-sections, there are significant differences in the fine scale spatial structure of the AIRS and NAST-I cross-sections, although the mean profiles are in reasonably good agreement. In this case, the AIRS retrievals look noisy compared to the spatially coherent NAST-I cross-sections.

In order to explain the fine scale spatial resolution differences shown in figure 7, AIRS level measurement noise was artificially added to the NAST-I radiance observations prior to performing the retrieval process. Figure 8 below shows the result. As can be seen, the retrieval cross-section based on the NAST-I, with AIRS level noise introduced, has now lost its spatial coherency; the cross-section appears to be noisy like the AIRS result. Thus, the likely explanation for the difference between the full resolution AIRS and NAST-I vertical resolution is due to the inferior effective radiance noise level of the AIRS data as compared to NAST-I. The effective radiance noise level is a function of the single sample instrument noise and the number of spectral channels used for the retrieval. In this case the NAST-I effective radiance noise is about one third that of the AIRS, since the NAST-I results consists of an average of three adjacent cross-track scan spots and three times as many spectral channels are used for the retrieval.



AIRS level single sample noise upsets spatial continuity of small scale vertical features

Figure 8. Cross-section of the full spatial resolution AIRS soundings and those retrieved from NAST-I radiances after AIRS level instrument noise was artificially added to the full resolution NAST-I radiance measurements.

Spatial averaging of the data can reduce AIRS random instrument noise. Thus, 3 x 3 averaging of the AIRS radiances were performed to produce a factor of 3 decrease in the noise level of the AIRS radiances used for the sounding retrievals. Figure 9 shows the AIRS retrieval result in comparison to retrievals from the NAST-I radiance measurements spatially averaged to the spatial resolution of the 3 x 3 averaged AIRS data. Also shown is the cross-section constructed with the three dropsondes along the flight track. Here the AIRS and NAST-I data above the NOAA G-4 aircraft level is blanked out for the purpose of the dropsonde intercomparison. As can be seen the spatially averaged AIRS retrievals now produce spatially coherent fine scale vertical structure which is in general agreement with that retrieved from NAST-I radiance measurements and observed with the dropsonde measurements. The residual difference in vertical sensitivity between the AIRS and the NAST-I results may be attributed to the higher spectral resolution of the NAST-I data. Both the AIRS and NAST-I retrieval cross-sections show the same features illustrated in the dropsonde cross-section, but at significantly lower vertical resolution. Whereas the dropsonde vertical resolution is on the order of several meters, the retrieved sounding resolution in the free troposphere varies from 1-2 kilometers, decreasing with increasing altitude.

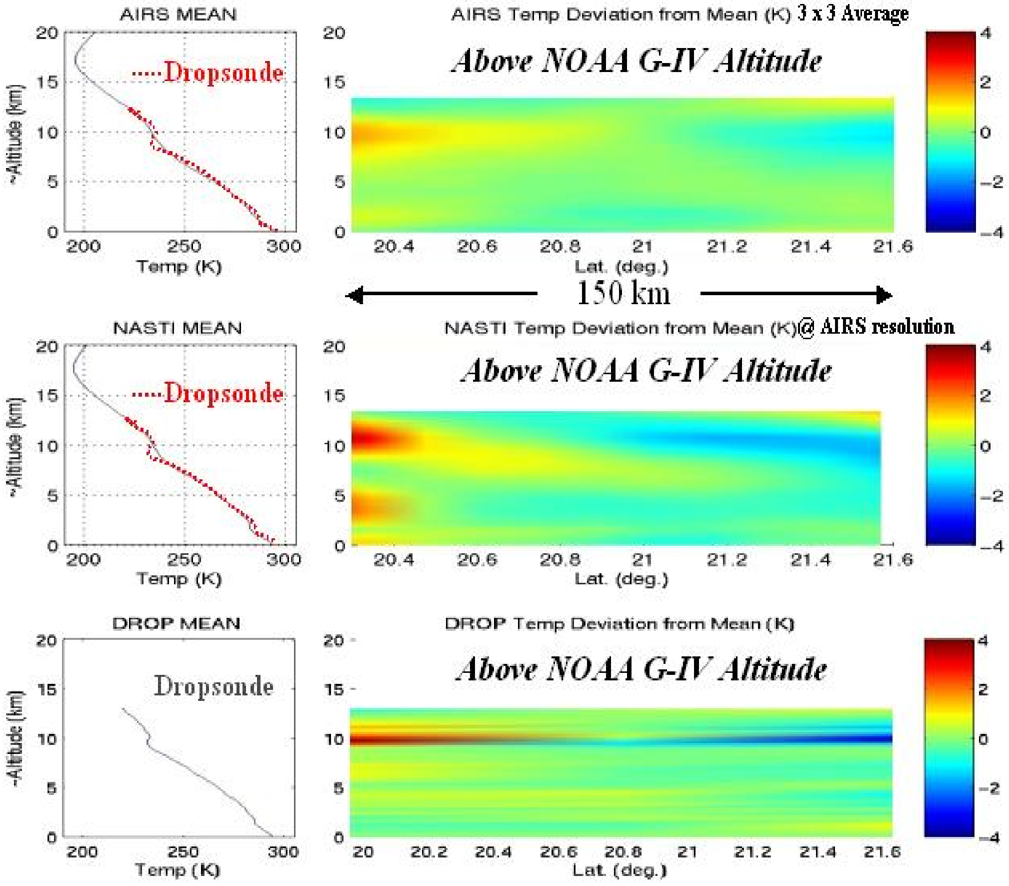


Figure 9. Comparisons of cross-sections of retrievals from AIRS and NAST-I radiance data for 3 x 3 spatially averaged AIRS radiance measurements. The NAST data was also averaged to the 3 x 3 average spatial resolution of the AIRS data. A cross-section constructed from G-4 dropsonde data is also shown for validating the AIRS and NAST-I retrieval results.

5. Summary and Implications for Future Satellite Sounding Capability

Initial results of comparing AIRS temperature sounding retrievals to much higher spatial resolution aircraft NAST-I retrieved soundings and dropsondes, clearly show the value of airborne satellite product validation campaigns. It is shown that high vertical resolution soundings can be achieved by transformation of the amplitudes of a relatively small set of eigenvectors (~ 30-40, depending on atmospheric condition) of large samples (~ 2000 – 5000 spectral points, depending upon the instrument) of spectrally independent atmospheric radiances, as the predictors of the atmospheric profiles. The eigenvector decomposition produces very high signal to noise radiance information input to the vertical sounding retrieval process. High signal to noise radiance input is important for resolving fine scale vertical features because the retrieval process is one of deconvolution of the spectral structure of the radiance measurements.

In the example shown here, AIRS measurements can provided high vertical resolution sounding information when the noise was reduced to one third of the single sample noise level. This reduction can be performed by 3 x 3 averaging of the AIRS data, however, this averaging will degrades the horizontal resolution of the AIRS products and introduce significantly more cloud contamination of the radiance used to obtain the retrieved products. The vertical structure of the retrieved atmospheric soundings appear to be consistent with the 1-2 kilometer vertical resolution expected from upwelling spectral radiances.

The physically based statistical retrieval method used here was trained to produce accurate soundings down to cloud top level. The above cloud top vertical extent limitation will soon be alleviated by training the algorithm to produce soundings below semi-transparent and/or broken cloud conditions. Also, it has been shown that simultaneous multi-spectral imaging spectrometer data provided by the Aqua MODIS instrument can be used to cloud clear the AIRS data to enable soundings to be obtained below a single layer of scattered to broken clouds[18].

The implications for future satellite sounding instruments (i.e., IASI, CrIS, and GIFTS) is that their effective noise level, and therefore vertical profile resolution, should be comparable, and in most cases better, than that achieved with the AIRS. In the case of the IASI, the detector noise performance should be comparable to AIRS, however the IASI possess 2-5 times higher spectral resolution, depending on the spectral region. The CrIS will have a spectral resolution comparable to AIRS, but its detector noise is expected to be considerably smaller than that associated with AIRS, at least for the longer wavelength region of the spectrum. The GIFTS will have a detector noise level comparable to AIRS, a somewhat higher spectral resolution in the water vapor band, but much higher (4 km vs. 15 km linear) spatial resolution. Thus, the effective sounding retrieval noise level of the future sounders should be smaller than the experimental AIRS instrument leading to generally higher vertical resolution atmospheric profile retrievals.

Acknowledgements

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6. References

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