Joint Airborne IASI Validation Experiment (JAIVEx) - An Overview

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Abstract:

The Joint Airborne IASI Validation Experiment (JAIVEx) was held during April and May 2007. Seven days of coincident MetOp satellite IASI and WB-57 aircraft NAST-I/S-HIS interferometer data were obtained over the DoE ARM CART-site and the Gulf of Mexico. Under flights of the NASA A-train of satellites were conducted on five of the mission days. Coincident dropsondes and remote sensing surface and atmospheric data were provided by the UK BAe-146 aircraft, which under flew the MetOp, A-train, and WB-57. An overview of the JAIVEx field program, and an example use of the JAIVEx data set, is presented.

1. Introduction

Airborne field campaigns are essential for the calibration validation of new satellite sounding systems, which have very high radiometric and geophysical product accuracy requirements. It is only through aircraft missions that near time and geographical location coincidence can be achieved with the spatial resolution of the satellite measurements to be validated. The aircraft payload must consist of well-validated and SI-traceable “state-of-the-art” remote sensing spectrometer and in-situ vertical profile measurement systems in order to validate the satellite radiance measurements, and the geophysical products derived from them, to within the satellite measurement resolution and accuracy objectives.

The specific objectives of airborne calibration validation campaigns are: (1) radiometric and spectral calibration of satellite sensors, (2) cross-validation of sensors in different orbit, (3) validation of forward radiative transfer models used for retrieval of geophysical variables, and (4) the provision of accurate in-situ and well calibrated ground-based, airborne and satellite radiance data sets. The airborne campaign data sets are crucial for the achievement of objectives 1,2,and 3 above, as well as for conducting studies to define limitations of current sensing techniques and to define more optimal sensing approaches. The campaign data sets can also be used to simulate instrument measurements and validate processing algorithms intended for future satellite systems. Regional Observing System Experiments (OSEs), conducted to define NWP impact of current and simulated future satellite systems, can also be performed with these airborne calibration validation campaign data sets.

The unique contribution of the airborne component of these campaigns is that it provides simultaneous, independent, and SI traceable, radiance measurements for absolute radiometric and spectral calibration validation of satellite sensors. The airborne radiance measurement data can also be used as a transfer standard for cross-validation of sensors in different orbits at more than a very limited number of polar latitudes. The aircraft sensors and flight patterns enable near simultaneous in-situ and remotely sensed geophysical variables that characterize the entire footprint of the satellite sounder as needed for the validation of satellite products and the forward radiative transfer models used for their derivation. In summary, the high spatial resolution, coupled with the high spectral resolution, of the aircraft interferometer radiance measurements enable a complete characterization of the satellite radiance measurement characteristics and their impact on the accuracy and spatial resolution of the derived products.

2. Joint Airborne IASI Validation Campaign (JAIVEx)

The Joint Airborne IASI Validation Experiment was a joint USA and European calibration validation campaign in support of the NPOESS and MetOp series of operational satellites. Although all measurements on the MetOp-A and A-train satellites are of interest, the focus of JAIVEx was on the validation of radiance observations and meteorological products from the Infrared Atmospheric Sounding Interferometer, IASI. Launched on MetOp-A on 19 October 2006, IASI is the first of the advanced ultra-spectral resolution temperature, humidity, and trace gas sounding instruments to be flown as a component of the Joint Polar System (JPS) of NPOESS and MetOp operational satellites[1]. The objective of the JPS is improved weather, climate, and air quality observation and forecasting. IASI measures radiation emission from the surface and atmosphere in the 645 – 2760 cm-1 (i.e., 3.6-15.5 µm) spectral band with high spectral resolution (i.e., 8461 spectral channels with a spacing of 0.25 cm-1). As MetOp-A orbits overhead, IASI scans the Earth between ± 49° providing a swath of data across the Earth of 2132 km. The scan swaths are made with a frequency to provide contiguous coverage across the Earth's surface as the satellite orbits overhead. Seven consecutive orbits, each with a 101 minute period, provides total Earth coverage every twelve hours. The aircraft employed for the JAIVEx were the NASA WB-57 and the FAAM BAe-146. The primary sensors on board the WB-57 were the NPOESS Airborne Sounding Testbed - Interferometer (NAST-I)[2]and the Scanning High resolution Interferometer Sounder (S-HIS)[3] spectrometers. The spatially scanning NAST-I has a spectral resolution and spectral coverage similar to the IASI, as described above, but with a horizontal resolution of 2 km from the WB-57 flight altitude. The S-HIS has approximately the same spectral coverage as IASI and spatial resolution of NAST-I but with a spectral resolution of 50% of that of IASI and NAST-I. The aircraft base location, dates of the experiment, satellite, airborne, and surface resources being used for JAIVEx, participants, and sponsors in figure 1.

Location/dates: Ellington Field (EFD), Houston, TX, 14 Apr – 4 May, 2007

Aircraft: NASA WB-57 (NAST-I, NAST-M, S-HIS); UK FAAM BAe146-301 (ARIES, MARSS, Deimos, SWS; dropsondes; in-situ cloud phys. & trace species; etc.)

Ground-sites: DOE ARM CART ground site: RAOBS (1.5 hr apart at overpass time), Raman Lidar, AERI, etc.

Satellites: MetOp-A (IASI, AMSU, MHS, AVHRR, HIRS, GOME, SBUV, ACAT); A-train (Aqua AIRS, AMSU, HSB, MODIS; Aura TES; CloudSat; and Calipso)

Participants: US: NASA/LaRC, NASA/JSC, UW, MIT-LL, MIT, NOAA, others; Europe: UKMO, FAAM, U. of Manchester, EUMETSAT, U of Bologna, ECMWF

Sponsors: US: IPO, NASA, NOAA; European: FAAM, UKMO, UK-NERC, EUMETSAT

Figure 1: An overview of the JAIVEx resources, participants, and sponsors. A more complete description of the sensors can be found in the publication describing the European AQUA Thermodynamic Experiment (EAQUATE) [4].

3. Flight Missions

The surface targets of the calibration validation flight missions were the U.S. Department of Energy (DoE) Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) facility in north central Oklahoma and the Gulf of Mexico. The ARM facility is well instrumented with in-situ and ground based remote sensors, as desired for meteorological product validation, while the Gulf of Mexico provides a relatively uniform surface background, as desired for spectral radiance measurement validation. One important goal of the JAIVEx was to inter-compare MetOp-A operational measurement capability with that provided by the A-train of advanced NASA research satellites.) (The A-train consists of the Aqua, Aura, Parasol, OCO, CALIPSO, and CloudSat satellites). Although the orbits of the MetOp and the A-Train are about four hours apart (MetOp-A being in a 09:30 descending orbit and the A-train being in a 13:30 ascending orbit), the aircraft missions were of a long enough duration to permit under flights of both the MetOp satellite and the A-train. The aircraft sensors were used as a relative calibration transfer reference for each of the satellite systems (e.g., the difference between MetOp and aircraft measurements being compared to the difference between A-train and aircraft measurements) in order to account for space and time difference between the measurements from the two satellite systems. This capability was particularly useful for characterizing the differences between the spectral radiance measurements and derived products from the Aqua AIRS and the MetOp IASI advanced sounding instruments. The figure below shows the flight tracks of the WB-57 aircraft during the JAIVEx missions. As can be seen, there were four flights over the ARM-site, 2 daytime and 2 nighttime, and three flights over the Gulf of Mexico, 2 daytime and 1 nighttime. There were a total of five joint MetOp and A-train under flights, 3-day time and 2-night time.

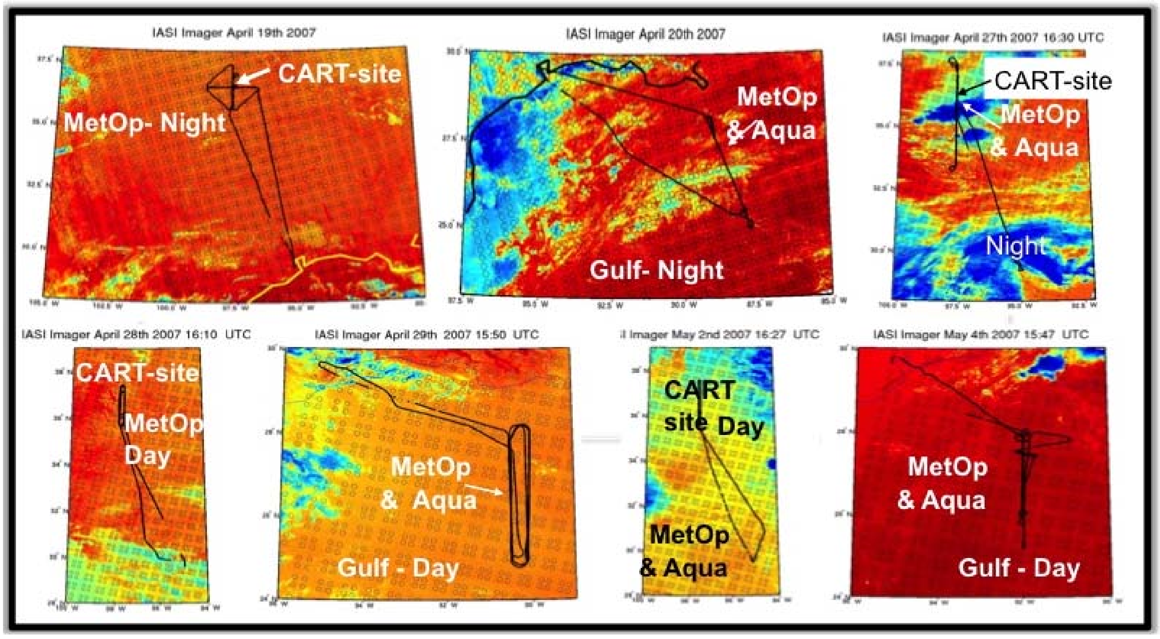

Figure 2. JAIVEx WB-57 flight tracks.

4. Radiometric and Spectral Calibration Validation of Satellite Sensors

The University of Wisconsin external blackbody used for the absolute calibration of the internal blackbodies of the S-HIS has been referenced to the International System of Units (SI) traceable National Institute of Standards and Technology (NIST) blackbody[5]. Subsequently, the NAST-I internal blackbodies have been referenced to the NIST traceable UW external blackbody. Thus, inter-comparisons of the radiances measured with these instruments with those measured with a satellite instrument provide an SI-traceable validation of the satellite observations.

Figure 3 below shows the intercomparison of the entire spectrum measured by the MetOp IASI with the radiances measured simultaneously by the NAST-I and S-HIS instruments over the SGP ARM-site on April 19, 2007. The spectral resolution of the IASI (0.25 cm^{-1}) and NAST-I (0.25 cm^{-1}) instruments was reduced to that of the lower resolution S-HIS (0.5 cm^{-1}) so that all three observations could be placed on a common spectral scale with a common Instrument Line Shape (ILS). As shown there is little difference between the three observations. The only significant differences shown are between the IASI and the aircraft measurements in spectral regions where there is a significant radiance contribution of the atmosphere above the aircraft flight level (~ 18 km) to the satellite measurements.

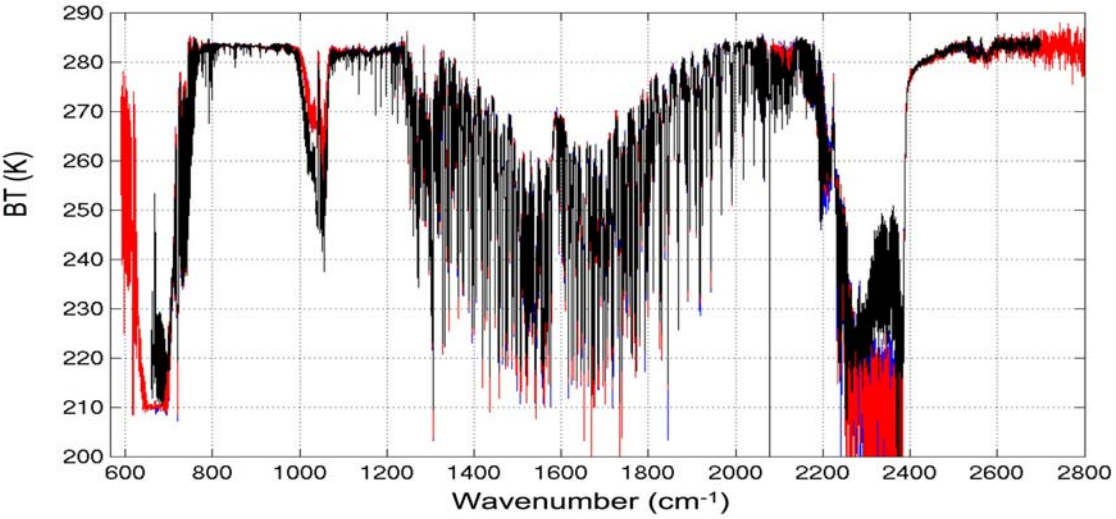

Figure 3. Comparison between time and space coincident IASI (black), NAST-I (blue), and S-HIS (red) radiance spectra, observed over the SGP ARM-site on April 19, 2007, processed to match SHIS spectral resolution. Discrepancies are due to radiance contributions to the IASI satellite measurements from the atmosphere above the NAST-I and SHIS aircraft altitude (~ 18 km).

The radiance contribution from the atmosphere above the aircraft can be accounted for using a Line By Line Radiative Transfer Model (LBLRTM) calculation based on two near simultaneous radiosonde observations, one launched one-hour before and the other at the time of the satellite overpass[6]. The one-hour before launch enables coincidence between the balloon measurements and the satellite measurements in the upper atmosphere near the time of the overpass. By producing a calculated radiance spectrum for both the aircraft and satellite measurement levels, the difference between observation and calculation for both the satellite measurements and the aircraft measurements can be inter-compared. The difference between the satellite "observed minus calculation" and the aircraft "observed minus calculation" (i.e., the double difference) alleviates the influence of the atmosphere above the aircraft level on the intercomparison.

Figure 4 shows the result of this aircraft validation of satellite radiance measurement technique for a longwave spectral region. As shown, there is little difference between the IASI and the aircraft observations. The double differences were averaged over 50 cm^{-1} intervals to minimize the effects of measurement noise in trying to establish the absolute accuracy of the IASI measurements. It is clearly seen that the absolute accuracy of the IASI measurements must be very good in order for their reduced spectral resolution values to agree to within 0.2 K of those observed by both the NAST-I and S-HIS instruments. Similar close agreement (not shown here) was obtained throughout the remainder of the infrared spectrum measured by the satellite IASI and airborne NAST-I and S-HIS instruments.

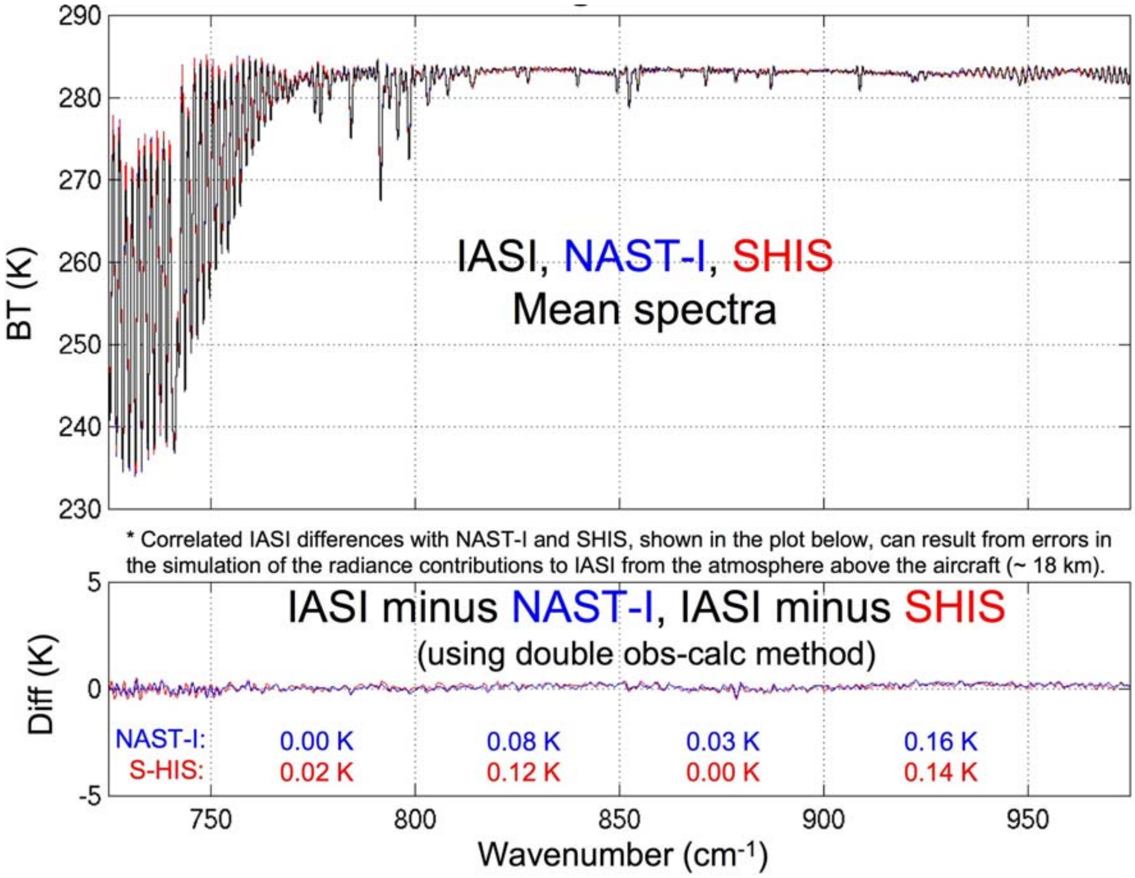

Figure 4. Spectra showing the close correspondence between satellite and aircraft interferometer measurements corresponding to the longwave spectral band. The numbers are the mean differences over 50 cm^{-1} wavenumber intervals.

2. Transfer Standard for Cross-Validation of Sensors in Different Orbits

The airborne spectral radiance data during JAIVEx was used to cross-validate MetOp IASI and Aqua AIRS radiances and derived sounding products. This cross-validation is otherwise difficult because of the four-hour time separation between the MetOp and Aqua orbits. However, with the aircraft interferometers, when the orbits nearly overlap geographically, the time variation of atmospheric radiance between orbits can be accounted for by inter-comparing the products from each satellite to aircraft observations of the same product obtained from time synchronized aircraft observations made over the same geographical regions of the satellite overpasses. As was noted earlier, there were a total of five joint under flights of the MetOp and the Aqua satellite.

Figure 5 below shows an example cross-validation of the MetOp IASI and Aqua AIRS radiances[7]. This figure shows false color latitude (25.5-27.5 N) cross-section of water vapor brightness temperature spectra (1540-1610 cm^{-1}), obtained near 90 W Longitude on April 29, 2007. The temporal variations indicated by the MetOp IASI (1550 GMT) and the Aqua AIRS (1919 GMT) observations are validated by the NAST-I radiance measurements obtained over exactly the same geographical regions sampled by each instrument nearly coincident with the overpass times of the Metop and Aqua satellites.

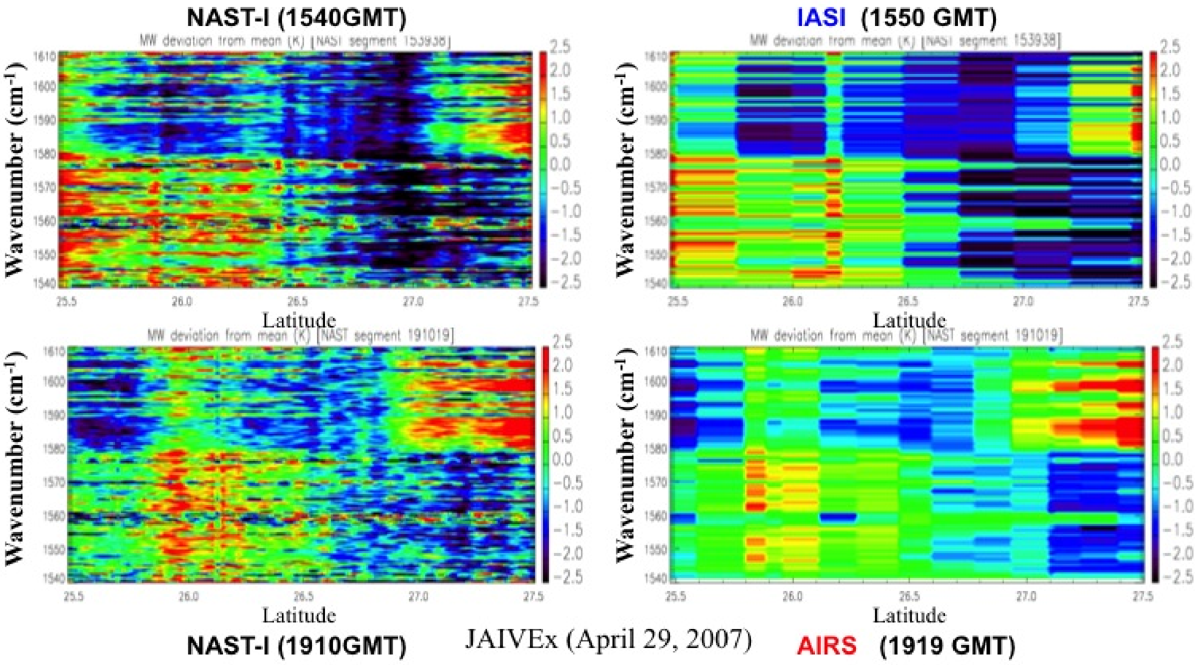

Figure 5. NAST-I, IASI, and AIRS False color latitude (25.5-27.5 N) cross-section of water vapor brightness temperature spectra (1540-1610 cm^{-1}) obtained near 90 W Longitude on April 29, 2007.

3. Validation of Forward Radiative Transfer Models

For the retrieval of atmospheric soundings from satellite radiance measurements the forward radiative transfer model used for this process plays a crucial role in that its accuracy limits the vertical resolution and absolute accuracy of the derived product. A "Fast-Forward Radiative Transfer Model (FFRTM) is generally used for the routine operational retrieval process in order for the processing to keep up with the real-time acquisition of the satellite data[8]. Although there are many FFRTMs, many of them are based on a library of radiance spectra simulated using the Line By Line Radiative Transfer Model (LBLRTM)[9], radio soundings, and the satellite Instrument Line Shape (ILS). Thus, it is important to validate the accuracy of the LBLRTM using the satellite data for which it is to be used.

Figure 6 shows the result of a validation recently performed[10] using the April 19, 2007 JAIVEx SGP ARM-site radiosondes and corresponding IASI radiance measurements. Two radiosondes, one launched 1-hour before the satellite overpass and one launch at the time of the satellite overpass, were blended together to portray the atmospheric state at the time of the satellite measurements. Small adjustments in surface skin temperature and emissivity, and a climate estimate of the ozone profile were made to eliminate obvious systematic differences between the observed and calculated radiance spectra due to uncertainties in these surface and atmospheric state parameters. As can be seen, the agreement between the calculation and the observation of the brightness temperature spectrum is exceptional, with the differences generally being less than 0.5 K. Relatively large, and spectrally random, differences occur in the shortest wavelength (i.e., longest wavenumber) region of the spectrum due to the increased IASI radiance measurement noise level in this particular region of the spectrum. This result provides confidence in both the accuracy of the IASI instrument radiance measurements and the fundamental radiative transfer models used to derive geophysical products from these measurements.

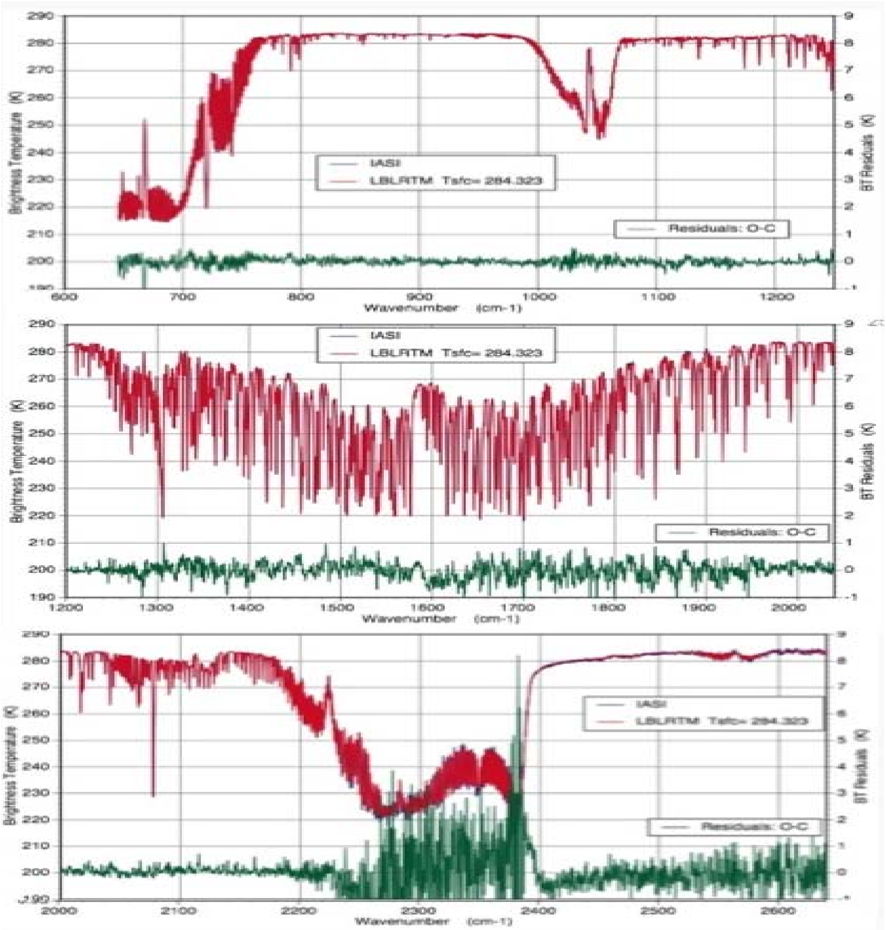

Figure 6. Comparison of an IASI spectrum observed over the SGP ARM-site on April 19,2007 with an LBLRTM calculated spectrum based on the IASI ILS.

4. Validation of Retrieved Geophysical products.

The JAIVEx data set is ideal for the validation of satellite profile retrieval techniques and the resulting satellite data product vertical resolution and accuracy. As an example, figure 7 shows retrievals produced from the JAIVEx data for the April 19,2007 SGP ARM-site overpass data compared with the two radiosondes, one launched one hour before the satellite overpass time and the other at the time of the satellite overpass. The retrieval solution is the one-dimensional variational physical solution, using an initial profile produced by the EOF (i.e., empirical orthogonal function) regression methodology[2]. A similar approach is used for the operational production of soundings from these data[11]. The radiative transfer model used was LBLRTM, as validated above, and no bias corrections were used in the production of the sounding product. It is apparent that the expectation to be able to resolve fine scale vertical structure, including temperature and moisture inversions, with the ultra-spectral sounder (i.e., IASI), is fulfilled.

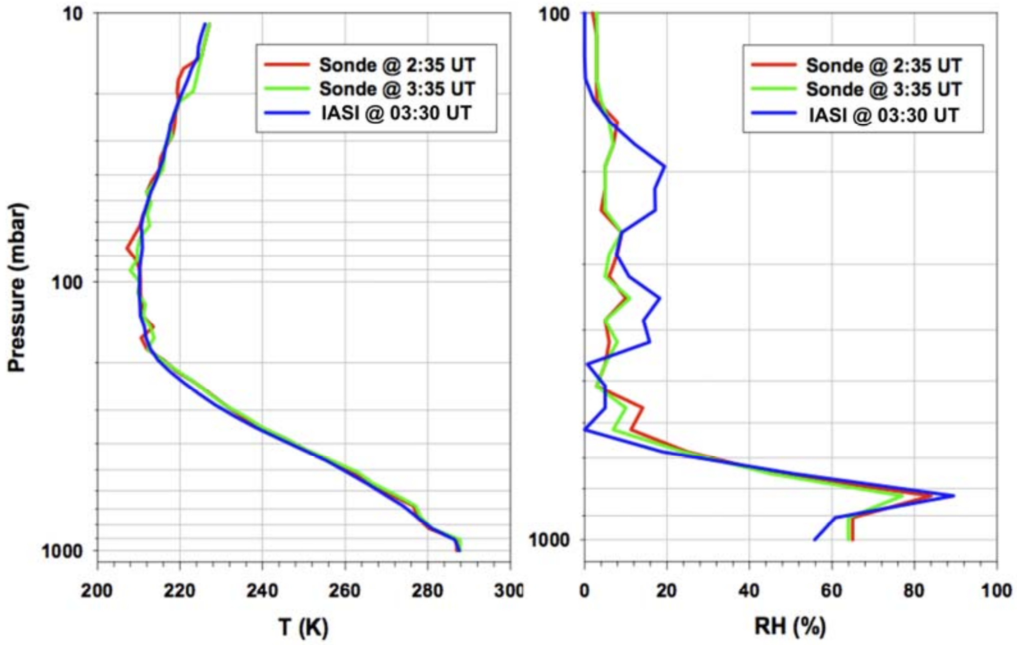

Figure 7. Comparison of a MetOp IASI retrieval with two ARM-site radiosondes, one released one hour before and the other at the time of the MetOp satellite overpass.

Another JAIVEx case, April 29, 2007demonstrates that mesoscale spatial resolution atmospheric temperature and moisture features can be resolved with the IASI ultra-spectral resolution data. Figure 8 shows the mesoscale sounding area (delineated by the red box) over the Gulf of Mexico for which fine scale atmospheric structure, obtained from the encircled 96 IASI Field of View (FOV) radiance spectra, is shown as eight North to South cross-sections shown in figure 9. Each North – South cross-section (arranged to be from the left to right on each color insert of figure 9) was constructed from the 12 soundings obtained along each of the NNW to SSE lines of radiance spectra. In figure 9, the cross-sections are arranged in a West to East fashion so as to provide a three dimensional view of the atmosphere as observed by the IASI instrument. The panels on the far right of the IASI temperature and moisture cross-sections are cross-sections obtained from the Dropsondes launched from the BAe-146 aircraft, which were obtained within a one hour time period centered on the MetOp satellite overpass time. Although the cross-section for the closely spaced dropsonde data cuts across four of the IASI cross-sections (i.e., is not aligned with any one of the IASI cross-sections shown), it serves to validate the North to South variations retrieved from the IASI data below the aircraft flight level pressure altitude of 400 mb. As expected, the dropsonde cross-sections display somewhat smaller vertical scale features of the atmosphere than do the IASI retrievals, but the general correspondence between the fine scale spatial features is striking, particularly for moisture, considering the very small region of atmospheric variability being observed. For temperature, there appears to be more spatial coherence in the small sale spatial variability retrieved from the lower spatial resolution IASI spectra than can be deduced from the spatially independent point measurements of the dropsondes for this very small range of atmospheric temperature variation.

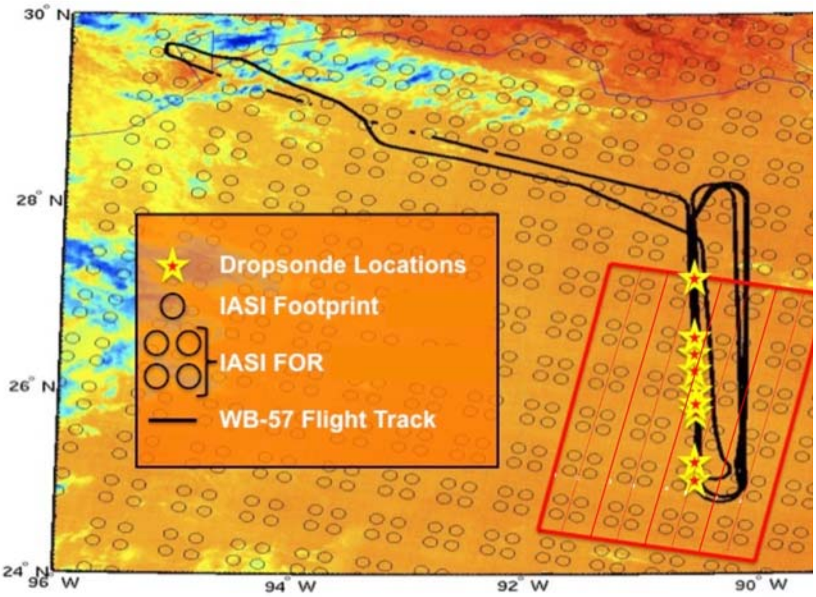

Figure 8. IASI footprints superimposed over a 10-12 μm infrared image showing the retrieval locations over the Gulf of Mexico on April 29, 2007 at 15:50 UTC. WB-57 aircraft flight track and BAe-146 Dropsonde locations are also shown.

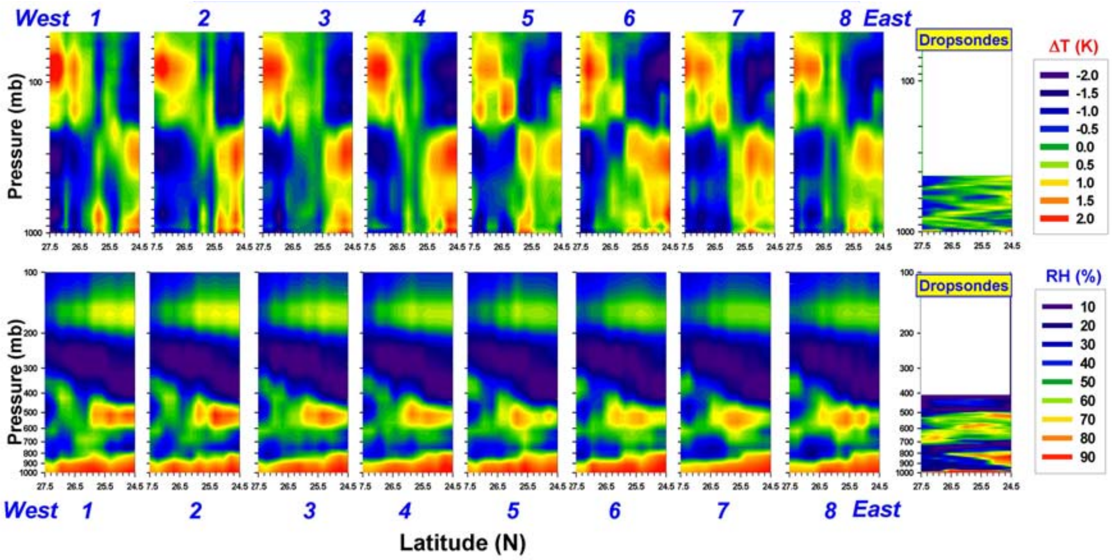

Figure 9. Eight adjacent 3-degree (333km) North-South cross-sections of temperature (deviation from the mean for each pressure level) and relative humidity obtained near 91 W longitude over the Gulf of Mexico on 29 April 2007 (see figure 8). The West to East spacing of the NNE to SSE oriented cross-sections is approximately 25 km.

Finally, figure 10 shows the radiance measurement and retrieval residual characteristics associated with the 96 IASI spectra analyzed for this case. These retrievals result from a three-step process in which an eigenvector (EOF) regression retrieval (Regr.Retr.) is used as an initial profile for a two-step variational inverse physical solution of the radiative transfer equation for the temperature and moisture profile. The procedure is similar to that which has used for trace gas (e.g., CO) profile retrieval from NAST-I data[12]. The first physical retrieval (Phys.Retr.-I) is obtained by solving for a water vapor profile perturbation of the EOF regression solution from the residuals of radiance calculated from the EOF regression retrieval, and that observed by IASI, by excluding uniformly mixed gas (e.g., CO_2 spectral channels from the retrieval process. The second, and final, physical retrieval (Phys.Retr.-II) is obtained by solving simultaneously for both the temperature and water vapor profile perturbations from the EOF regression temperature profile and Phys.Retr.-I water vapor profile using the entire spectrum (CO_2, "window", and H_2O channels) of residuals between the calculated and observed radiances. The purpose of the three-step process is to alleviate the errors, which would otherwise result, from the highly non-linear nature of the water vapor inverse solution of the radiative transfer equation (i.e., the accuracy of the water vapor solution being highly dependent on the accuracy of the temperature profile solution). As can be seen, this procedure produces retrievals that minimize the retrieval radiance residuals to a level very close to the random error level of the measurements.

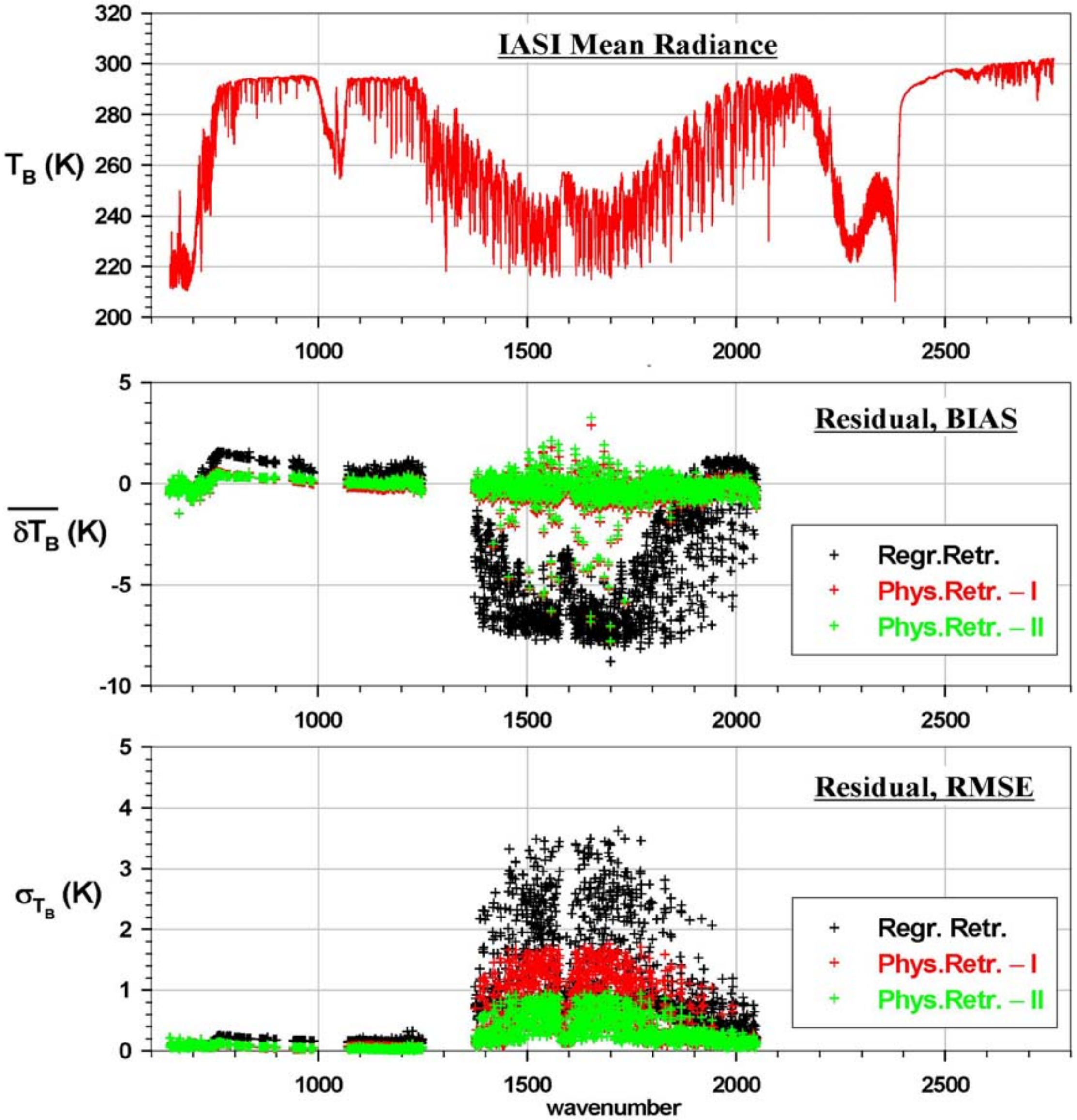

Figure 10. IASI radiance and retrieval residual statistics for the 96 retrievals used to produce the mesoscale sounding results shown in figure 9.

5. Summary and Conclusion

The JAIVEx was a very successful airborne calibration validation campaign. A unique collection of simultaneous satellite, surface-based, and aircraft in-situ and remote sensing measurements were acquired which can be used for the calibration validation of radiances and derived products obtained from a large family of satellites in orbit and viewing the JAIVEx campaign measurement region (e.g., MetOp, A-train, and GOES).

Results from two of the seven JAIVEx observation days were shown as examples of how the data can be used for validation of observed and forward radiative transfer model calculated radiances and the geophysical products derived from them. It is concluded that the IASI radiance measurements are well within an absolute radiometric accuracy of 0.5K, as demonstrated through inter-comparisons with two independent airborne interferometer spectrometer systems SI traceable through their reference to a NIST standard calibration blackbody. It is also shown that the airborne interferometer spectrometer measurements can serve as a reference for the cross-validation of sensors in different orbits (e.g., IASI on MetOp and AIRS on Aqua). Near-simultaneous atmospheric profile measurements from radiosondes launched one-hour before and at the MetOp satellite overpass time have been used to validate the accuracy of the LBLRTM calculations relative to measurements from the IASI. The results indicate that the error resulting in LBLRTM calculations are close to the single sample random error level of the satellite measurements. Finally, the unique combination of JAIVEx radiosonde and dropsonde data has been used to demonstrate the fine scale vertical and horizontal atmospheric measurement capability of ultra-spectral sounding systems, such as the IASI validated here.

The JAIVEx data set is now available on two web-sites (http://cimss.ssec.wisc.edu/jaivex/ and http://badc.nerc.ac.uk/data/jaivex/). A DVD of data sets for five case study days (19, 28, 29, 30 April and 4 May, 2007) has been put together by the UK Met Office participants in the JAIVEx and is available, upon request, from Jonathan Taylor (jonathan.p.taylor@metoffice.gov.uk).

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