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REPORT ON AIRCRAFT CAMPAIGNS WITH SI TRACEABLE INSTRUMENTS

In response to CGMS Recommendation 35.05 (Aircraft campaigns with SI traceable instruments should continue to provide absolute calibration opportunities for critical satellite instruments, such as IASI, AIRS and CrIS)

In response to CGMS Recommendation 35.05, NOAA WP-13 summarizes the importance of aircraft campaigns with SI traceable instruments for the calibration of future polar and geostationary satellite sensors and provides, as an example, results of the validation of IASI measurements during the Joint Airborne IASI Validation Experiment (JAIVEx) conducted during April and May 2007.

Aircraft campaigns with SI traceable instruments

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Background: Airborne field campaigns are essential for many aspects of maintaining a high quality long-term satellite program, beginning with the demonstration of new instrument and remote sensing concepts, development and refinement of retrieval techniques that can deal with the subtleties of real world effects, and ending with validation over the life of the system. This report describes the importance of the later phase, the validation of new satellite sounding systems, which have very high radiometric and geophysical product accuracy requirements. For current systems that rely on instrument calibration stability over the life of the mission, it is only through aircraft missions that a connection with international radiometric standards (SI traceability) can be maintained throughout the mission. 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. Aircraft observations are capable of very high accuracy, because near time and geographical location coincidence can be achieved with the spatial resolution of the satellite measurements to be validated. Flying at high altitude above the majority of the atmosphere, the aircraft observations provide the most direct "apples-to-apples" validation of the satellite observations, avoiding the direct use of radiative transfer modeling and other techniques which break the SI traceability chain.
The specific objectives of airborne calibration validation campaigns are: (1) radiometric and spectral calibration of satellite sensors over the life of the mission, (2) cross-validation of sensors in different orbits, and (3) the provision of accurate in-situ, ground-based, and airborne data sets coincident with the satellite measurements for the validation of geophysical products derived from the satellite radiance measurements. 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 is also 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 measurements and their impact on the accuracy and spatial resolution of the derived products.

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. Two different aircraft were employed for the JAIVEx, the NASA WB-57 and the FAAM BAe-146. Both of these aircraft were based at NASA's Ellington Field facility in Houston TX. The primary sensors on board the WB-57 were the NPOESS Airborne Sounding Testbed - Interferometer (NAST-I) and the Scanning High resolution Interferometer Sounder (S-HIS) spectrometers. The spatially scanning NAST-I has a spectral resolution and spectral coverage similar to the IASI, but with a much higher horizontal resolution (i.e., 2 km Vs 12 km). 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 surface targets of the calibration validation flight missions were the U.S. Department of Energy (DoE) Southern Great Plans (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 for mid-latitude conditions, not possible with simultaneous nadir comparisons occurring only near 73° latitude.

Radiometric and Spectral Calibration Validation of Satellite Sensors: To verify the calibration accuracy and provide direct NIST traceability of the aircraft radiance observations, laboratory tests of the S-HIS and the NIST Transfer Radiometer (TXR) were conducted earlier this year. The TXR was used to accomplish a more direct connection to the blackbody reference sources maintained by NIST than the normal traceability of blackbody temperature scales and paint emissivity measurements. The test involved the S-HIS and the TXR (observing at 5 and 10 microns) each observing a highly stable and accurate Atmospheric Emitted Radiance Interferometer (AERI) blackbody for a wide range of scene temperatures (227 to 290 K) while operating the S-HIS under typical flight conditions, with the optical bench at about 260 K. The test results show brightness temperature differences between the TXR and the S-HIS to be, on average, less than 40 mK. This verifies the S-HIS calibration accuracy and provides NIST traceability of the S-HIS radiance observations and the satellite validation results. In addition to the S-HIS sensor validation, this test and a companion TXR-based AERI blackbody emissivity test also provide validation of the uncertainty budget for the UW AERI blackbody 3-sigma. Subsequently, the NAST-I internal blackbodies have been referenced to the NIST traceable UW AERI 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 1 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 (0.25-0.5 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.

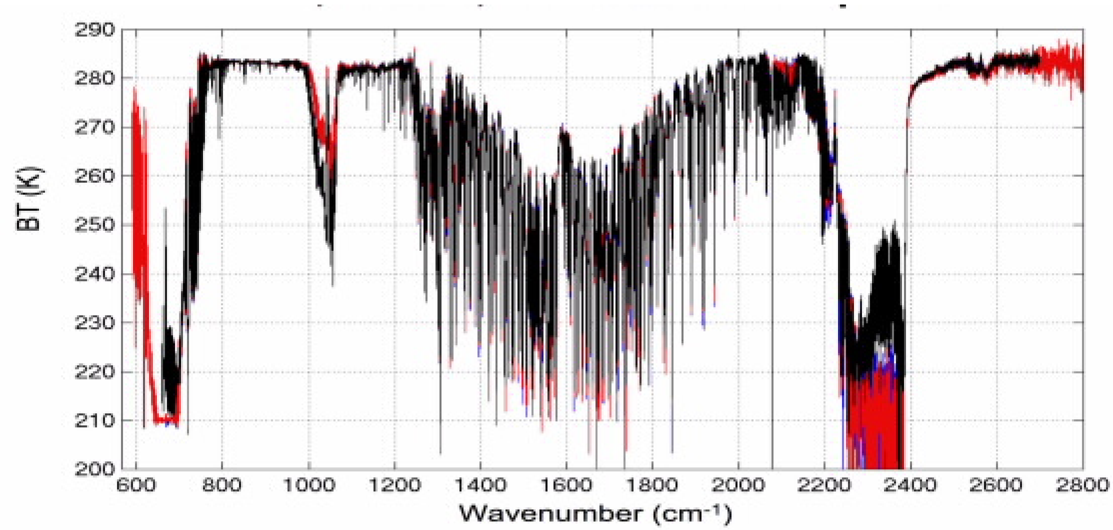

Figure 1. Comparison between time and space coincident IASI (black), NAST-I (blue), and S-HIS (red) radiance spectra, observed over the SGP ARM-site on April 19, 2007, processed to match SHIS spectral resolution. Discrepancies are due to radiance contributions to the IASI satellite measurements from the atmosphere above the NAST-I and SHIS aircraft altitude (~ 18 km).

Any viewing angle differences and small radiance contributions from the atmosphere above the aircraft can be accounted for using a Line By Line Radiative Transfer Model (LBLRTM) calculation based on near simultaneous radiosonde observations. 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) corrects for small differences in the inter-comparison from geometrical viewing differnces and the influence of the atmosphere above the aircraft level for channels not strongly effected. Figure 2 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 to achieve agreement to within 0.2 K of those observed by both the NAST-I and S-HIS instruments. Similar close agreement (not shown here) is obtained throughout the remainder of the infrared spectrum measured by the satellite IASI and airborne NAST-I and S-HIS instruments.

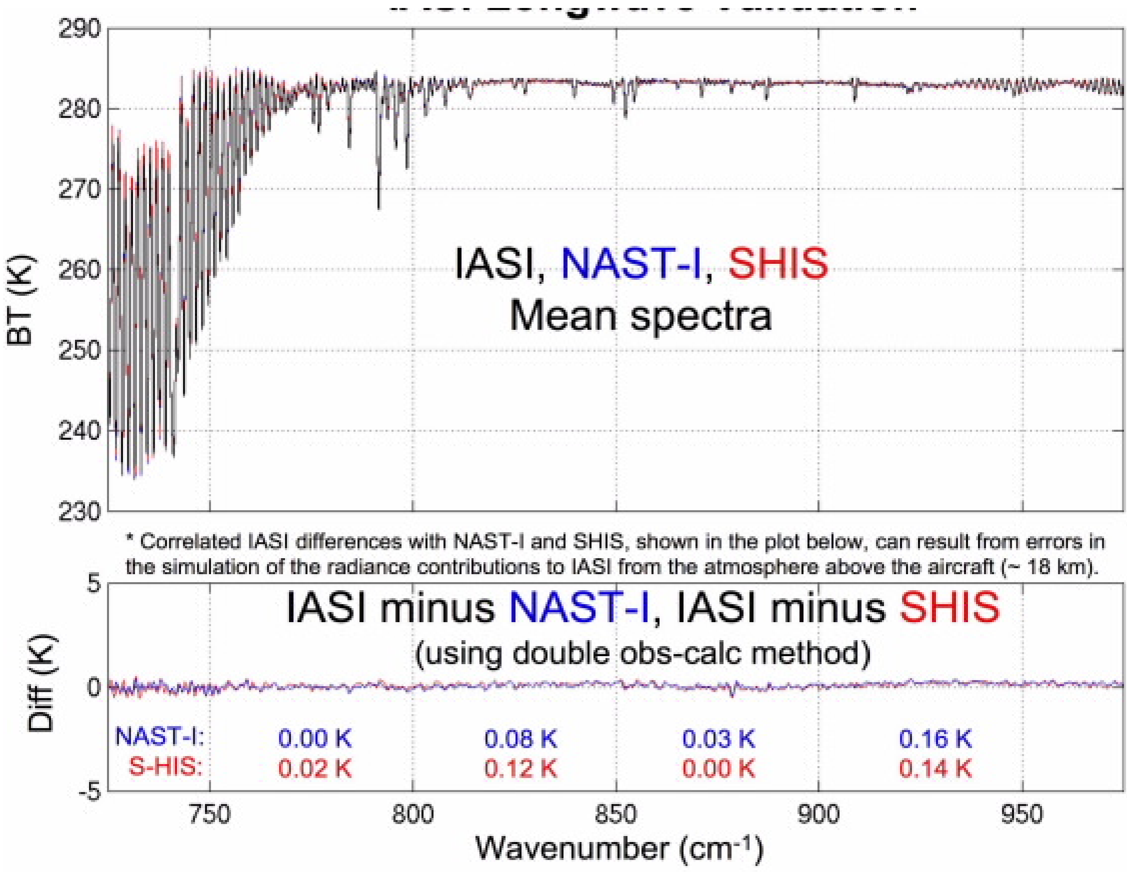

Figure 2. Spectra showing the close correspondence between satellite and aircraft interferometer measurements corresponding to the longwave spectral band. The numbers are the mean differences over 50 cm^{-1} wavenumber intervals.

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 3 below shows an example cross-validation of the MetOp IASI and Aqua AIRS radiances. 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.

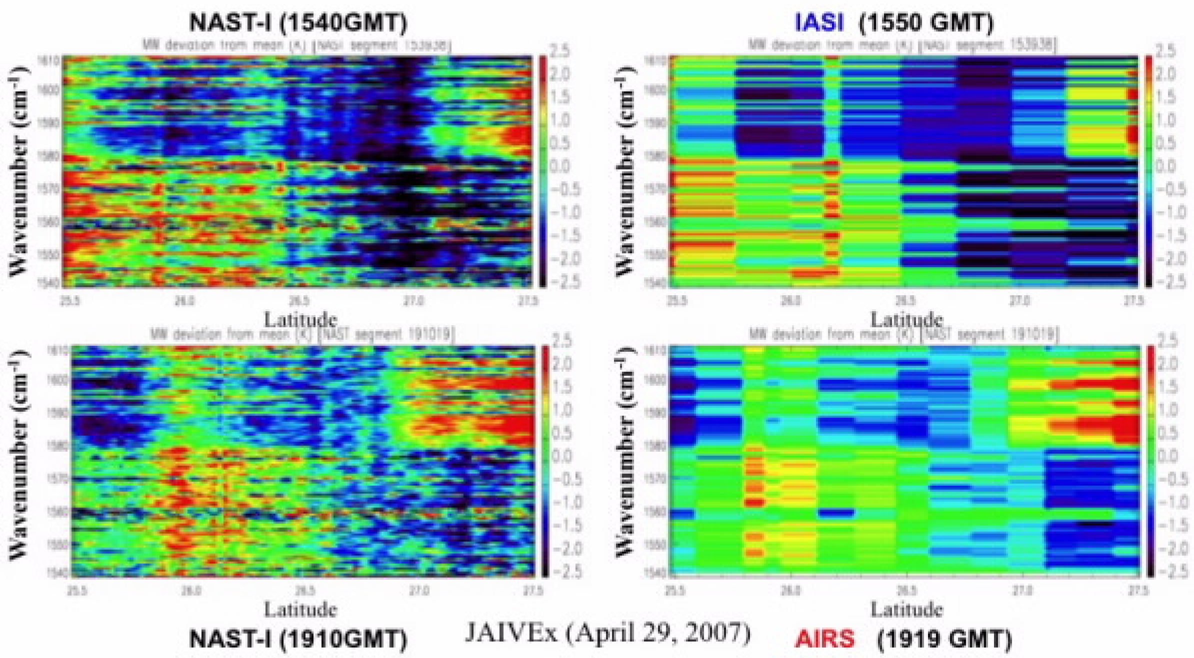

Figure 3. NAST-I, IASI, and AIRS False color latitude (25.5-27.5 N) cross-section of water vapor brightness temperature spectra (1540-1610 cm^{-1}) obtained near 90 W Longitude on April 29, 2007.

Validation of Retrieved Geophysical products: Airborne campaign calibration validation data sets are ideal for the validation of satellite profile retrieval techniques and the resulting satellite data product vertical resolution and accuracy. As an example, figure 5 shows retrievals produced from the JAIVEx satellite IASI and aircraft NAST-I radiance data for the April 19,2007 SGP ARM-site MetOp overpass time compared with 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. A similar approach is used for the operational production of soundings from these data. The radiative transfer model used was Line-by-Line Radiative Transfer Model (LBLRTM) 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 validated. The aircraft NAST-I sounding retrievals, based on the same methodology as the IASI retrievals, are particularly useful to determine whether discrepancies of the satellite retrievals and the radiosonde observations result from errors in the radiance measurements or simply due to the difference in the spatial and temporal resolutions of the remote sounding and the in-situ radiosonde observations.

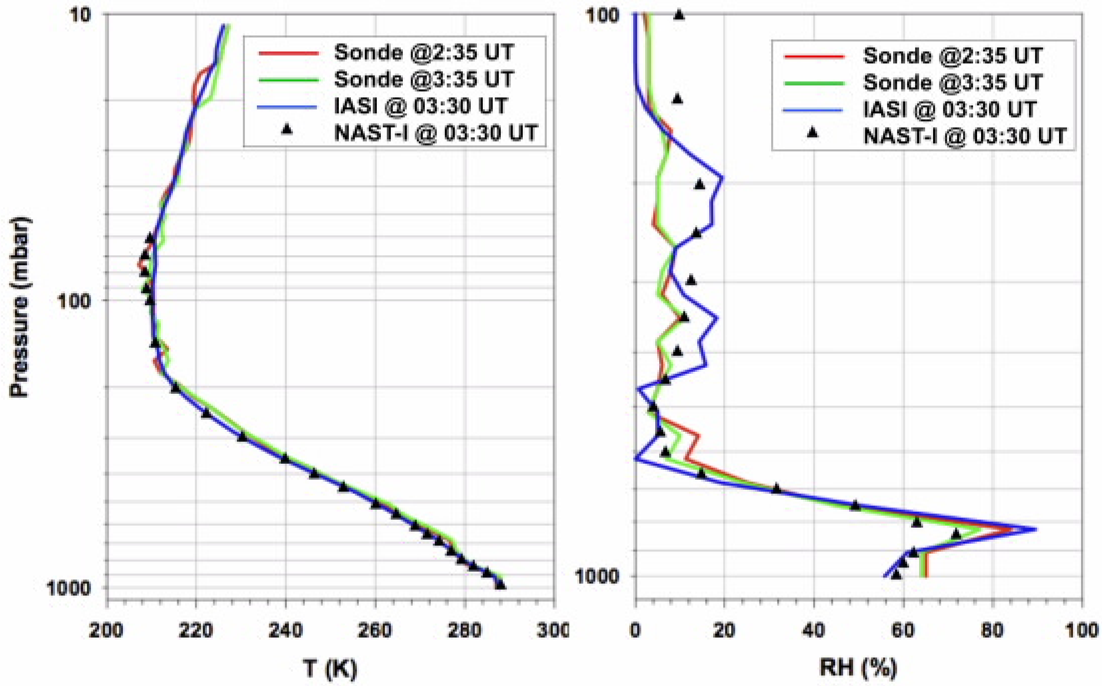

Figure 4. Comparison of MetOp IASI and WB-57 NAST-I retrievals with two ARM-site radiosondes, one released one hour before and the other at the time of the MetOp satellite overpass.

Summary and Conclusion: Airborne calibration validation campaign data sets provide a unique collection of simultaneous satellite, surface-based, and aircraft in-situ and remote sensing measurements that can be used for the calibration validation of radiances and derived products obtained from a large family of polar and geostationary satellites in orbit. These data can be used for validation of observed and forward radiative transfer model calculated radiances and the geophysical products derived from them. The airborne interferometer spectrometer systems provide an SI traceable validation measurement through their reference to a NIST standard calibration blackbody. This is the only way to conclusively resolve any change in the calibration accuracy after launch or drifts over the mission lifetime. The airborne interferometer spectrometer measurements also serve as a reference for the cross-validation of sensors in different orbits. The unique combination of aircraft measured radiance spectra, radiosondes, and dropsonde data can be used to validate the vertical and horizontal resolution of the satellite geophysical products as well as their absolute and relative accuracy. Thus, experience with data gathered from prior airborne calibration validation field campaigns, such as JAIVEx, provides strong support for CGMS Recommendation 35.03 that "Aircraft campaigns with SI traceable instruments should continue to provide absolute calibration opportunities for critical satellite instruments, such as IASI, AIRS and CrIS".