IASI validation studies

S. M. Newman[1], F. Hilton[1], S. Clough[1] and J. P. Taylor[1], A. D. Collard[2], W. L. Smith[3] and A. Larar[4]

[1] *Met Office, FitzRoy Road, Exeter EX1 3PB, UK*
[2] *European Centre for Medium-Range Weather Forecasts, Reading RG2 9AX, UK*
[3] *Hampton University, Hampton, Virginia 23668*
[4] *NASA Langley Research Center, Hampton, Virginia 23681*

Abstract

The Joint Airborne IASI Validation Experiment (JAIVEx) was a dedicated IASI calibration and validation campaign, taking place during April-May 2007. The resulting dataset, combining collocated hyperspectral infrared radiance measurements and in situ sampling of the atmospheric state, has been used to validate IASI radiances and identify sources of error in the radiative transfer modelling. The calibration accuracy of IASI radiances is shown by independent means to be valid to within 0.2 K. This dataset is available to the wider community for investigations into the exploitation of IASI data in numerical weather prediction.

1. Description of the campaign

The methodology underpinning airborne research studies into satellite calibration and validation is to characterise rigorously both the absolute upwelling atmospheric radiance and the state of the atmosphere (in particular fields of temperature and humidity). Temporal and spatial collocation of these measurements is crucial to minimise representativeness errors. Airborne hyperspectral sounders have been demonstrated to be of particular benefit in constraining calibration errors and developing algorithms for retrieval of atmospheric state vectors (Taylor et al., 2008; Tobin et al., 2006).

The Joint Airborne IASI Validation Experiment (JAIVEx) brought together the UK Facility for Airborne Atmospheric Measurements (FAAM) BAe 146 aircraft and the NASA WB-57 high altitude research aircraft. Both are comprehensively instrumented airborne research platforms, well suited to satellite cal/val exercises of this kind. Flights of the two aircraft were coordinated with overpasses of IASI on the MetOp-A satellite. The campaign was based in Houston, Texas during April and May 2007, with sorties conducted over ocean (Gulf of Mexico) and over land (ARM Southern Great Plains facility, Oklahoma).

The FAAM aircraft instrument capabilities include:

- Airborne Research Interferometer Evaluation System (ARIES) measuring upwelling and downwelling infrared radiances at 1 cm^{-1} spectral resolution;
- Heimann broadband infrared radiometer for mapping surface temperatures;
- AVAPS dropsonde system, allowing profiles of temperature and humidity below the aircraft to be sampled at high spatial resolution;
- Onboard temperature and humidity probes for measuring in situ atmospheric conditions, and aerosol and cloud probes for measuring particulates;
- Onboard chemistry probes for measuring in situ atmospheric concentrations of trace gases such as ozone and carbon monoxide.

The WB-57 aircraft carries two state-of-the art interferometers:

- Scanning High-resolution Interferometer Sounder (S-HIS) measuring upwelling and downwelling infrared radiances at 1 cm^{-1} spectral resolution;
- National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Testbed – Interferometer (NAST-I) measuring upwelling radiances at 0.5 cm^{-1} spectral resolution (comparable to IASI).

In the case studies described here only measurements within the same geographic area and small time window have been considered, to give maximum confidence that all measurements relate to the same atmospheric airmass. Exclusively clear sky fields of view for radiometric measurements have been analysed, as determined from onboard observations and MetOp AVHRR imagery.

2. Line-by-line simulations

Atmospheric profiles for input to a line-by-line radiative transfer code, representative of the observed radiances, were constructed in the following way:

1. The nearest collocated dropsonde profile was used for temperature and humidity below the FAAM 146 altitude (typically around 9 km);
2. Trace gas profiles for ozone and carbon monoxide were derived for this lower atmosphere range from in situ aircraft probes;
3. In the absence of closely coincident radiosonde observations, temperature and humidity for the upper atmosphere (above around 9 km) were derived from operational NWP model fields. Fields were available from both the Met Office and ECMWF global model forecast (run from the closest previous analysis). Ozone was available as a variable parameter from the ECMWF model.
4. The surface skin temperature was derived from Heimann radiometer measurements, coupled with spot retrievals of temperature and emissivity using ARIES hyperspectral radiances.

GENLN2 (Edwards, 1992) has been used as the reference line-by-line code, alongside some comparisons using LBLRTM (Clough, 2005). Recent updates to spectroscopic parameters (HITRAN 2004) and the water vapour continuum (MT_CKD_1.0) were implemented in the simulations.

3. IASI spectral calibration

The design specification for IASI spectral calibration accuracy is 2 ppm ($\delta\nu/\nu < 2 \times 10^{-6}$) (Blumstein et al., 2007). This can be tested by comparing observed spectra with accurate simulations, and scaling the nominal IASI frequency to optimise agreement between the two. This is achieved in practice (Figure 1) by comparing the first derivatives with respect to frequency, and computing the correlation coefficient as a function of the applied frequency scaling.

This procedure can be carried out for any IASI data for which accurate simulations are available (e.g. dedicated FAAM cal/val flights). Figure 2 shows the fitted scaling as a function of frequency bins across the IASI spectral range, with all observations over ocean, for four cases during 2007 and 2008. (B290 was a JAIVEx flight, the others comprise case studies from around the UK.) It is apparent that at the time of the B265 flight on 2 February 2007 the accuracy of the spectral calibration was approximately 3×10^{-5}, a result corroborated by the work of Strow and Hannon (2007). This result was entirely to be expected in the early post-launch phase, and routine corrections to the configuration file parameters by the Technical Expertise

Centre in Toulouse improved the calibration accuracy significantly. All flights since 30 April 2007 show a fitted calibration accuracy which is comparable to the uncertainty of the determined value.

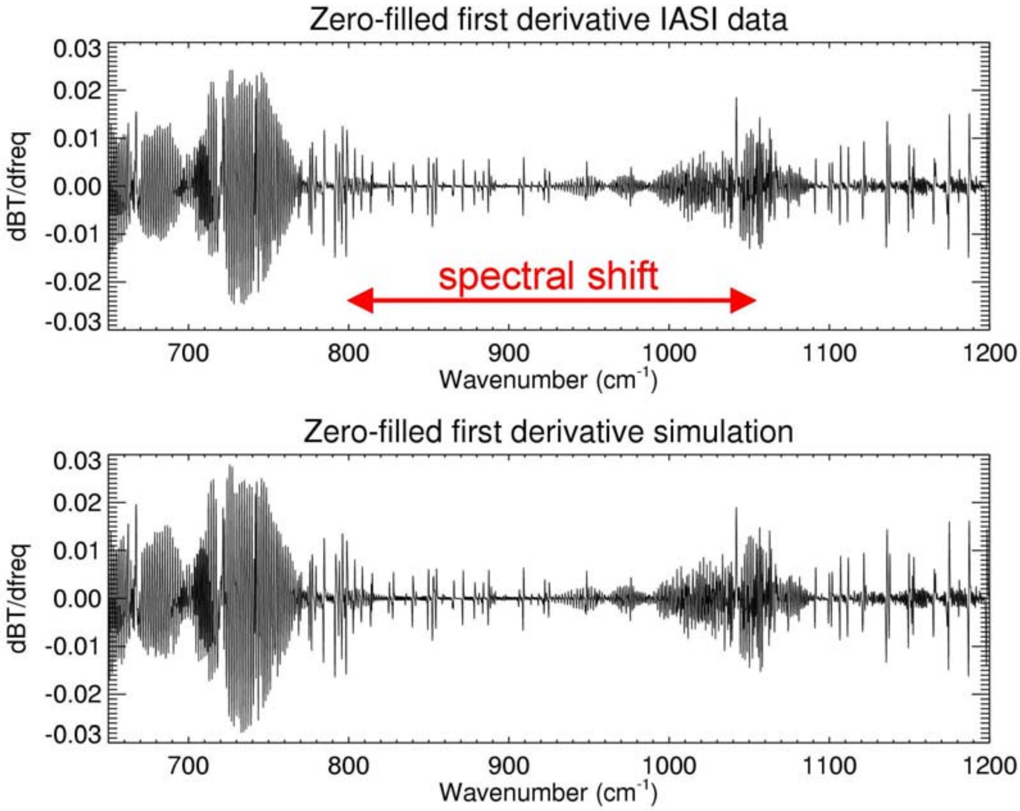

Figure 1: First derivatives with respect to frequency of (top) observed and (bottom) simulated brightness temperature spectra. A spectral shift is applied to the observations from which the optimal value is derived by computing the correlation coefficient.

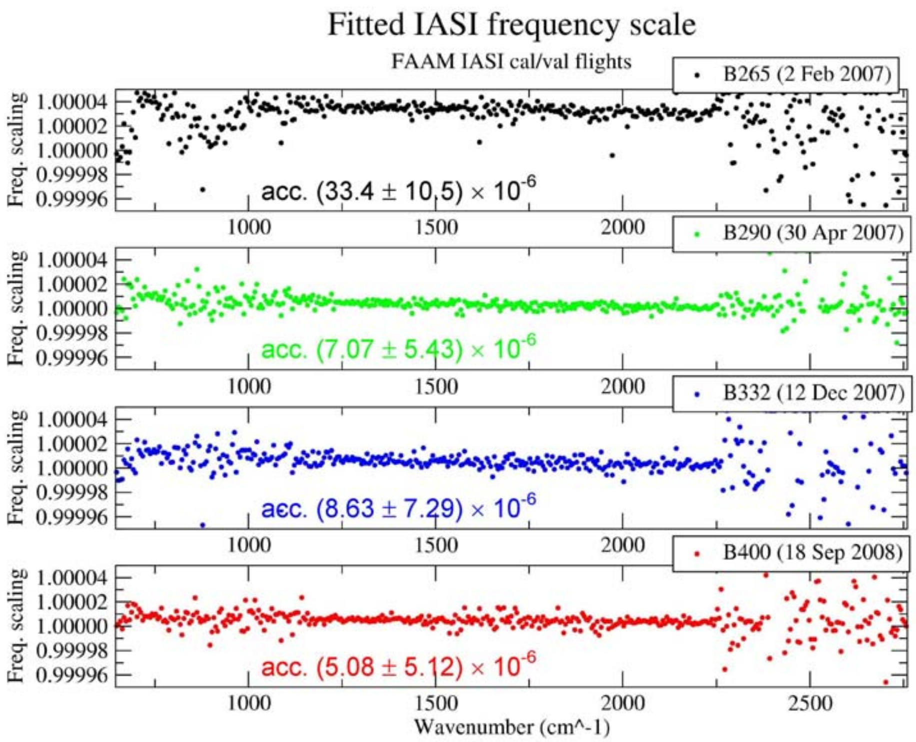

Figure 2: Fitted frequency scaling for four case studies on FAAM flight days. The implied spectral calibration accuracy and standard deviation is shown for each plot.

It is worthy of note that great care needs to be taken in deriving frequency scaling factors in this way. Influences such as scene inhomogeneity may act to introduce spurious spectral shifts that are unconnected with the calibration performance of the instrument (D. Blumstein, personal communication).

4. IASI direct radiance validation

In order to test the radiometric calibration accuracy of IASI we seek to identify, from within the JAIVEx dataset, the best clear sky cases over ocean where the uncertainties in radiative transfer modelling and surface emission are minimised. It is of crucial importance to optimise the collocation of sensors (satellite and aircraft) with simultaneous measurements of the atmospheric state. The surface emission is constrained using ARIES measurements from low level (35 m altitude) which enable the retrieval of surface skin temperature and emissivity (Newman et al., 2005).

GENLN2 simulations were run for each sensor, matched to the nearest coincident profile information, and observed – calculated residuals computed. The average residuals for a case over the Gulf of Mexico are plotted in Figure 3 for the longwave spectral region. The residuals generally lie within the ± 1 K level; exceptions to this include the region above 1200 cm^{-1} where the spectra are sensitive to methane (not measured during the campaign) and for IASI in the ozone band 1000-1100 cm^{-1} which relies on ozone concentrations from NWP models. The Met Office fields do not include variable ozone, hence climatological values have been used.

Excluding the ozone band, the residuals in the 800-1200 cm^{-1} atmospheric window (sensitive mainly to sea surface emission and tropospheric water vapour continuum) are very small, on average –0.2 K. Importantly, the window region residuals for ARIES and IASI differ by less than 0.1 K, giving confidence in the absolute calibration accuracy.

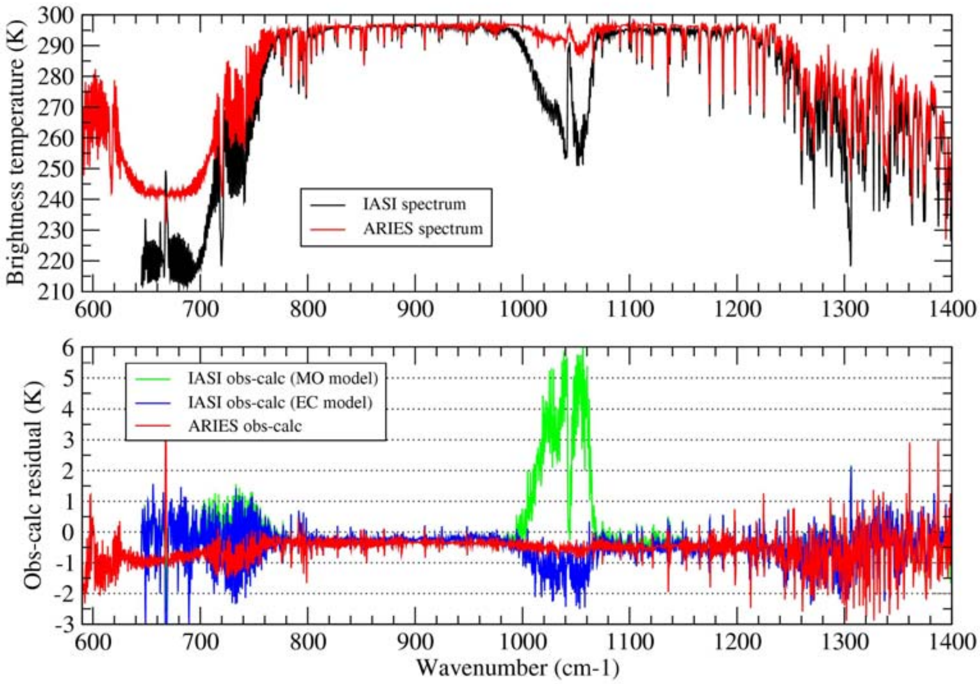

Figure 3: Upper panel: IASI and ARIES clear-sky upwelling brightness temperature spectra recorded on 30 April 2007. Lower panel: residual differences (observed – calculated GENLN2 spectrum) for both Met Office and ECMWF upper atmosphere fields, see legend.

The good level of agreement between observed and calculated radiances in Figure 3 can be attributed to a well constrained atmospheric profile and surface characteristics coupled with good calibration performance of the interferometers. However, the level of agreement in the temperature-sounding CO_2 band below 800 cm^{-1} is less good. Figure 4 compares the GENLN2 with results generated with the LBLRTM code (Clough, 2005). LBLRTM contains more recent updates to some key spectroscopic parameters, particularly CO_2 line mixing. Figure 4 appears to show that LBLRTM is more successful than GENLN2 at reducing the size of residuals in the CO_2 band between 700-770 cm^{-1}.

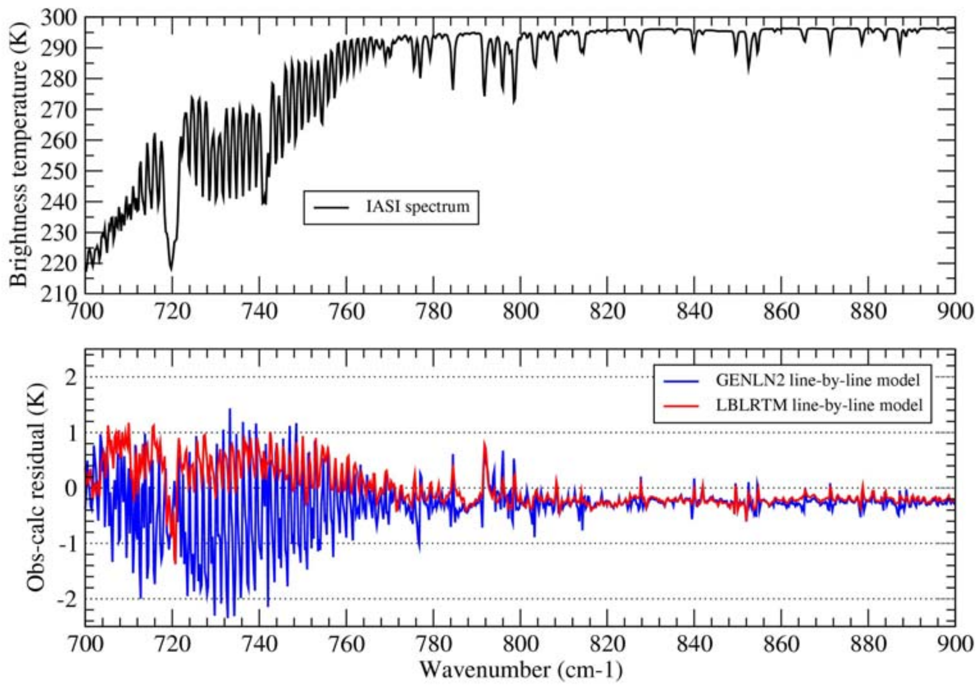

Figure 4: (Upper panel) IASI clear-sky upwelling brightness temperature spectrum for 30 April 2007. (Lower panel) residual differences (observed – calculated) for GENLN2 and LBLRTM (see legend) using ECMWF reference profile for the upper atmosphere.

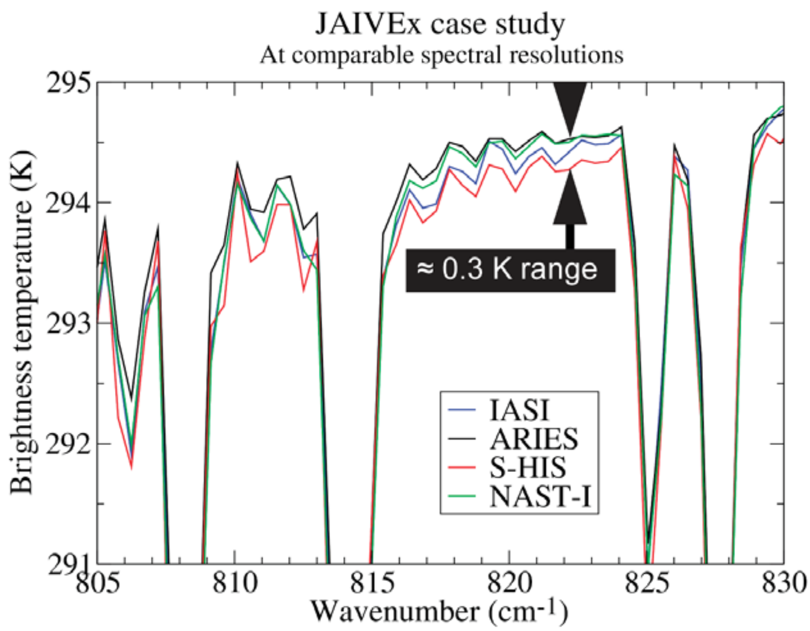

Figure 5: Comparison of observed brightness temperatures from the four interferometers involved in JAIVEx (see legend) from the dataset collected on 29 April 2007.

Another powerful test of the radiometric accuracy of IASI is a cross-comparison of collocated interferometer measurements (four interferometers on three platforms during JAIVEx). In particular, we expect all four instruments to receive the same radiance in the atmospheric window region, since this signal is overwhelmingly dominated by emission from the surface and the self-broadened water vapour continuum emission in the lower troposphere. Figure 5 presents data from the case study of 29 April 2009, with all interferometers viewing the same scene simultaneously. The higher resolution instrument data (IASI and NAST-I) have been degraded to match the spectral response functions of ARIES and S-HIS. In regions of the spectrum such as that pictured at 820 cm^{-1} the measured brightness temperatures agree to within 0.3 K; IASI falls within the spread of measurements.

Therefore, both from comparisons with tightly-constrained simulations and collocated interferometer data, the IASI radiometric calibration is validated to within 0.2-0.3 K. All three aircraft interferometers undergo periodic calibrations themselves against national standard blackbody sources, establishing a traceable chain of calibration from IASI to absolute standards.

5. IASI cross-validation with AIRS

A key aim of JAIVEx was to intercompare IASI on MetOp with AIRS on Aqua. As described in detail by Larar et al. (2009), aircraft interferometer measurements provide a robust way of comparing AIRS and IASI radiance measurements which are collocated in space but not in time. Figure 6 shows the situation on 29 April 2007, with overpasses of both satellite instruments over a clear sky portion of the Gulf of Mexico separated by 3½ hours. Also shown is the flight track of the WB-57 aircraft, which flew over the area spanning the times of the two overpasses. Hence, NAST-I measurements were made in spatial and temporal coincidence with, separately, IASI and AIRS, which enables an indirect validation of the two satellite instruments with each other.

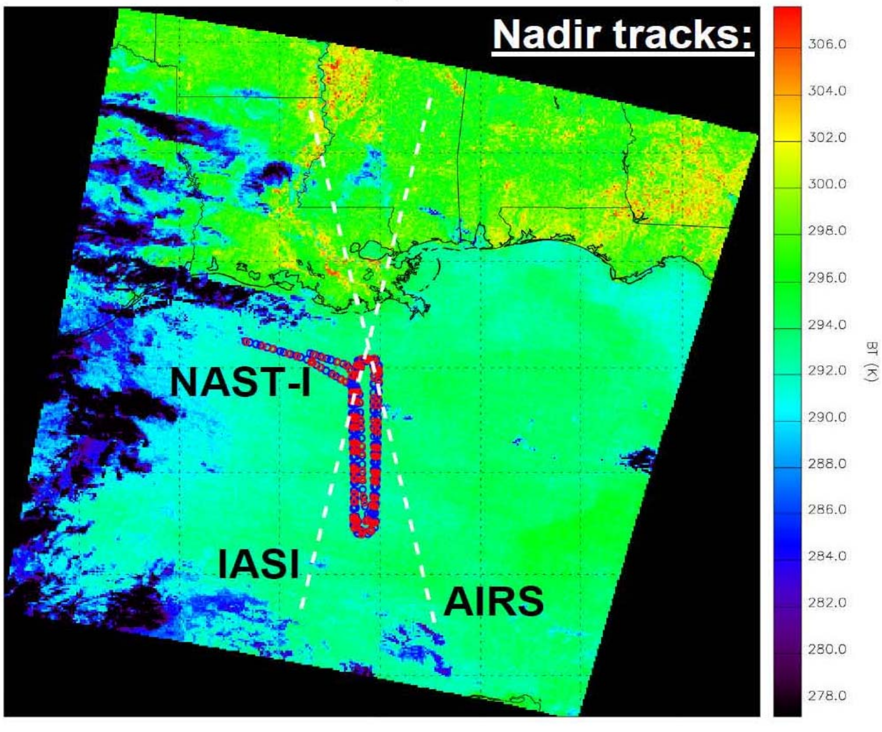

Figure 6: View from IASI imager over the Gulf of Mexico on 29 April 2007. Overlaid are the sub-satellite tracks of IASI (overpass at 1550 UTC) and AIRS (1919 UTC), together with NAST-I footprints from WB-57 flight.

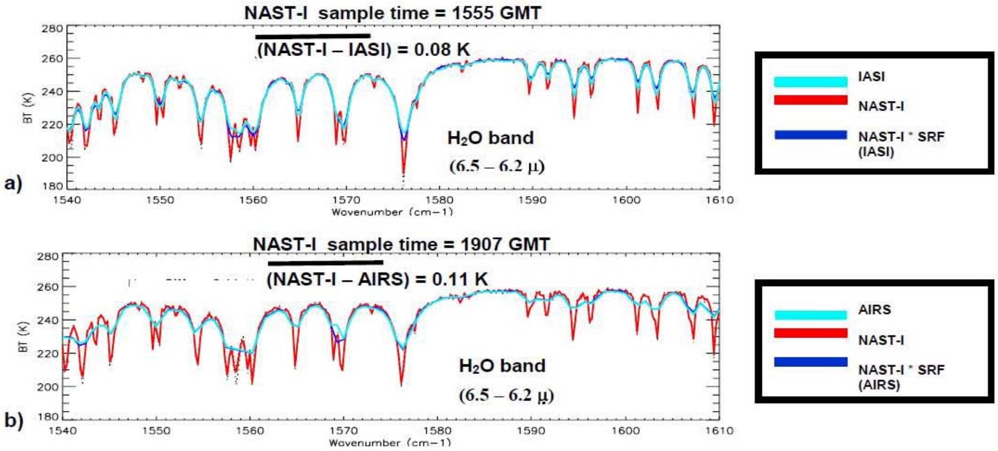

Figure 7: Comparisons of NAST-I brightness temperatures with spatially and temporally matched IASI and AIRS observations, with focus on the strong mid-IR water vapour band. NAST-I spectra have been convolved with the respective satellite instrument spectral response functions for quantitative comparison (see legend). From Larar et al. (2009).

An example of the level of agreement between the sensors is shown in Figure 7. The mean discrepancy between NAST-I and IASI brightness temperatures is 0.08 K, compared with 0.11 K between NAST-I and AIRS. In the longwave region (not shown) the mean difference is 0.13 K versus IASI and 0.11 K versus AIRS; in the shortwave region the comparison is 0.10 K versus IASI and 0.05 K versus AIRS. There is, therefore, strong evidence that IASI and AIRS are calibrated to within 0.13 K (absolute with NAST-I) and indirectly 0.05 K (IASI relative to AIRS via NAST-I).

6. Identification of model biases

We have noted that we rely on operational NWP model fields to “top-up” in situ profile information above the maximum altitude of the FAAM aircraft. These were obtained from the Met Office and ECMWF global models. During the analysis of JAIVEx case studies it became apparent that these two sets of model fields gave widely different results when included in line-by-line simulations of IASI spectra. Figure 8 demonstrates that ECMWF fields produce residuals in the strong water vapour band close to zero, whereas significant negative residuals are seen with Met Office fields, in accord with Met Office operational statistics.

The reason for this different behaviour is seen in Figure 9, which compares the respective model fields. Whereas the ECMWF and Met Office temperature fields agree within 1 K through most of the atmosphere, there is a major discrepancy between the water vapour fields: the Met Office fields show a significant dry bias relative to ECMWF. Detailed analysis by one of us (Sid Clough) reveals this is not just a local effect specific to this case study, but is replicated at the tropopause level globally during April 2007.

Operational statistics during this period confirm persistent negative O-B departures for the Met Office, whereas for ECMWF there is a positive, though smaller, O-B bias for channels sensitive to water vapour around the tropopause level (Figure 10). This finding has encouraged a number of changes in the Met Office data assimilation scheme:

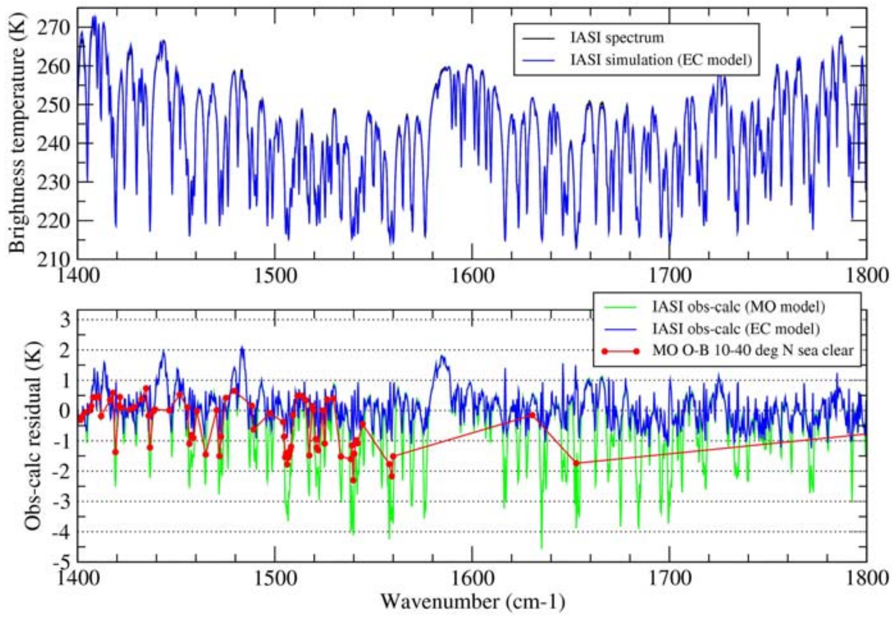

Figure 8: Top panel: IASI spectrum and simulation incorporating ECMWF temperature and humidity fields above 9 km, for case on 30 April 2007. Bottom panel: obs-calc residuals derived with Met Office and ECMWF upper atmosphere fields (see legend). Also shown are Met Office operational obs-background biases for assimilated channels between 10-40°N in clear skies over ocean.

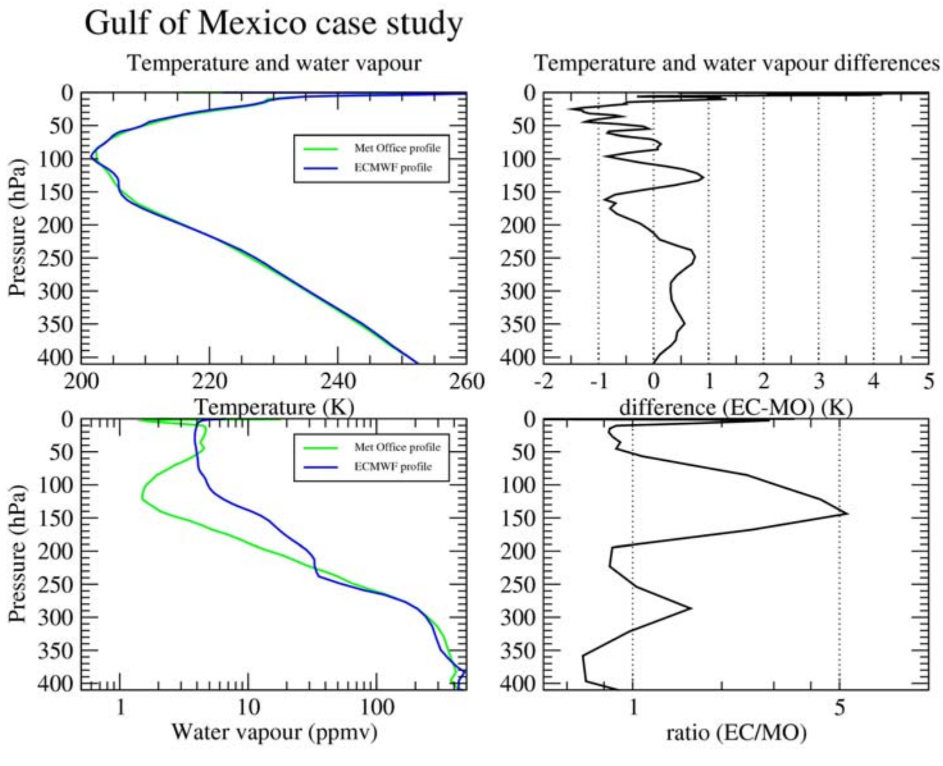

Figure 9: Model fields from JAIVEx case study on 30 April 2007. Top: comparison of temperature fields at case study time and location. Bottom: comparison of water vapour fields.

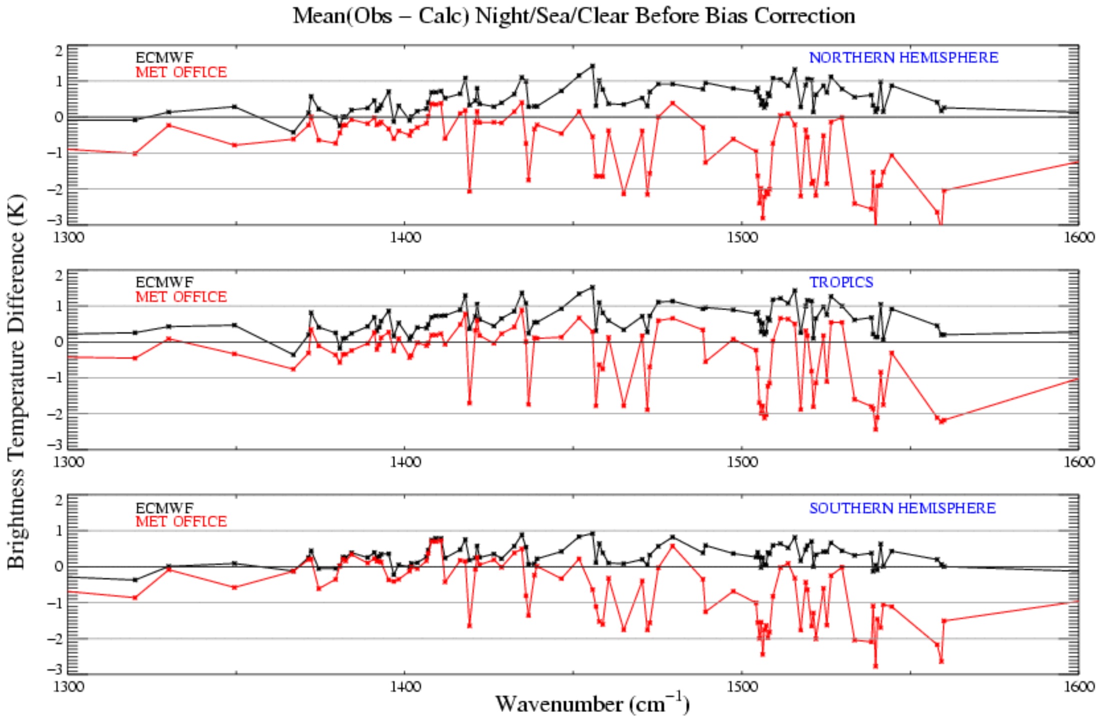

Figure 10: ECMWF and Met Office obs-calculated departures for three latitude ranges (see legend) during the JAIVEx campaign.

1. More conventional water vapour observations assimilated by changing radiosonde upper threshold limits.
2. Satellite biases have been reset in the absence of water vapour observations aloft.
3. A new definition of tropopause for 4D-Var has been implemented. Previously this used a constant value of potential vorticity which resulted in a tropopause that was too low.
4. Humidity increments are set to zero above the tropopause rather than allowing them to reset to a negative increment.

A more detailed discussion can be found in Newman et al. (2008). These results are seen alongside continuing problems in obtaining significant NWP impact through assimilating IASI water vapour channels at operational centres. Future research with the FAAM aircraft will focus on improving the understanding of water vapour spectroscopy (including the continuum) in this region, which will be necessary if these channels are to be used successfully to “anchor” water vapour in the higher atmosphere.

7. Summary

The JAIVEX campaign, bringing together hyperspectral radiance measurements with high-density collocated observations of the atmospheric state, has produced a valuable dataset for validation of satellite calibration accuracy and retrieval algorithms.

Clear sky case studies have been used to test the absolute calibration accuracy of IASI. The frequency shift error in the IASI spectral calibration seen immediately after launch has been successfully addressed by routine corrections to the configuration file parameters. Line-by-line simulations of radiances measured over ocean match the observations to within 0.2 K over the 800-1200 cm^{-1} region, and within 1.0 K over much of the rest of the spectrum. Allied with agreement of four independent interferometer measurements to within 0.3 K, and exceptional correspondence of IASI and AIRS with reference NAST-I measurements to within 0.13 K at worst, these results confirm the high quality of the IASI radiometric calibration.

The JAIVEx dataset is freely available for academic research, contact stu.newman@metoffice.gov.uk for more information.

Acknowledgements

This work has been partially funded under EUMETSAT contract Eum/CO/06/1596/PS. The FAAM BAe 146 is jointly funded by the Met Office and the Natural Environment Research Council. The US team was sponsored by the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO) and NASA.

References

Blumstein, D., Tournier, B., Cayla, F. R., Phulpin, T., Fjortoft, R., Buil, C. and Ponce, G., 2007: In-flight performance of the infrared atmospheric sounding interferometer (IASI) on METOP-A, *Proc. SPIE,* **6684**, H6840

Edwards, D. P., 1992: GENLN2: A general line-by-line atmospheric transmittance and radiance model, *NCAR Tech. Note NCAR/TN-367+STR, National Center for Atmospheric Research, Boulder, Co., USA.*

Clough, S. A., M. W. Shephard, E. J. Mlawer, J. S. Delamere, M. J. Iacono, K. Cady-Pereira, S. Boukabara, and P. D. Brown, 2005: Atmospheric radiative transfer modeling: a summary of the AER codes, Short Communication, *J. Quant. Spectrosc. Radiat. Transfer*, **91**, 233-244

Larar, A. M., W. L. Smith, D. K. Zhou, X. Liu, H. Revercomb, J. P. Taylor, S. M. Newman and P. Schlüssel, 2009: IASI spectral radiance performance validation: case study assessment from the JAIVEx field campaign, *Atmos. Chem. Phys. (submitted)*

Newman, S. M., Smith J. A., Glew M. D., et al., 2005: Temperature and salinity dependence of sea surface emissivity in the thermal infrared, *Quart. J. Royal Meteorol. Soc.* **131** (610), 2539-2557

Newman, S. M., F. Hilton, S. Clough and A. D. Collard, 2008: Identification of biases in the modelling of high peaking water vapour channels from IASI, *Proceedings of ITSC-XVI, Angra dos Reis, Brazil, 7th-13th May 2008*

Strow, L. and Hannon S., 2007: Initial IASI validation, *UMBC publication*

Taylor, J. P., W. Smith, V. Cuomo et al., 2008: EAQUATE – An International Experiment For Hyper-spectral Atmospheric Sounding Validation, *Bull. Am. Meteorol. Soc.*, **89**, 203-218

Tobin, D. C., Revercomb H. E., Knuteson R. O., et al., 2006: Radiometric and spectral validation of Atmospheric Infrared Sounder observations with the aircraft-based Scanning High-Resolution Interferometer Sounder, *J. Geophys. Res.*, **111** (D9), D09S02.