

# Aircraft and satellite hyperspectral measurements investigating the radiative impact of atmospheric water vapour

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## 1 Introduction

The successful launch of the Infrared Atmospheric Sounding Interferometer (IASI), with significant improvements in forecast skill in operational weather forecasting models, demonstrates the value of hyperspectral measurements from space. However, the extension of hyperspectral data assimilation to include more channels sensitive to water vapour is an ongoing challenge. Uncertainties in the spectroscopy of water vapour, and in the formulation of the water vapour continuum, remain, and radiative transfer models require validation against observational data.

The UK's Facility for Airborne Atmospheric Measurements (FAAM) BAe 146 research aircraft has been involved in two recent campaigns where the radiative impact of water vapour has been investigated. The Joint Airborne IASI Validation Experiment (JAIVEx), based in Houston, Texas, gathered a high quality data set of co-located interferometer radiances and atmospheric profile measurements in high humidity conditions. Subsequently, as an integral part of the Continuum Absorption at Visible and Infrared wavelengths

and its Atmospheric Relevance (CAVIAR) project, combined ground-based and airborne measurements have been collected at midlatitudes, centred on southwest England and the Jungfraujoch research station in Switzerland. Combined, these measurements span a range of humidity conditions and allow radiative transfer models of atmospheric water vapour absorption and emission to be tested.

## 2 Airborne campaigns

This work draws on results from two dedicated campaigns involving the FAAM aircraft.

JAIVEx (<http://cimss.ssec.wisc.edu/jaivex/>) coordinated measurements from the UK's FAAM aircraft operating in the troposphere and NASA's WB-57 stratospheric research aircraft. These flights during April-May 2007 were planned to coincide with overpasses of the IASI interferometer on the MetOp-A satellite for calibration/validation activities. Eight MetOp cases were investigated, five over the Gulf of Mexico and three over the Oklahoma Southern Great Plains ARM site. JAIVEx has proved beneficial in spectral radiance validation (Larar et al., 2010) and in testing one-dimensional variational retrievals from hyperspectral sounders (Zhou et al., 2009).

CAVIAR (<http://www.met.reading.ac.uk/caviar/>) is a cross-disciplinary project combining expertise from UK universities and research institutes. The consortium aims to understand the theoretical basis of the water vapour continuum and improve formulations of the continuum in radiative transfer models. Part of this research involved two field campaigns, with a ground-based high spectral resolution solar-tracking interferometer (from the National Physical Laboratory) obtaining measurements in conjunction with observations from the FAAM aircraft. The campaigns took place at the Camborne radiosonde station in southwest UK in August-September 2008 and at the Jungfraujoch high altitude observatory in Switzerland in July-August 2009.

The key capabilities of the FAAM aircraft in radiative transfer validation studies involve:

- release of dropsondes from mid-to-high altitudes in the troposphere for direct measurement of temperature and water vapour profiles;
- instrumentation for in situ measurements including temperature, humidity, ozone and CO trace gas concentrations, and cloud and aerosol particulates (surface to 10 km altitude);

- mid-infrared (3.3-18  $\mu\text{m}$ ) measurements of upwelling and downwelling radiances from the Met-Office’s ARIES interferometer;
- far-infrared (15-125  $\mu\text{m}$ ) measurements of upwelling and downwelling radiances from Imperial College’s TAFTS interferometer;
- Heimann broadband infrared radiometer for monitoring of surface temperatures;
- microwave measurements of upwelling and downwelling radiances from the Met Office’s MARSS radiometer.

### 3 Atmospheric profile constraints

Typically we seek to validate radiative transfer models by comparing simulations (which take as input the best available estimate of the atmospheric state) with measurements, e.g. from spaceborne or airborne interferometers. In order to interpret these comparisons correctly we need to characterise the error associated both with the atmosphere and the instrument observations.

As far as practicable we sample the atmosphere using aircraft instrumentation to be spatially and temporally co-located with radiance observations (here we apply a threshold criterion of not more than 15 minutes separation, taking the nearest available profile which will usually lie within 25 km). With frequent releases of dropsondes from the FAAM aircraft we obtain good coverage of the temperature and humidity structure below 10 km altitude. Above this ceiling we rely on model fields (such as from ECMWF) to define the atmospheric profile.

The principles of estimation theory are widely used in satellite data assimilation to obtain, in an optimal way, the atmospheric state taking into account the error covariances of the initial (first guess) atmospheric state and of the observations (Rodgers, 2000). For instruments such as IASI on MetOp it is a key aim to exploit channels sensitive to water vapour for humidity retrieval, although this relies on accurate forward models to achieve this. The purpose of this paper is to test the underlying water vapour radiative transfer at infrared wavelengths, for which we need to reduce uncertainties in our first guess humidity profile. To achieve this we exploit aircraft microwave observations which are sensitive to water vapour absorption.

The Microwave Airborne Radiometer Scanning System (MARSS) operates at AMSU-B frequencies between 89-183 GHz. Given that MARSS scans pointing upwards as well as downwards, the three channels centred on the

183 GHz H<sub>2</sub>O line may be used to modify the background humidity field above the aircraft for which the model field may be inaccurate.

We follow the treatment in Rodgers (2000) to perform the iteration

$$x_{i+1} = x_a + (\mathbf{K}_i^T \mathbf{S}_\epsilon^{-1} \mathbf{K}_i + \mathbf{S}_a^{-1})^{-1} \mathbf{K}_i^T \mathbf{S}_\epsilon^{-1} [\mathbf{y} - \mathbf{F}(x_i) + \mathbf{K}_i(x_i - x_a)] \quad (1)$$

where  $x_{i+1}$  is the retrieved state vector following iteration  $i$ ,  $x_a$  is the a priori (first guess) state vector,  $\mathbf{y}$  represents the observed radiances,  $\mathbf{F}$  is the forward model,  $\mathbf{K}$  is the Jacobian representing the derivative of forward modelled radiances with respect to the state vector, and  $\mathbf{S}_a$  and  $\mathbf{S}_\epsilon$  are the error covariance matrices of the a priori state and the observed radiances respectively. The forward modelling of microwave radiances and associated Jacobian calculations are performed using the MonoRTM code (Clough et al., 2005).

The use of uplooking MARSS data is intended to reduce uncertainties in the atmospheric state above the maximum altitude of the FAAM aircraft. It is important to represent realistically the error covariance of the first guess state vector (and indeed observation errors) for the retrieval to be successful. We follow the example of Haeefe and Kampfer (2010), for retrieval of water vapour profiles from microwave data, to define the a priori covariance matrix as

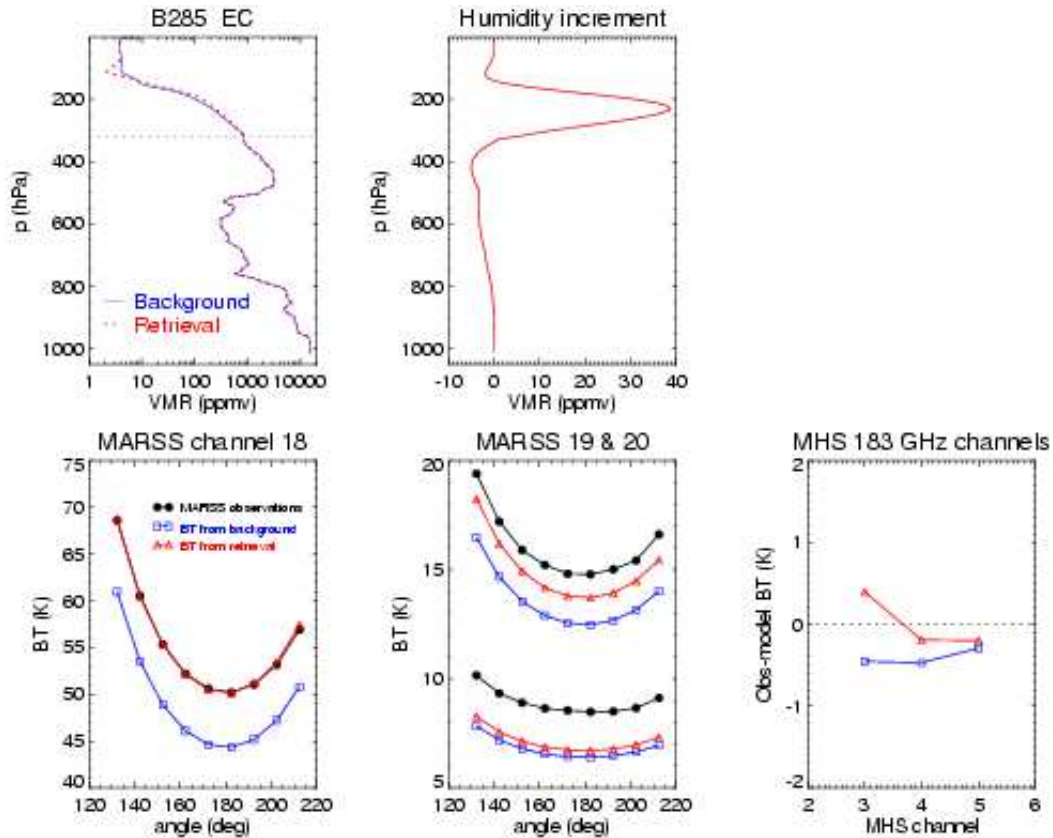
$$\mathbf{S}_a(i, j) = \sigma(i)\sigma(j) \exp \left( -4 \left[ \frac{z(i) - z(j)}{l_c(i) + l_c(j)} \right]^2 \right) \quad (2)$$

where  $\sigma(i)$  is the standard deviation of atmospheric level  $i$  at altitude  $z(i)$  with level-dependent correlation length  $l_c(i)$ . The a priori standard deviation is estimated below the maximum aircraft altitude (uncertainty in dropsonde profiles) as 5% relative humidity. Above the aircraft, where the a priori background profile is derived from ECMWF model profiles,  $\sigma(i)$  is assumed to be 80% absolute humidity. The correlation length is set to 2 km. The observation error covariance matrix  $\mathbf{S}_\epsilon$  is assumed diagonal, with brightness temperature standard deviations of 1.0 K for all MARSS channels. Only water vapour (not temperature) is included in the state vector for this exercise, since we have limited information in the three MARSS channels at 183 GHz and, as has been demonstrated for the JAIVEx data set, model temperature fields tend to be less variable than those for humidity.

Figure 1 shows the results for a retrieval from flight B285 on the night of 19/20 April 2007 over the Gulf of Mexico. The key findings are:

1. The retrieval introduces a relatively small, positive humidity increment, peaking around 250 hPa.

2. Calculated MARSS channel 18 ( $183 \pm 1$  GHz) brightness temperatures (i.e. forward modelled from retrieved atmospheric profile) match the observed brightness temperatures very well.
3. Calculations for MARSS channels 19 & 20 ( $183 \pm 3$ ,  $183 \pm 7$  GHz) are less well modelled. The reason for this is not clear, although recently (Turner et al., 2009) uncertainties have been highlighted in the microwave water vapour continuum around 150 GHz.
4. As an experiment, MHS observations from the same time/location have been included in addition to the MARSS data. This results in

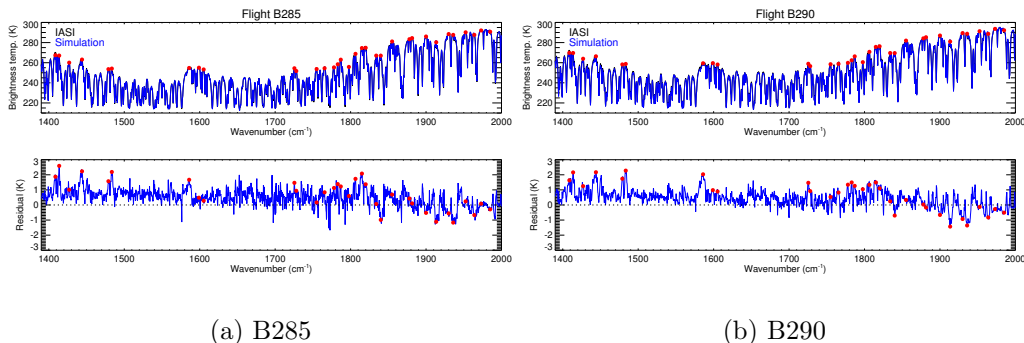


**Figure 1:** Use of MARSS data from FAAM aircraft to modify atmospheric humidity profile. Top row: background and retrieved profiles of  $H_2O$  mixing ratio (dotted line indicates dropsonde/model boundary), with humidity increment produced by the retrieval. Bottom row: background and retrieved brightness temperatures, compared with observations, for MARSS over a range of uplooking view angles, and for downlooking MHS on MetOp.

slightly improved obs-calculated departures (in red) compared with obs-background (in blue). However, the use of MHS data does not materially alter the retrieval, since the 183 GHz downlooking Jacobians peak in the troposphere where the error covariance matrix  $\mathbf{S}_a$  constrains the profile to closely match the a priori.

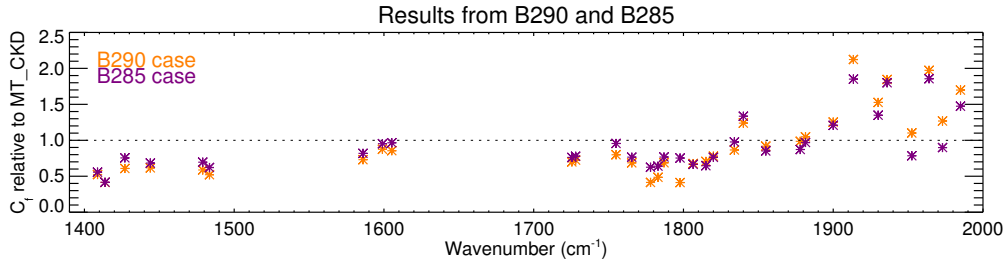
## 4 JAIVEx results

Having used microwave observations to retrieve a modified water vapour profile, this profile may be used in forward modelling of IASI at infrared frequencies. We use LBLRTM version 11.7 (Clough et al., 2005) as our forward model, which includes recent updates to water vapour spectroscopy in the mid-infrared region of interest. Figure 2 shows results from the case studies B285 on 19/20 April and B290 on 30 April 2007. The obs-calc differences in the two plots show a great deal of consistency, with (broadly speaking) positive or neutral residuals below 1850  $\text{cm}^{-1}$  and negative residuals above this frequency.



**Figure 2:** Comparison of IASI data with simulations for two case studies. The upper plots show IASI brightness temperatures overlaid with simulations from LBLRTM. The lower plots show obs-calc residual differences. Red dots identify IASI channels which have been selected for significant continuum contribution.

LBLRTM includes the facility to modify the continuum strength. This has been done for the two cases in Fig. 2, in order to estimate what modification to the MT\_CKD water vapour model is required to eliminate the residual differences seen. Since the foreign-broadened continuum is greatly stronger than the self-broadened continuum in this spectral region, only foreign broadening has been considered in this study.



**Figure 3:** Inferred foreign continuum strength relative to MT\_CKD model in LBLRTM, based on residuals for selected continuum channels for two case studies shown in Fig. 2.

Figure 3 presents these fitted foreign continuum strengths, relative to the most recent edition of MT\_CKD. The fitted continuum varies between approximately 0.5 and 2.0 times the MT\_CKD values. These results are discussed in the context of the Jungfraujoch results in the next section.

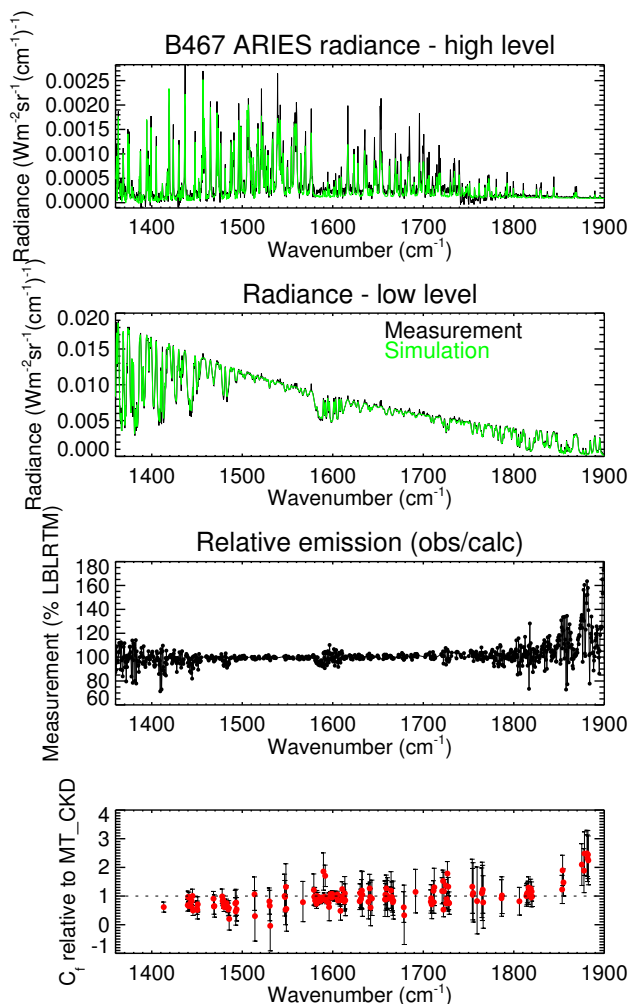
## 5 CAVIAR results

We focus here on the Summer 2009 field campaign over the Swiss Alps, where the FAAM research aircraft operated at altitudes of 15,000 feet (minimum flight altitude over the Jungfraujoch mountain observatory) to 35,000 feet (maximum operating altitude). This enabled measurements with the ARIES interferometer, uplooking, to investigate the strength of the water vapour continuum. A typical flight pattern was as follows:

1. Initial straight-and-level run at high altitude, with ARIES measurements looking up to measure the (small) downwelling radiance from stratospheric water vapour.
2. Spiral descent of the aircraft over the Jungfraujoch observatory, measuring in situ water vapour concentrations with frost point hygrometer and optical fluorescence probes.
3. Further straight-and-level run at minimum altitude, obtaining uplooking ARIES spectra.

Figure 4 shows comparisons between ARIES and LBLRTM-simulated radiances for one of the Jungfraujoch flights, for the 1360-1900  $\text{cm}^{-1}$  region.

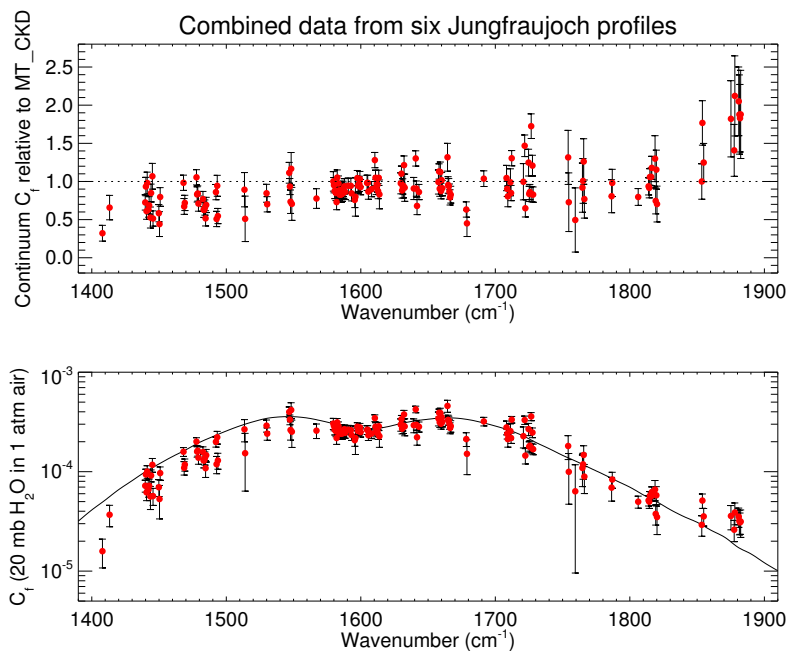
At 35,000 ft altitude the downwelling emission is small (note that ARIES exhibits some noise in this part of the infrared spectrum, which accounts for some differences compared with LBLRTM simulations). Having descended to 15,000 ft, ARIES measures increased downwelling emission due to the greater water vapour column above the instrument. Using water vapour pro-



**Figure 4:** Results from CAVIAR flight B467 on 19 July 2009. The panels show (a) measured and simulated ARIES upwelling radiances at an altitude of 35,000 ft; (b) measured and simulated ARIES upwelling radiances at 15,000 ft; (c) ratio of observed to calculated radiances at 15,000 ft; (d) foreign water vapour continuum coefficient, expressed relative to MT\_CKD, required to bring simulation into agreement with observed radiances.



file measurements from the FAAM aircraft (the fluorescence measurements have the fastest time response, and can be validated with frost point hygrometer data), LBLRTM has been used to simulate the downwelling radiance. These data are then used to derive foreign broadened continuum coefficients relative to MT\_CKD for frequencies most sensitive to uncertainties in continuum strength. For example, between 1800-1900  $\text{cm}^{-1}$  the observed emission is greater than in the LBLRTM simulation, so inferring a stronger continuum than in MT\_CKD.



**Figure 5:** Combined results from six flights during the Switzerland campaign. For selected frequencies the retrieved foreign-broadened continuum coefficient is shown (upper plot) expressed as a fraction of the values in MT\_CKD. The lower plot shows the absolute values on a logarithmic scale, where the solid line is the MT\_CKD continuum. ARIES data are shown with error bars denoting the standard deviation of retrieved values.

In Fig. 5 the most recent results from six analysed flights are summarised. The ARIES data confirm the overall shape of the continuum, but departures are seen, particularly near the edges of the strong water vapour band. More work is required to refine the continuum strength estimates shown. However, it is interesting that the derived continuum shares many of the features of that shown for the JAIVEx IASI case in Fig. 3. Recent results from the

Molecular Spectroscopy Facility at the Rutherford Appleton Laboratory in the UK (*K. Smith, pers. comm.*) indicate that the continuum exhibits a more structured spectral shape than currently formulated in MT\_CKD. The CAVIAR project aims to bring together latest research on the continuum and publish results over the next twelve months.

## 6 Summary

- A combination of satellite, aircraft and ground-based measurements is being used to investigate the water vapour spectrum, its spectroscopy and continuum.
- Although recent spectroscopy updates in LBLRTM are significant (some strong water vapour transitions increased in strength by 5-10%), obs-calc departures are still seen in case studies from JAIVEx and CAVIAR.
- Simulated IASI spectra from JAIVEx agree with measurements largely to within 2 K, with the largest magnitude residuals for channels sensitive to the water vapour continuum.
- Preliminary results from a recent CAVIAR campaign allow foreign-broadened continuum coefficients to be estimated, showing frequency-dependent departures from MT\_CKD.
- The CAVIAR consortium continues to investigate the continuum and its causes through a combination of theoretical calculations, laboratory measurements and field campaign data.

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