Development and validation of Gastropod, a fast radiative transfer model for the advanced sounders

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Abstract

Gastropod is a fast radiative transfer code designed to meet the requirements of a day one radiative transfer operator for AIRS (and eventually IASI) for use in variational data assimilation systems. This paper gives an overview of the model methodology adopted, and summarises the results from line-by-line radiative transfer model validation of the Gastropod forward model and Jacobian code for dependent and independent profile sets. Issues relating to modelled water vapour absorption are described briefly here and treated in detail in a companion paper.

Introduction

Fast and accurate radiative transfer forward models – and the corresponding adjoint and/or Jacobian codes – are required to exploit data from the advanced infrared sounders. Validation of fast model simulations with reference line-by-line calculations, and through comparison with other fast models is an essential step in the model development process: these studies allow fast model errors to be characterised, and can lead to the development of improved fast models.

In this paper we summarise the main choices we made in the development of the Gastropod model, based on a previous intercomparison study of fixed pressure grid fast models for IASI [Sherlock, 2000]. We then present results from line-by-line validation of the Gastropod forward model and Jacobians, and compare forward model errors with statistics for AIRS simulations with RTTOV-7, as reported by Matricardi et al. [2001].

Gastropod validation results led to a study to improve modelled absorption in water vapour line centres. We summarise the main results of this study, which offer the perspective of marked improvements in modelled water vapour line absorption in an upcoming release of the Gastropod model.

Gastropod development strategy

Gastropod is a fixed presure grid fast model. As in most fast model developments, an approximate solution to the radiative transfer equation is sought in terms of convolved layer to space transmittances. Further, these convolved transmittances are estimated from a regression based prediction of effective layer optical depth.

The fast model methodology adopted in Gastropod follows that of the PFAAST model [Hannon et al., 1996]. This model was selected based on the results of a previous intercomparison of fixed pressure grid fast models for IASI [Sherlock, 2000], and was favoured principally because of low forward model errors in spectral intervals where water vapour absorption dominates.

PFAAST error characteristics are attributed to two main features of the Hannon et al. [1996] methodology: separate prediction of water vapour line and continuum absorption and use of weighted regression. The separation of water vapour line and continuum absorption gives three major advantages: 1. the different absorber abundance and temperature dependencies of the line and continuum absorption are modelled separately, thus allowing 2. fewer predictors in both regressions and 3. easy incorporation of corrections to the description of the water vapour continuum without computationally expensive recalculation of line-by-line transmittances. Weighted regression (downweighting data in the water vapour line absorption regression where the overhead column is optically opaque) is key to achieving the required accuracy for the fast model transmittance prediction scheme.

The main reason for not adopting the PFAAST model as it stood was the fact that the corresponding adjoint/Jacobian code had not been written, nor was there any plan to do so. Thus the Gastropod model extends the PFAAST methodology, with the complete suite of forward model, tangent linear, adjoint and K code.

Prior to the Gastropod development, fast models for the advanced sounders had used different regression schemes for water vapour depending on the optical depth of the overlying column. However this leads to discontinuities in modelled Jacobians. Gastropod uses a single regression scheme for water vapour absorption. This has required redefinition of the regression weighting function proposed by Hannon et al. [1996].

Based on the results of a previous study of the vertical discretisation required for fast models for the advanced sounders [Sherlock, 2001b], we use a simple representation for layer mean radiative properties. This in turn gives a marked speed-up in adjoint and Jacobian calculations (over a weighted Curtis-Godson approximation).

Finally, we have included interface modules which allow profile input and Jacobian output on arbitrary (i.e. user defined) pressure levels.

Convolved transmittances for the generation of the regression coefficients were provided by Scott Hannon at the University of Maryland, Baltimore County. A detailed description of the Gastropod model is given in Sherlock [2001a].

Line-by-line validation of Gastropod forward model and Jacobian calculations

The accuracy of fast model radiance simulations is dependent on the predictive accuracy and representativity of the underpinning regression models. For this reason it is essential to quantify forward model errors for an independent profile set. It is equally important (and often very informative for diagnosing errors) to quantify fast model Jacobian errors, as these derivatives must be modelled accurately if data is to be used optimally in assimilation [Sherlock et al., 2000]. Because accurate description of water vapour absorption in the ν_2 band has proved challenging for fast models, and because current fast model formulations and error characteristics for modelling water vapour absorption differ we focus here on results for the H_2O ν_2 band.

Forward model error estimates

In Figure 1 we present results from the line-by-line validation of the Gastropod forward model using kCARTA version 1.10. Nadir view brightness temperature differences have been evaluated for 176 independent profiles from the ECMWF 50 Level diverse profile set [Chevallier, 1999]. Corresponding statistics for the independent profile set are illustrated with black curves. Equivalent statistics for the dependent profile set (48 profiles) are illustrated in red.

With the exception of some line centres, biases are very low ($\sim$ 0.02 K) across the 1400–1600 cm^{-1} spectral interval. In line centres the maximum bias is of the order of 0.05 – 0.1 K.

The standard deviation of the differences varies between 0.02 and 0.2 K, with maximum standard deviations occuring in line centres. In the wings of lines standard deviations are well below AIRS instrumental noise specifications (NEdT=0.1 K at 250 K scene temperature), and there is no inflation of error when passing from the dependent to independent profile sets. In line centres forward model errors are comparable with instrumental noise, and there is modest error inflation ($\sim$ 30 %) on passing from the dependent to the independent profile set.

These statistics can be compared with those reported for the AIRS simulations with RTTOV-7, based on a 117 profile subset of the 176 diverse profile set [Matricardi et al., 2001]. Biases for the RTAIRS model range from -0.05 to -0.1 K and standard deviations range from 0.1 to 0.2 K across the 1400–1600 cm^{-1} interval. Standard deviations are inflated by a factor of $\sim$2 on passing from the dependent to the independent profile set.

Jacobian error estimates

In Figure 2 we present results from the line-by-line validation of the Gastropod temperature and humidity Jacobians for the dependent profile set[1], as characterised by the Garand measure of fit [Garand et al.,

[1] Given the modest error inflation described above, these results should not differ significantly for an independent profile set – alternatively they can be interpreted as lower bounds for Jacobian measures of fit for an independent profile set.

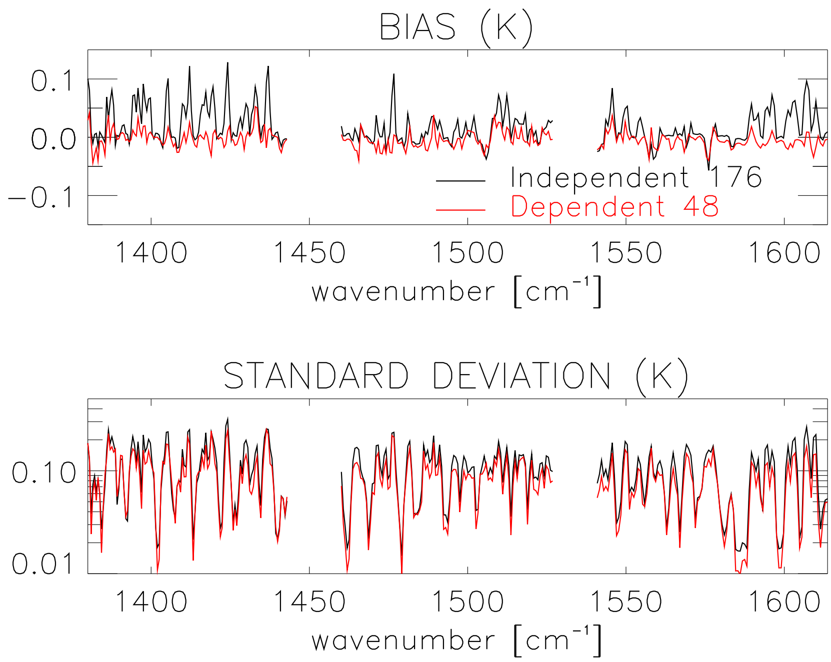

Figure 1: Line-by-line validation of the Gastropod forward model on the 1400–1600 cm^{-1} wavenumber interval. Bias and standard deviation [K] are illustrated for nadir view brightness temperature simulations for the dependent profile set (48 profiles, red curve), the full 176 ECMWF 50L diverse profile set (black curve).

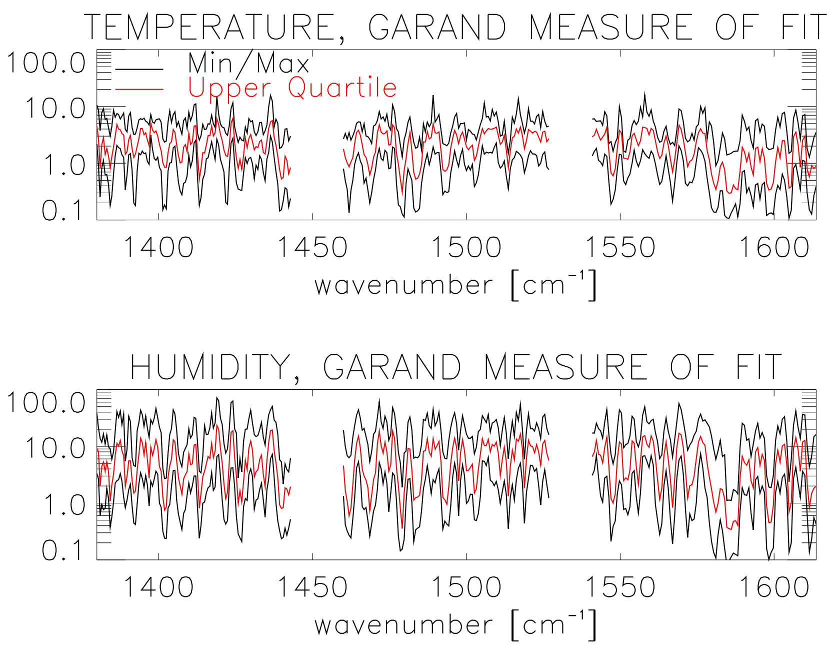

Figure 2: Line-by-line validation of Gastropod Jacobians for the dependent profile set. The minimum, maximum and upper quartile of the Garand measure of fit are illustrated for each channel, as a function of channel central wavenumber, for the 1400–1600 cm^{-1} interval. Results for temperature Jacobians dT_B/dT and humidity Jacobians $dT_B/dln(q)$ are illustrated in the upper and lower panels respectively.

2001]:

$$\text{Garand Measure of Fit}_{\,\mathrm{i}} \quad = \quad 100 \times \sqrt{\frac{\sum_{\mathrm{k}}(\nabla\mathcal{H}_{\mathrm{i,k}} - \nabla\mathcal{H}_{\mathrm{i,k,ref}})^2}{\sum \nabla\mathcal{H}^2_{\mathrm{i,k,ref}}}}$$

where i is the channel (wavenumber) index, k indexes profile elements, $\mathcal{H}(\mathrm{x})$ denotes the forward model and ref denotes reference values estimated by a line-by-line model. A Garand measure of fit of ≤ 10 is generally accepted as being indicative of well modelled Jacobians, while a measure of fit of ≥ 25 is considered indicative of serious errors in modelled Jacobians. Jacobian measures of fit for the dependent profile set are summarised by the minimum, maximum and upper quartile of the Garand measure of fit for each channel.

Temperature Jacobians are well modelled (Garand measures of fit ≤ 10) for all channels in the 1400–1600 cm^{-1} interval. As previously, maximum Jacobian errors occur in line centres. A similar spectral pattern is evident in the fitting results for humidity Jacobians. In this case, the Garand measure of fit is ≤ 10 for 75 $\%$ of all profiles at all wavenumbers, and in the wings of lines, the Garand measure of fit is ≤ 10 for all profiles. However in line centres 25$\%$ of profiles have Garand measures of fit of between 10 and 50. Some of these gross error cases were associated with dry atmospheres, where a small absolute error in Jacobians gives a large relative error. While undesirable, in these cases errors will arguably have a smaller impact in assimilation, as the weight accorded to the observations is lower. However there was a second class of profiles which have layered structure in upper tropospheric humidity, where the corresponding absorption is poorly predicted in the Gastropod model, and this was of more concern.

Thus, while Gastropod's description of water vapour absorption in line wings achieves high accuracy both in terms of forward model and Jacobian errors, the description of water vapour absorption in line centres was not deemed adequate, and a study was undertaken to improve the modelling for this absorption regime.

One of the major results of this study, detailed in Sherlock [2002], was the identification of a lead predictor for water vapour absorption in the ν_2 band which was absent from the predictor set proposed by Hannon et al. [1996] (and therefore not implemented in Gastropod). With the introduction of this predictor forward model errors in line centres are reduced to the 0.1 K level (significantly less than the instrumental noise at the scene temperature). Jacobian errors associated with structured upper tropospheric humidity profiles are markedly improved, with the maximum Garand measures of fit for humidity Jacobians of ≤ 20.

In our opinion, errors of this level would tend to preclude the existence of significant errors associated with the implementation of the regression based prediction of effective layer optical depth. As such they are deemed acceptable for a day one radiative transfer model. Spectroscopic uncertainties and the effects of non-linearity are expected to give significantly larger brightness temperature departures than the estimated forward model errors in this spectral region. Fast model accuracy should be adequate to allow these problems to be diagnosed.

Conclusions

To summarise the results presented here for the H_2O ν_2 band: with the exception of water vapour line centres, the Gastropod model as it stands gives accurate forward model and Jacobian calculations. Biases are of the order of 0.02 K and standard deviations are significantly less than the AIRS instrumental noise specification of 0.1 K at a scene temperature of 250 K. Further, these error characteristics are robust – there is little or no error inflation on passing from the dependent to the independent profile set, even in instances where there is a local extrapolation of the regression relations. Finally, Garand measures of fit are less than 10 for all profiles in the dependent set, for both temperature and humidity Jacobians.

These fitting errors are characteristic of Gastropod model errors in other spectral intervals covered by the AIRS instrument (CO_2 ν_2 and ν_3 bands, O_3 ν_1 and ν_3 bands and infrared window regions). Forward model errors are well below AIRS instrumental noise specification everywhere, except in water vapour line centres and the ozone band, where they are comparable with instrumental noise (but note no study has been undertaken to improve the description of ozone absorption to date). Jacobians are also well modelled, with Garand measures of fit generally less than 10 (upper quartiles less than 5) for both temperature and humidity Jacobians.

In water vapour line centres fitting errors are comparable with the AIRS noise specification, and poor Garand measures of fit were found for 25 % of the dependent profile set. The identification of a lead predictor for water vapour absorption on this spectral interval, which is absent from the predictor set proposed by Hannon et al. [1996] allows marked improvements in model performance in line centres. Standand deviations are reduced to the 0.1 K level, well below the AIRS instrumental noise specification at the corresponding scene temperature, and maximum Garand measures of fit are reduced to ≤ 20 for humidity Jacobians (< 10 for temperature Jacobians). Work to identify an optimal subset of predictors for water vapour line absorption is near completion, and will be included in an upcoming release of the Gastropod model.

The development of the Gastropod fast model results from careful, ongoing intercomparison and validation of fast radiative transfer models. Where performance of fast models has differed, we have sought to identify the origin of this difference, and to adopt the best modelling stategy in each case. We believe the performance achieved, particularly in the H_2O ν_2 band, testifies to the benefit of such an approach.

Acknowledgements

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