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Clear Sky Forward Model Development for GIFTS

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There is a current effort at the CIMSS/SSEC/UW-Madison to develop an accurate and efficient clear sky forward model for GIFTS (and other high spectral resolution sensors) with the various features required for atmospheric profile and radiance data assimilation in a NWP context. This includes development and validation of the underlying line-by-line absorption and radiative transfer models, efficient and representative parameterization of the line-by-line results, and development of analytical jacobians and adjoints of the parameterized model. This paper discusses our ongoing progress on the forward and adjoint model for the GIFTS satellite. Special attention is given on how to evaluate the models.

1. INTRODUCTION

Infrared hyperspectral sounding instruments with broad spectral coverage have the potential to provide unprecedented atmospheric profiling information.[1] Retreiving atmospheric parameters from these radiances requires accurate and fast radiative transfer algorithms. The associated tangent linear, adjoint, and k-matrix models are also needed to incorporate the radiances as a part of a NWP model.

Remote sensing of profile atmospheric conditions such as temperature, humidity and fixed gases depends on the ability to calculate observed radiances from the profile information; this is the “forward problem.” Line -by - line models which accurately compute atmospheric transmittance are too slow to be practical.

Generally, the “fast forward” model is developed with a training set of profiles spanning a large range of atmospheric conditions. Using the profiles, a line-by-line model calculates accurate transmittances. The transmittances are regressed against profile derived predictor values. The resulting coefficients can be applied to any profile to quickly calculate radiances.

Section 2 describes in greater detail the GIFTS clear sky forward model. How the model is evaluated is given in Section 3.

Often the calculated radiances are compared to observed radiances, and their differences are used in the adjoint model to calculate adjustments to the profile to match the observed radiances better. This is further discussed in Section 4.

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2. GIFTS CLEAR-SKY FORWARD MODEL PARTICULARS

The GIFTS forward model, “LBLRTM based PLOD fast model”, is developed under the framework of Pressure Layer Optical Depth (PLOD) [2]. At fixed pressure layers, regressions are made to line-by-line transmittance calculations obtained with LBLRTM[3]. LBLRTM is under constant improvement. Our LBLRTM runs used the HITRAN96[4] database with MTCKD[5] v1.0 H_2O & 15 μm CO_2 continuum.

The line-by-line transmittance data are monochromatic values, and need to be mapped to the GIFTS spectral domain. The mapping uses a maximum optical path difference of 0.872448 cm, with an effective spectral resolution of 0.6 cm^{-1}, and apodized[5] prior to performing the regression analysis.

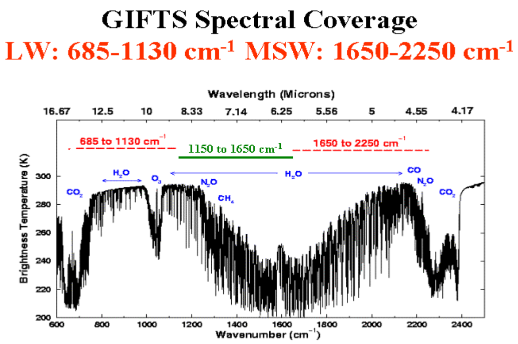
We use 32 training profiles from a NOAA database. Each profile has 100 vertical layers and are used at 6 satellite view angles. The predictors generated from the profiles are the same ones used in the AIRS instrument.

Three regressions are made at every layer for 3073 channels between 587 and 2347 cm^{-1}: one for fixed gases, H_2O, and O_3. Each gas type has its own set of predictors, and therefore, its own regression coefficients.

Figure 1 displays the current planned spectral coverage of GIFTS measurements with clear-sky brightness temperature calculated from the U.S. standard atmosphere.

3. EVALUATION OF MODEL

The accuracy of the forward model is judged by comparing model derived transmittance with line-by-line values for the training set of profiles; the dependent set statistic. The degree of accuracy goal is to be significantly below the instrument noise.


GIFTS Spectral Coverage

LW: 685-1130 cm^{-1} MSW: 1650-2250 cm^{-1}

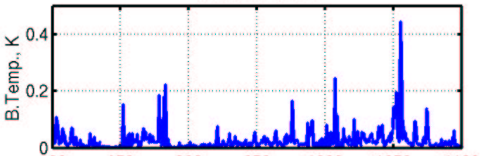
Fig. 1: GIFTS spectral coverage and its brightness temperature spectrum.

Regressions are made for different gas types. We evaluate them separately and combined. Figure 2 shows the RMS differences in brightness temperature for the region between 800 and 1100 cm^{-1}. The plots lines describe RMS errors for fixed gases (top), ozone (middle) and water vapor (bottom). Maximum brightness temperature errors occur in the strong absorbing lines of the water centers and in the ozone bands.

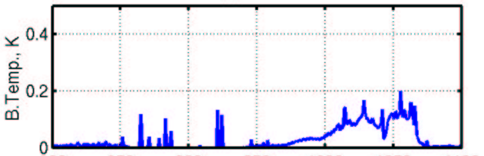
While at some bands the errors exceed the instrumental noise, these errors are greatly improved from the previous model. Ridge regression which is subject to singularities or ill conditioning, was replaced with SVD regression.

Other improvements include optical depth weighting. The accuracy of the forward model transmittance calculation is improved if the data is weighted before the regression is made. Radiative transfer is insensitive to layers where the change in the layer transmittance is near zero. So the layer optical depths and the total optical depths of all the layers above the layer under consideration are weighted with a bell shaped curve.[2]

(a) Fixed Gases



(b) Ozone



(c) Water Vapor

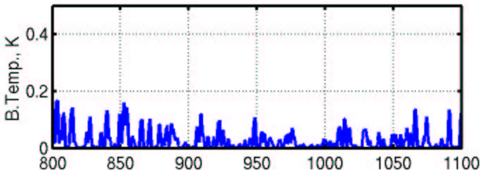


Fig. 2: RMS errors for dependent set profiles; fixed gases (top), ozone (middle), and water vapor (bottom).

The model will, of course, be used with profiles different from ones in the training set. Their accuracy, an independent set statistic, is related to both the dependent set statistics and how well our training profiles represent the given profiles. We have compared our 32 profiles from a NOAA database with other profile sets used in the forward modeling community and found them to be warmer and wetter in the troposphere. Future work will consider more carefully the impact of the chosen training profiles.

Our algorithm is flexibile to development changes. The code was rewritten to allow for future expansion of its capabilities which include reflected components, explicit assignment for other gases, extended satellite zenith angles, etc.

Speed is another consideration. The run time for our clear sky forward model is ~0.8 sec on a 1 GHz CPU. Although is will ultimately be an critical factor, our current emphasis is on accuracy.

4. ADJOINT MODEL

In meteorology, assimilating data into a model and sensitivity analysis are crucial. Whereas the forward model calculates the radiance given an atmospheric profile, the tangent linear model (TL) gives the perturbation in radiance given a perturbation in an atmospheric profile. The adjoint model (AD) is given by the transpose of the TL model, a powerful tool providing the perturbations of physical parameters for a given perturbation in radiance. One can iteratively minimize the difference between the forward model and the observations with a well-defined cost/penalty function.

Figure 3 illustrates the how the algorithms and data might work with one another. The top left panels shows a temperature profile, and its corresponding spectrum calculated using a forward model (top right panel).

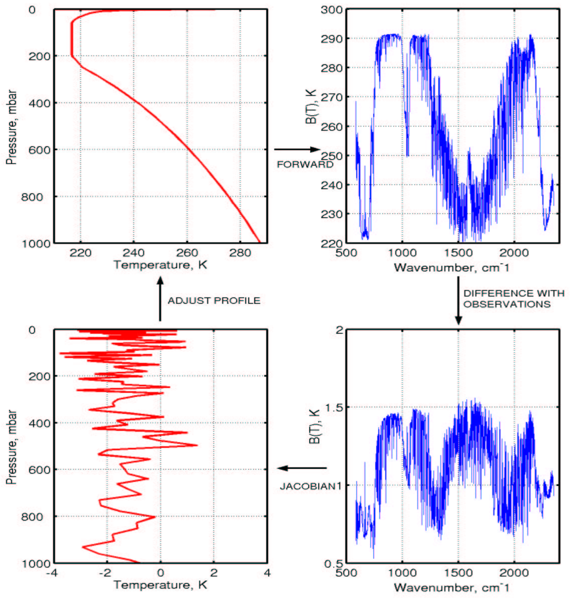


Fig. 3: Schematic of data flow through algorithms.

The spectrum is compared to

observations (the difference is shown in the bottom right panel). Then the difference is used with an adjoint model to derive profile temperature adjustments compatible with observations.

The tangent linear model is the linearization of the forward model about the initial condition, in our case, the profile. To test the TL model, varying perturbations are made to the initial condition and run through both the forward and TL models.

Figure 4 shows an example of the differences between the forward and TL models as a function of perturbations made to the temperature profile. As the name implies, the TL model must be linear for all perturbations and tangent to the forward model results when the perturbation is zero.

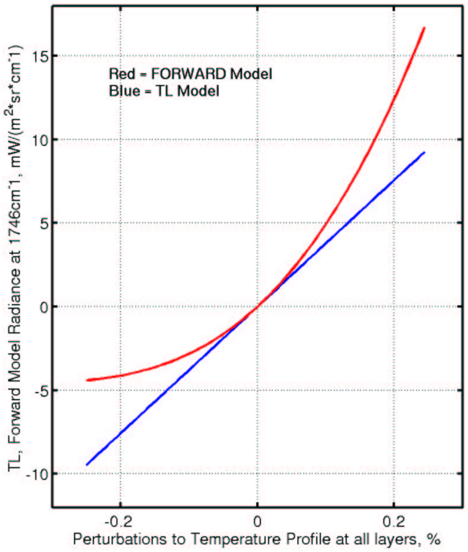


Fig. 4: Forward and TL model output for perturbations about the temperature profile input.

Writing the AD model is laborious but involves a well defined set of rules to be applied to the TL code. The methods of testing the codes are definitive; the comparison between the TL and AD must match to within machine precision.

Figure 5 is an example of the testing of the AD model for a subroutine which converts temperatures for 101 levels into 100 layer averaged temperatures. The AD operator has been thought of as running the TL in the reverse direction. Their differences must be zero.

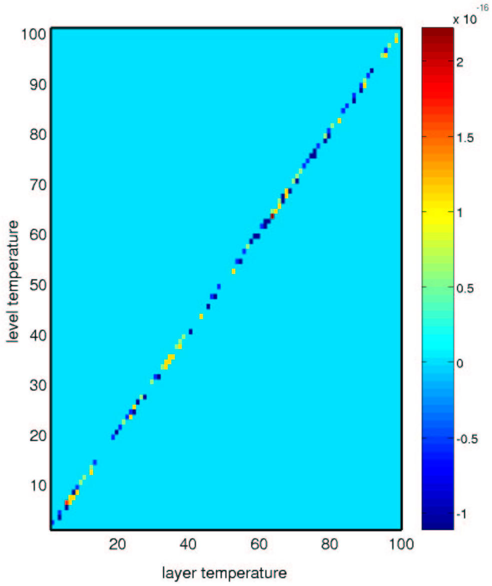


Fig. 5: Difference between TL and the AD code for converting level temperature values into layer averages.

The adjoint variables accumulate the sensitivities of each channel. By shifting the channel independent adjoint code to be inside the channel loop, a more useful Jacobian operator (or k-matrix code) is produced.[7]

CONCLUSIONS

The GIFTS clear sky forward model and its associated tangent linear and adjoint models are under development. Great improvements have been made in accuracy and efficiency.

The algorithm was rewritten to allow

for easy development testing and changes. Future expansion of its capabilities includes reflected components, explicit assignment for other gases, extended satellite zenith angles, etc.

The mean dependent set RMS error was reduced by more than half mainly due to the SVD and optical depth weighted regression. The largest improvements occurred in the water bands.

The tangent linear and adjoint code is complete and tested, but undergoing code improvements for efficiency and ease of use.

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