P5.32 KCARTA : A FAST PSEUDO LINE-BY-LINE RADIATIVE TRANSFER CODE WITH SCATTERING

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1. INTRODUCTION

Line-by-line radiative transfer algorithms are the basis for fast forward models used in the retrieval of atmospheric parameters from satellite measured radiances. As we begin the era of high-spectral resolution infrared sounding the availability of accurate, fast, and easy-to-use line-by-line models will become even more important. High-spectral resolution sensors, compared to the present wide-band filter-based sounders, will stress the accuracy of the line-by-line models. This is especially true for channels in-between spectral lines where difficult to model line-wing effects dominate. Note that these channels are also the best choices for sounding since they have sharper weighting functions than channel sitting on the top or sides of spectral lines.

We have previously developed a highly compressed pre-computed database of monochromatic atmospheric optical depths that is accurate, relatively small (600 Mbytes), and easy to use, Strow et al. (1998). We call the radiative transfer algorithm that uses this compressed database *kCARTA*, DeSouza-Machado et al. (1997), which stands for the k-Compressed Atmospheric Radiative Transfer Algorithm. The original version of the *kCARTA* optical depth database used *GENLN2* Edwards (1992) to generate the database.

Although *GENLN2* does include first-order CO_2 line-mixing, it does not include a physically-based model for P/R-branch CO_2 line-mixing or duration-of-collision effects, both of which are important for temperature sounding. Subsequently, we developed our own line-by-line code (in MATLAB) that includes all of these important effects, DeSouza-Machado et al. (1999). However, because accurate transmittance calculations of line-mixing and duration-of-collision effects using physically-based models is much more complicated, and far slower, than standard line-by-line calculations, this line-by-line code is quite slow, which is one reason we developed the *kCARTA* compressed look-up table approach.

Radiances computed using *kCARTA* are as accurate as those computed with a line-by-line code since our lossy compression algorithm procedure introduces errors well below spectroscopy errors. *kCARTA* can also provide very fast temperature and gas amount radiance Jacobians for sensitivity studies and retrieval algorithms.

In this paper we present an overview of the capabilities of *kCARTA* and introduce a new version that includes three scattering algorithms, *RTSPEC* Deeter and Evans (1998), *DISORT* Stamnes et al. (1998), and our own *TWOSTREAM* scattering code. The speed and relative simplicity of our compressed database allows us to easily interface it to other codes with almost no performance penalty. *DISORT* is interfaced to *kCARTA* primarily to easily test the accuracy of other scattering approximations, since it is often too slow for many monochromatic applications.

2. OVERVIEW OF *kCARTA*

The *kCARTA* database currently spans 605 to 2830 cm^{-1} at a point spacing of 0.0025 cm^{-1}. Each of these 0.0025 cm^{-1} points is an average of five points on a 0.0005 cm^{-1} grid centered about each 0.0025 cm^{-1} grid point. Thus *kCARTA* is not truely monochromatic, although for both existing and planned satellite instruments, it can be considered monochromatic for all practical purposes. The compressed optical depths are tabulated for 11 temperatures covering all possible atmospheric conditions. The default layering of the atmosphere is 100 layers, which are the same as those used for the *AIRS* (Atmospheric InfraRed Sounder, Aumann and Pagano (1994)) fast forward model Hannon et al. (1996).

Generation of monochromatic transmittances from

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this database for an arbitrary Earth atmosphere temperature, pressure and gas amount profile is more than an order of magnitude faster than using a line-by-line code. Interpolation to arbitrary profile layering in temperature and pressure can be done using the compressed version of the optical depths, leading to significant compute savings. Both up- and down-welling radiance computations are possible, although limb-viewing is not supported.

kCARTA serves as the *AIRS* "Reference Forward Model" and is used to generate the *AIRS* fast forward model Hannon et al. (1996) and to validate the *AIRS* radiance products.

For a downward looking instrument in a clear sky, the surface and layer emission terms are automatically included in the radiative transfer calculation. In addition, reflected background thermal and solar terms can also be included. The reflected thermal contribution is accurately computed at each spectral point by using a diffusive angle that varies with the layer to ground absorption, instead of $\arccos(3/5)$ at each layer. The program can either assume a plane parallel atmosphere, or include effects on the satellite viewing angle due to the curvature of the earth.

While uncompressing the database, *kCARTA* can compute the gas amount *and* temperature radiance Jacobians very rapidly DeSouza-Machado et al. (1997). Jacobians are very useful in analyzing which part of the atmosphere the radiance is most sensitive to a change in the amount of one of its constituents and/or temperature.

Radiative fluxes can also be computed by computing radiance intensities at various angles for each layer. The speed of *kCARTA* makes it an attractive alternative to other existing "line by line" codes for radiance and flux calculations.

3. SCATTERING

If an atmosphere is to be modeled more realistically, the effects of clouds and/or aerosols should be included. For infrared applications, especially for small particle clouds, relatively simple scattering approaches can be quite accurate. The speed gain with a simple two-stream approach, for example, is extremely important for a pseudo-monochromatic codes such as *kCARTA* and it's application to the high-spectral resolution radiances that will be measured by *AIRS*.

The radiative transfer equation to be solved is Deeter and Evans (1998); Liou (1980) :

$$\mu \frac{dI(\nu)}{d\tau_e} = I(\nu) - B(\nu,T)(1-\omega_0) -$$

$$\frac{\omega_0}{2} \int_{-1}^{+1} I(\nu,\tau_e,\mu\prime) P(\mu,\mu\prime) d(\mu\prime) -$$

$$\frac{\omega_0}{4\pi} \pi F_{sun} P(\mu,-\mu_{sun}) e^{-\tau_e/\mu_{sun}}$$

This involves an integral over the intensities at various angles, weighted by a phase function P. I is the radiance at viewing angle $\arccos(\mu)$, $B(T)$ is the Planck radiance at temperature T, ω_0 is the single scattering albedo and F_{sun} is the incident solar flux. Depending on the number of stream angles intensities used to evaluate the integral, one has a n stream solution to the problem.

kCARTA has been interfaced with two well known scattering packages, *DISORT* Stamnes et al. (1998) and *RTSPEC* Deeter and Evans (1998). *DISORT* can include the effects of solar beam scattering but is quite slow. *RTSPEC* uses two streams to compute the solution, and is very fast; however it does not include the effects of solar beam scattering. Our *TWOSTREAM* scattering package includes solar beam scattering and is fast.

Similar to *DISORT* and *RTSPEC*, *TWOSTREAM* uses an exponential-in-tau layer temperature variation in the cloudy layers, while it uses an average layer temperature in the clear layers. Background thermal is also included for a down-looking instrument. *TWOSTREAM* computes the reflection, transmission, emission and beam coefficients for the cloud by adding together the coefficients for the individual cloud layers. As interfaced, the three scattering codes assume that the cloud particles are spheres (Mie scattering); however more general routines could be used to compute the phase function, single scattering albedo and asymmetry factor for other particle shapes, and used in any of the three algorithms.

Figure 1 shows a comparison run of the three scattering codes in the infrared for a nighttime down-looking instrument for a 1 km thick cirrus cloud. One can see that the three agree very well with each other, even though *DISORT* uses more than two streams, as compared to *RTSPEC* and *TWOSTREAM* that each use two. The main use of this code will be in the window regions, where the agreement is quite good. *RTSPEC* is a little more accurate than our *TWOSTREAM* code, but as stated earlier, *RTSPEC* cannot do solar scattering.

On a Linux PC *kCARTA* can compute the clear-sky up-welling radiance from 605 to 2830 cm^{-1} in approximately 5 minutes using the 100 *AIRS* layers. Introducing a 3-layer cloud, our *TWOSTREAM* algorithm takes about 20% more time than the clear-sky calculation.

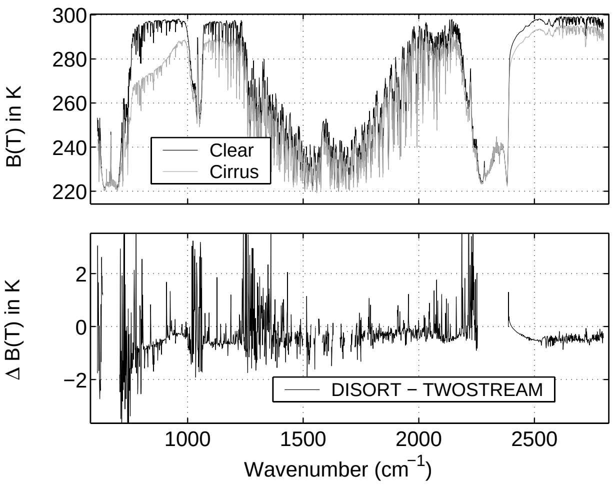

Figure 1: Clear sky vs cloudy sky computations, from Ground to TOA. A 1 km thick cirrus cloud is at 10 km in a US Standard Atmosphere, with average particle size of 10 μm and IWP = 2 g/m^2

Our initial use of this new capability of *kCARTA* will be to measure cirrus cloud properties using *AIRS*, and using a new high-resolution radiometric interferometer we are presently installing on Mauna Lao in Hawaii.

4. CONCLUSIONS

kCARTA is a fast pseudo line-by-line code which offers the user many desirable features. It provides very fast line-by-line accuracies, and the accuracy of its spectroscopic database has been extensively compared against *GENLN2*, although with the inclusion of P/R-branch line-mixing and duration-of-collision effects *kCARTA* will now produce somewhat different radiances than *GENLN2* in some CO_2 regions. Analytic temperature and gas amount clear sky Jacobians are rapidly computed. The computed radiances include the solar contribution as well as an accurate estimate of the background thermal. The package can allow the user to include the effects of scattering as well, with three package choices being available. The three packages give roughly the same results for the same conditions.

5. ACKNOWLEDGMENTS

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References

Aumann, H. H. and R. J. Pagano: 1994, Atmospheric Infrared Sounder on the Earth Observing System. *Optical Engineering*, **33**.

Deeter, M. and K. Evans: 1998, A hybrid eddington-single scattering radiative transfer model for computing radiances from thermally emitting atmospheres. *J.Quant.Spectrosc.Radiat.Transfer*, **60**, 635–648.

DeSouza-Machado, S., L. Strow, and S. Hannon: 1997, kCompressed atmospheric radiative transfer algorithm (kCARTA). *Satellite Remote Sensing of Clouds and the Atmosphere*, Proceedings of the European Symposium on Aerospace Remote Sensing #3220, Europto Series, Institute of Electrical Engineers, London, Great Britain.

— 1999, Improved atmospheric radiance calculations using CO_2 P/R branch line mixing. *Satellite Remote Sensing of Clouds and the Atmosphere*, Proceedings of the European Symposium on Aerospace Remote Sensing #3867, Europto Series, Florence, Italy.

Edwards, D.: 1992, Genln2: A general line–by–line atmospheric transmittance and radiance model. *NCAR Technical Note 367+STR*, National Center for Atmospheric Research, Boulder, Colo.

Hannon, S., L. L. Strow, and W. W. McMillan: 1996, Atmospheric infrared fast transmittance models: A comparison of two approaches. *Proceedings of SPIE Conference 2830, Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research II*.

Liou, K.: 1980, *An Introduction to Atmospheric Radiation*. Academic Press.

Stamnes, K., T. S-C., W. W., and K. Jayaweera: 1998, Numerically stable algorithm for discrete ordinate method radiative transfer in multiple scattering and emitting layered media. *Appl. Opt.*, **27**, 2502–2509.

Strow, L., H. Motteler, R. Benson, S. Hannon, and S. De Souza-Machado: 1998, Fast computation of monochromatic infrared atmospheric transmittances using compressed look-up tables. *J. Quant. Spectrosc. Rad. Trans.*, **59**, 481–493.