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Fast radiative transfer in multiple scattering atmospheres at far and mid infrared wavelengths

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Abstract. Recognizing the value of Far Infrared Region (FIR) observations, in September 2019, the European Space Agency (ESA) selected FORUM (Far-infrared Outgoing Radiation Understanding and Monitoring) as the 9th Earth Explorer (EE9) (Palchetti et al., 2020) whose launch is foreseen in 2027. FORUM, dedicated to mapping Earth's far-infrared emission globally, will produce an enormous quantity of new data, requiring the implementation of fast radiative transfer models applicable to the entire IR spectral region for an effective data exploitation and analysis. Full physics models (i.e. DISORT, Stamnes et al., 1988) rely on robust and accurate numerical methodologies to solve the radiance field in presence of multiple scattering events for specific scenarios. The complexity of the multiple scattering effects makes this class of models extremely time consuming and inappropriate for large dataset analysis. To save computational time, fast radiative transfer models adopt multiple strategies which might account for approximation of the physical problem, simplified numerical solutions, code parallelization, and the extensive use of parametrizations. In the first part of this study, we investigate the level of accuracy of the Chou's approximation (Chou et al., 1999), a fast methodology, widely used in operative frameworks for its simplicity and easy implementation. The performance of this approximate solutions is evaluated with respect to a full-physics approach over a widespread collection of atmospheric scenarios using the goal NESR of FORUM as reference metric. The results show not negligible inaccuracies when the Far InfraRed (FIR) is considered (Martinazzo et al., 2021). In the second part the study, to reduce the bias of the Chou scaling method, a correction term is modelled and computed using the solution recently proposed by Tang (Tang et al. 2018). The Tang methodology, originally created to refine the Chou flux computations, is here adapted to simulations of radiance fields over the FIR spectral range, exploiting appropriate multiplicative coefficients. The range of validity of the new methodology is then evaluated, as already done for the Chou scheme, by comparing this fast solution against full physics simulations. The comparisons show an overall reduction of the radiance residuals overs most of the cloudy cases encountered in nature. In particular, the use of the Tang methodology with the new coefficients is accurate for the computation of radiance fields in presence of thin cirrus clouds which are one of the targets of the FORUM mission.

METHODOLOGY AND RESULTS

The Chou approximation allows to save computational time by avoiding the direct computation of the multiple scattering. In this scheme, the scattering contribution is accounted for by replacing the extinction optical depth (τ) of each atmospheric layer with an apparent absorption optical depth ($\tilde{\tau}$), given by:

$$\tilde{\tau} = (1\text{-}\omega)\tau + b\omega\tau \qquad (1)$$

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Where b is called Chou's backscattering parameter and quantifies the hemispheric backscattered radiation. In this work, b is accurately computed based on realistic particle size distributions of liquid water and ice particles and by exploiting state of the art optical properties databases.

Applying the Chou approximation, the radiative transfer equation become a Schwarzschild-like equation, whose solution is easy and fast to obtain:

$$\mu \frac{d\,I(\mu)}{d\,\tilde{\tau}} = I - B \tag{2}$$

Where μ is the cosine of the observation angle, $I(\mu)$ is the radiance in the direction μ and B is the Planckian emission term. In this analysis, top of the atmosphere synthetic spectral radiances are computed for each scenario by considering alternatively an accurate and time-consuming methodology, such as the discrete ordinate solution (DISORT), or the approximate methodologies. The residuals are evaluated at far- and mid-infrared wavelengths and compared with the goal noise of the future 9th Earth Explorer FORUM satellite sensor. In case of both water and ice cloud scenarios, the approximate solutions perform well in the mid infrared for most of the cases studied. When the FIR region is considered, the discrepancy can be significant in accordance with the observational conditions accounted for in the simulations. Figure 1 shows the differences between the Chou solution and the full-physics solution at $410\ cm^{-1}$ for a mid-latitude atmosphere (50°N) at the nadir. In this example, column aggregate ice clouds are considered.

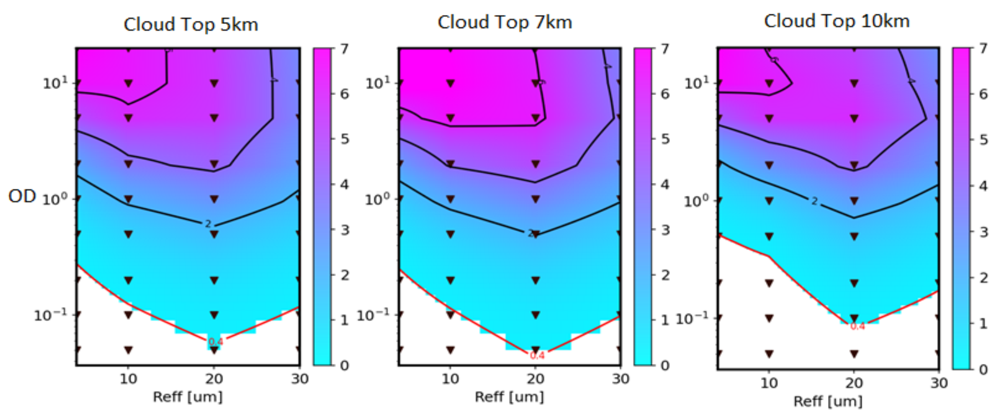

FIGURE 1: Radiance (ΔL, contour in $\frac{mW}{m^2\ sr\ cm^{-1}}$) differences between Chou's solution and full-physics approaches at 410 cm−1 (FIR), for ice clouds. The white color indicates differences below the FORUM noise level, marked by the red contour line. Y-axes are in log scale.

To reduce the computational errors of this basic scaling method, a correction term is modelled and computed using the solution proposed by Tang et al. (2018) which assumes a downward radiance term not necessarily equal to the blackbody radiance, as is done in Chou's approximation. Under this scheme, the equations of the radiative transfer become:

$$\begin{cases} \mu \frac{d\,I(\mu)}{d\tilde{\tau}} = I - B, & \mu < 0 \\ \mu \frac{d\,I(\mu)}{d\tilde{\tau}} = I - B - \frac{\omega\, b}{1-\omega(1-b)}[I(-\mu) - B], & \mu > 0 \end{cases} \tag{3}$$

Solving this set of differential equations allows to obtain a correction term I'' for the Chou routine. The correction for the upward radiance at the top of the single n-*th* cloud layer is given by:

$$I''_n = \frac{1}{2} \frac{\omega\, b}{1-\omega\,(1-b)} \left[(I_n(-\mu) - B_n) - (I_n(-\mu) - B_n) e^{-2(\tilde{\tau}_{n-1} - \tilde{\tau}_n)/\mu} \right] \tag{4}$$

As suggested by Tang in his article, based on numerical simulations, a correction coefficient k is used to replace the $\frac{1}{2}$ coefficient in the above equation (correction term).

$$I''_n = k \frac{\omega\, b}{1\text{-}\omega\,(1\text{-}b)} [(I_n(\text{-}\mu)\text{-}B_n) - (I_n(\text{-}\mu)\text{-}B_n) e^{-2(\tilde{\tau}_{n-1}-\tilde{\tau}_n)/\mu}] \tag{5}$$

High spectral resolution simulations are performed to derive the correctional k coefficient as a function of the viewing angle μ. The values of k for each different scenario are obtained as the fraction between the integrals over the FIR of Chou residuals (ΔI_{chou}) and the total correction term at the top of the atmosphere.

$$k = \frac{1}{2} \frac{\int_{v1}^{v2} \Delta I_{chou}\, dv}{\int_{v1}^{v2} I''\, dv} \tag{6}$$

Where the integration is calculated over the spectral interval $[v_1, v_2]$. The resulting coefficients are then parametrized as a second order polynomial function of the reciprocal of the effective radius of the particle size distribution of the considered cloud. Figure 2 shows the values of the k coefficient and its polynomial parameterization for ice clouds in the FIR. The results are obtained considering an observation angle $\mu=1$.

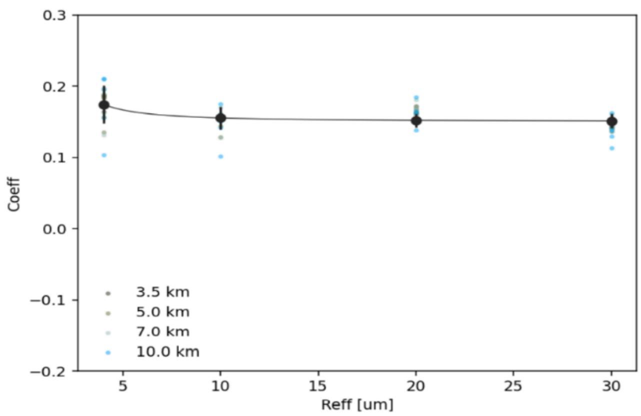

FIGURE 2: Adjustment coefficient k calculated for an ice cloud at the FIR and parameterized as a function of the effective radius of the cloud particle size distribution. The black bars show the variance around the fit point. The coefficients are computed considering a nadir observation angle.

This new set of coefficients, together with the Tang routine, is used to simulate the solutions of the radiative transfer problem in the same scenarios already considered for the Chou scheme analysis. Figure 3 shows the differences between the Tang solution and the full-physics solution at $410\ cm^{-1}$ for a mid-latitude atmosphere (50°N) at the nadir. In this example, a column aggregate ice cloud is considered.

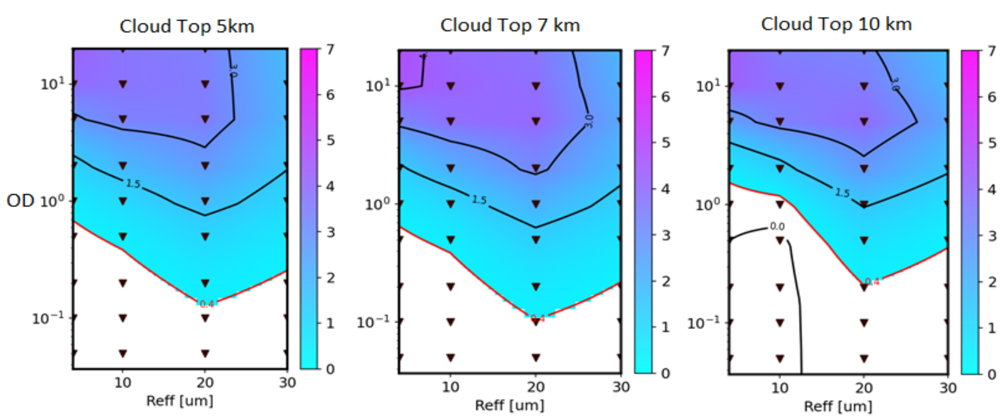

FIGURE 3: Radiance (ΔL, contour in $\frac{mW}{m^2\ sr\ cm^{-1}}$) differences between Tang's solution with the coefficients and full-physics approaches at 410 cm−1 (FIR), for ice clouds. The white color indicates differences below the FORUM noise level, marked by the red contour line. Y-axes are in log scale.

CONCLUSIONS

The application of the new methodology shows a reduction of the radiance residuals overs most of the cloudy cases encountered in nature. In particular, the use of the Tang methodology with the new coefficients is accurate for the computation of radiance fields in presence of thin cirrus clouds which are one of the targets of the FORUM mission. Note that the multiplicative coefficients are computed for the zenith view as well as for 4 additional Gaussian angles (not shown), allowing an angular characterization of the whole radiance field and a fast and accurate computation of fluxes by Gaussian quadrature. Nevertheless, inaccuracies are still encountered for medium-large optical depths (OD>1) and small effective radii, highlighting the need for more accurate approaches to envisage all possible cloudy conditions. Finally, the whole set of radiative parameters needed to solve the radiative transfer equation using the previously described approximations is parametrized by mean of polynomial functions of the effective dimension of the cloud particle size distribution. The parametrized parameters are then implemented in the sigma-FORUM code, a forward model designed for the fast calculation of radiance and its derivatives with respect to atmospheric and spectroscopic parameters of nadir-looking hyperspectral instruments. The σ-FORUM model is an updated version of sigma-IASI model (Amato et al., 2002), a monochromatic radiative transfer model based on a look-up table of optical depths parametrized as a polynomial concerning the atmospheric temperature and constituents. The strategy enables fast, accurate radiance and analytical derivatives calculations in clear sky or in presence of cloud and aerosol layers.

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