Fast spectral radiance computations in cloudy conditions at far and mid infrared wavelengths using the σ-IASI-F2E code

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Introduction

A fast radiative transfer model (σ-IASI-F2E) is presented for application to large dataset of high spectral resolution radiances in presence of clouds at far and mid infrared wavelengths.
The algorithm exploits a correction term which is modeled and computed using the Tang methodology, originally designed to refine the Chou flux computations. This methodology is adapted to simulate cloudy radiance fields at any observational angles, using appropriate multiplicative coefficients to reduce bias in the Chou scaling method.
The validity of the new methodology is evaluated by comparison with a full physics code. The results show that the Tang methodology with the new coefficients is more accurate than the Chou scheme for the computation of radiance fields, especially in the presence of thin cirrus clouds, which are among the targets of the FORUM mission.

Approximate Methodologies

Chou Approximation

The Chou scaling solution, initially applied for fluxes computations, is adapted for radiances. Improved backscatter parameters are computed for updated ice and liquid water PSDs [Martinazzo et al., 2021]. The scattering contribution is accounted for by replacing the optical depth (τ) with an apparent optical depth for extinction:

$$\tilde{\tau} = (1-\omega_0)\tau + b\omega_0\tau$$

The main assumptions are:

- Downwelling radiation is equal to the blackbody emission of the layer.
- The radiation field is isotropic in the two hemispheres.

Tang's Adjustment Scheme

It is a correction routine designed to improve scaling approximations. Also, this routine is nicely applied to fluxes computations.
Unlike the Chou scheme, the Tang methodology does not assume the downward radiance ($I(-\mu)$) to be equal to the blackbody emission from the layer. Otherwise, the $I(-\mu)$ is computed (using a Chou approx.).
A correction term is obtained by solving:

$$\mu\frac{dI'}{d\tilde{\tau}} = I'(\mu) - \frac{\omega_0 b}{1-\omega_0(1-b)}[I(-\mu) - B]$$

Tang's Adjustment Scheme for Radiances Computation

The adjustment scheme proposed by Tang et al. (2018) in the context of the fluxes computation results in a correction term which has the following form (for a single layer):

$$I'_n(\mu) = \frac{1}{2}\frac{\omega_0 b}{1-\omega_0(1-b)}\left[I(-\mu)_n - B - (I(-\mu)_n - B)e^{-2(\tilde{\tau}_{n-1}-\tilde{\tau}_n)/\mu}\right]$$

- $I(-\mu)_n$ is the downward radiance computed using the Chou approximation,
- $\tilde{\tau}_n$ is the apparent optical depth from the layer n to the top of the atmosphere (TOA).

Based on numerical simulations, Tang et al. (2018) suggests to substitute the ½ coefficient with 0.3 for a better description of the upwelling fluxes. Following the same approach, a coefficient k is used to extend the application of this correction routine to upwelling radiances calculation.

$$I''_n(\mu) = \boldsymbol{k}(\mu)\frac{\omega_0 b}{1-\omega_0(1-b)}\left[I(-\mu)_n - B - (I(-\mu)_n - B)e^{-2(\tilde{\tau}_{n-1}-\tilde{\tau}_n)/\mu}\right]$$

A set of coefficients $\boldsymbol{k}(\mu)$ are computed for a multiple set of:

- observational angles,
- particle type (**ice columnar aggregate and liquid water sphere**),
- effective radius of the particle size distribution.

The coefficient accounts for the anisotropy of ambient radiation which is not considered in the original scheme.

Coefficients Computation

Code chain (figure 1.) used to quantify the impact of scaling methods in the computation of the spectral radiances, the focus is on the FIR-MIR spectral region that will be observed by the 9th ESA Earth Explorer mission: FORUM

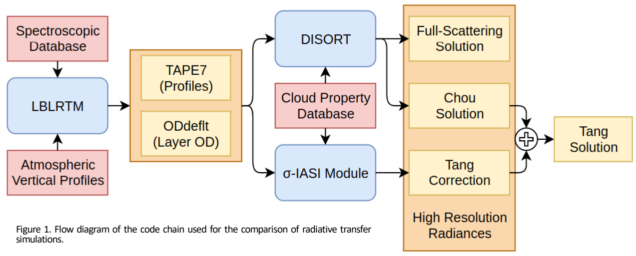

Figure 1. Flow diagram of the code chain used for the comparison of radiative transfer simulations.

Given the total correction $I''(\mu)$ at the TOA, the coefficient $k(\mu)$ is computed as:

$$k(\mu) = \frac{1}{2}\frac{\int_{\upsilon_1}^{\upsilon_2}\Delta I_c(\mu)d\upsilon}{\int_{\upsilon_1}^{\upsilon_2} I'(\mu)d\upsilon}$$

- ΔI_c are the differences between the Chou solution and the full-physics approach,
- $[\upsilon_1, \upsilon_2]$ is a spectral interval representative of the FIR or MIR.

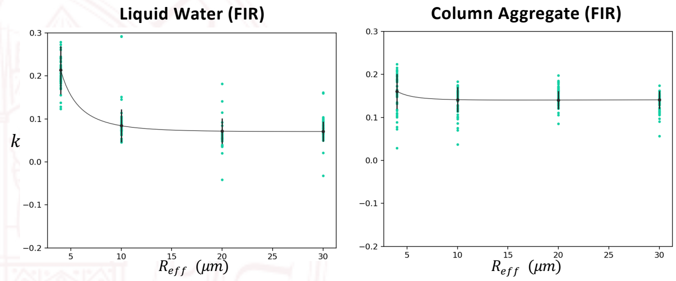

Figure 2. Table containing the coefficients k values (green dots) and parameterization (black line) for a liquid water cloud and an ice cloud. The results are shown for a nadir looking geometry.

The value of the coefficient $k(\mu)$ is then parametrized as a second order polynomial of the inverse of the effective radius.

$$k(\mu) = c_0 + c_1\frac{1}{R_{eff}} + c_2\frac{1}{R_{eff}^2}$$

The angle dependence of $k(\mu)$ is provided for zenith observations plus 4 Gaussian angles thus the computation of fluxes is available.

Results

The new σ-IASI-F2E code implements the improved Chou parameters b (below reported using the same parametrization proposed by Chou) and Tang methodology with new correction coefficients k(μ).

$b = \sum_i a_i\, g^{i-1}$

Chou Parameter	a_0	a_1	a_2	a_3
Column Aggregate	0.500	0.288	0.555	-0.343
Liquid Water	0.500	0.445	-0.319	0.374

In the σ-IASI-F2E code, the b parameters are provided as a 6° order polynomial function of the inverse effective radius for each wavenumber.

Tang k expansion	c_0	c_1	c_2
Column Aggregate FIR	0.143	-0.069	0.570
Column Aggregate MIR	-0.063	1.091	-3.328
Liquid Water FIR	0.074	-0.206	3.055
Liquid Water MIR	0.022	-0.636	3.435

The code allows fast monochromatic (0.01 cm-1) radiance computations in presence of all types of scattering layers (clouds and aerosols).
The scattering radiative properties are parametrized in terms of the PSD effective dimensions thus analytical jacobians can be generated and the michrophysical properties can be retrieved.

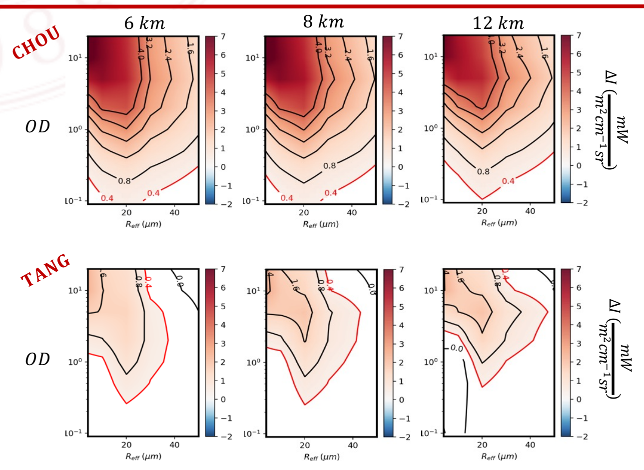

Figure 3. Radiance (ΔI, contour) differences between approximate solution and the full-physics code at 410 cm^{-1} (FIR), for ice column aggregates, considering a Mid-Latitude atmosphere. The white regions highlight the difference values below the FORUM noise goal, denoted by the red contour line. Y-axes are in log scale.

Conclusions

- In case of both water and ice cloud scenarios, the approximate solutions (improved Chou and Tang with correction coefficients) are accurate (within the FORUM NESR) in the MIR.
- The new Tang methodology significantly improves radiance computations with respect to Chou approximation. At FIR wavelengths, most of thin cirrus clouds are simulated within the FORUM NESR.
- The new Tang adjustment scheme is implemented in the σ-IASI-F2E code; all cloud radiative properties are parametrized in terms of effective radius thus allowing the computation of analytical derivatives for multiple observational angles.

[1]: M. Martinazzo et al., *"Assessment of the accuracy of scaling methods for radiance simulations at far and mid infrared wavelengths"* (2021), DOI: https://doi.org/10.1016/j.jqsrt.2021.107739
[2]: U. Amato et al., *"The σ-iasi code for the calculation of infrared atmospheric radiance and its derivatives"*, (2002), DOI: 10.1016/S1364-8152(02)00027-0
[3]: Tang et al., "Improvement of the Simulation of Cloud Longwave Scattering in Broadband Radiative Transfer Models" (2018). DOI: https://doi.org/10.1175/JAS-D-18-0014.1.