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On Fast Computations of Upwelling Far- and Mid-Infrared Radiances for All-Sky analysis

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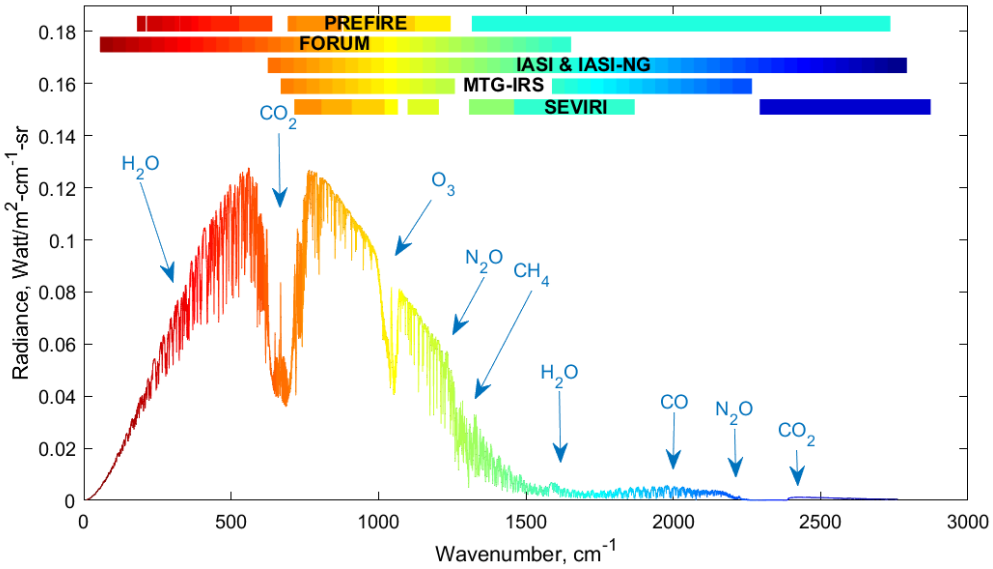
σ-FORUM (σ-IASI/F2N) - forward model

σ-FORUM (*https://zenodo.org/record/7019991#.Y3ns-S8w1B3*) is a fast, accurate physical rt model derived from the σ-IASI code (originally developed by University of Basilicata). It is currently under development in the FIT-FORUM project supported by ASI (PI: Univ. of Bologna)



Main Features

- Spectral range 5-3000 cm^{-1}
- Resolution: 0.01 cm^{-1} (adjustable)
- Gas OD databases (parametrized in T and concentration)
- Clouds and aerosols properties (parametrized – r_{eff} and concentration)
- In the presence of scattering layers the code accounts for a Chou+Tang solution
- Analytical Derivatives

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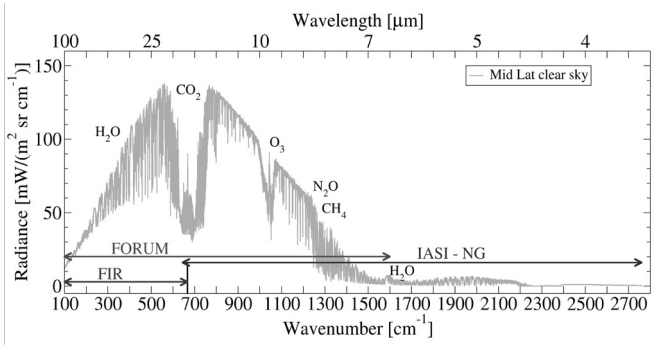
Why a fast, physical RT model?

The **FORUM** mission (ESA 9th Earth Explorer) will observe the FIR part of the spectrum which has never been observed spectrally from space before with the same accuracy.



Our knowledge of some important processes is still poor. Two examples:

Spectroscopy

- The knowledge of water vapor continuum absorption is still subjected to large uncertainties (especially at low temperatures and low pressure)

Cloud microphysics and optics

- The 410 cm^{-1} minimum in the imaginary part of the refractive index of ice enhances the role of scattering at FIR. Cirrus scattering properties at FIR are strongly dependent on crystal shape.
- Ice refractive index at FIR depends on temperature. Currently this dependency is not accounted for in reference database.

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Tang's adjustment scheme implementation

The contribution from a single layer is given by:

$$I^n_{tang} = \boldsymbol{k}_{tot} \frac{\omega_{tot} b_{tot}}{[1-\omega_{tot}(1-b_{tot})]} \left[\left(I^{\downarrow}_n - B_n\right) - \left(I^{\downarrow}_n - B_n\right) e^{-2\tau^*_n} \right]$$

Where the apparent optical depth of the layer is:

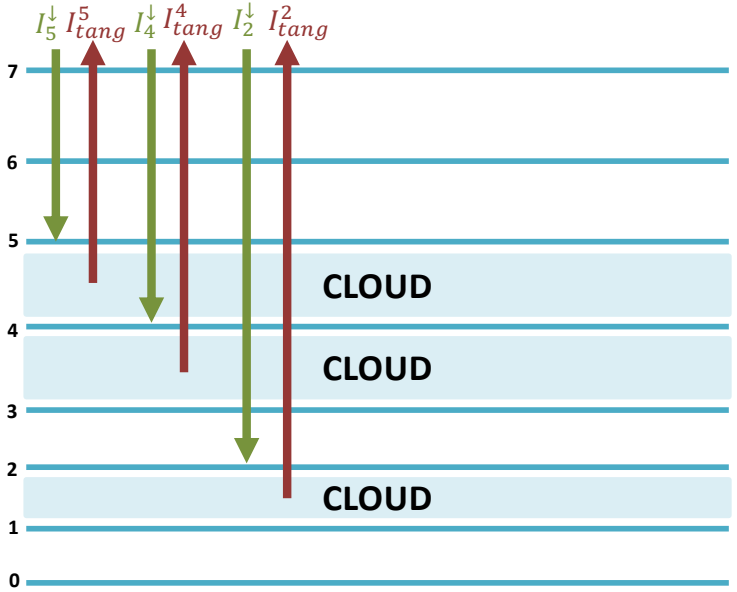
$$\tau^*_n = [1-\omega_{tot}(1-b_{tot})]\tau_n$$

And the optical properties τ_n, b_{tot}, ω_{tot} and k_{tot} are calculated for the whole layer (particles and gas).

In case of liquid and ice phase in the same layer:

$$\omega_{tot} = \frac{\beta^{sca}_{ice} + \beta^{sca}_{wat}}{\beta^{ext}_{ice} + \beta^{ext}_{wat} + \beta^{ext}_{gas}} \qquad b_{tot} = \frac{b_{ice}\beta^{sca}_{ice} + b_{wat}\beta^{sca}_{wat}}{\beta^{sca}_{ice} + \beta^{sca}_{wat}}$$

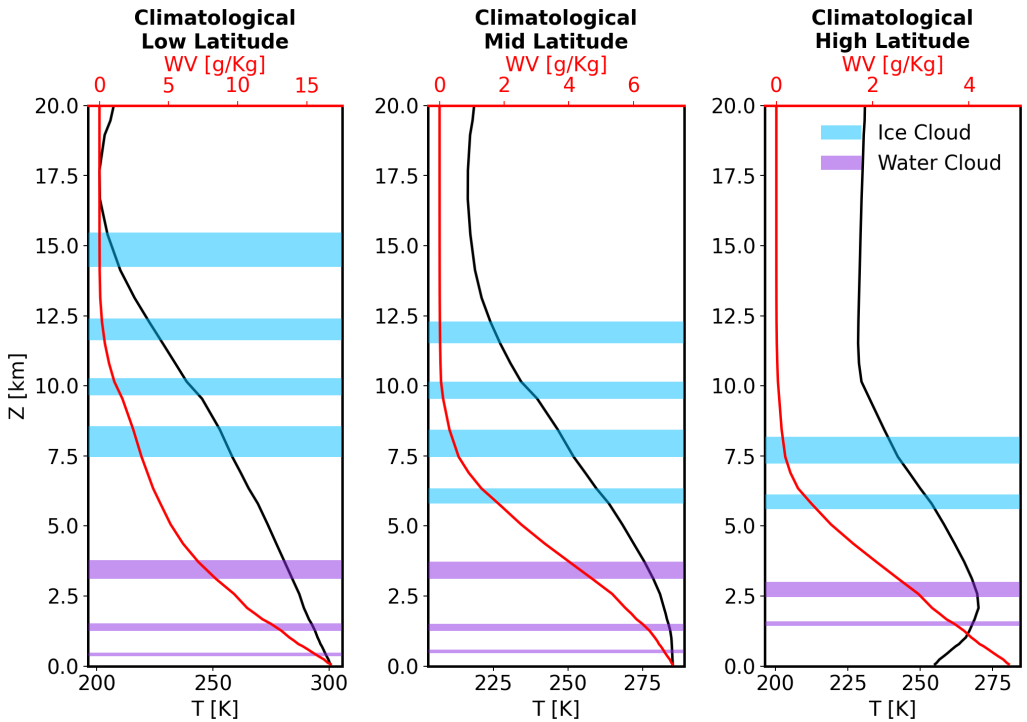
where the coefficient β in [1/m]



New quantities computed by σ-FORUM.

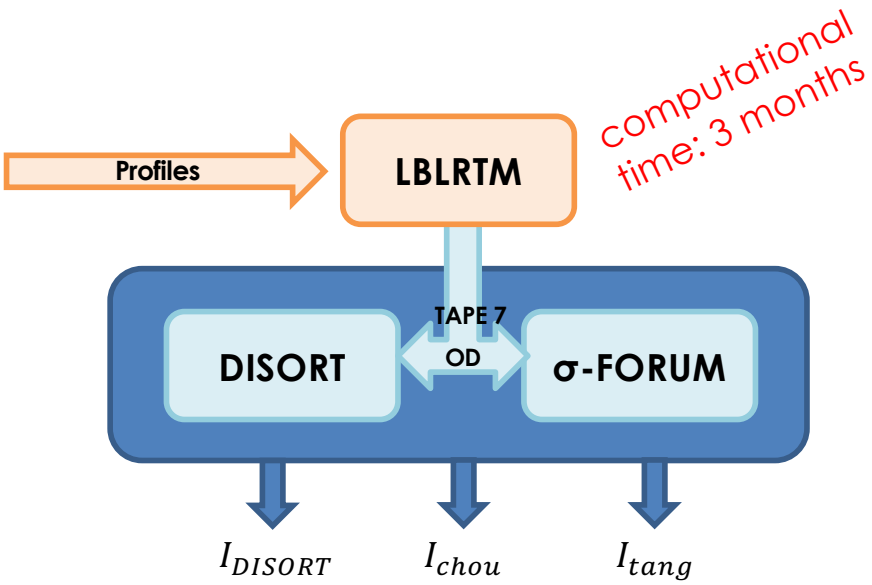
Tang's coefficients (k) computation

Adjustement coefficients are derived by comparison with a 32 stream disort solution



	Effective Radii	OD	Height
Liquid Water	4-30 μm	1-50	0.5-3.5 km
Columnar Aggregate	4-100 μm	1-20	6.0-15.0 km

Range of properties used for the calculation of k.



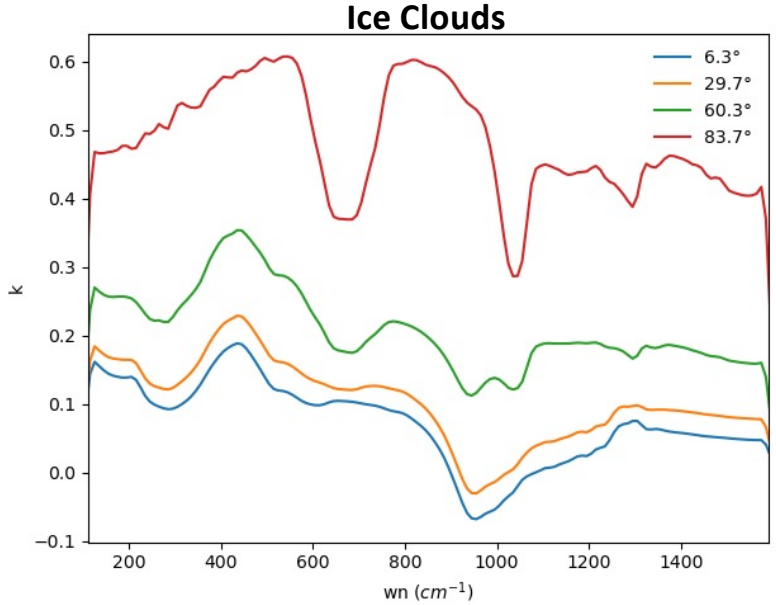
$$\Delta I_v(\mu) = I_{chou,v}(\mu) - I_{DISORT,v}(\mu)$$

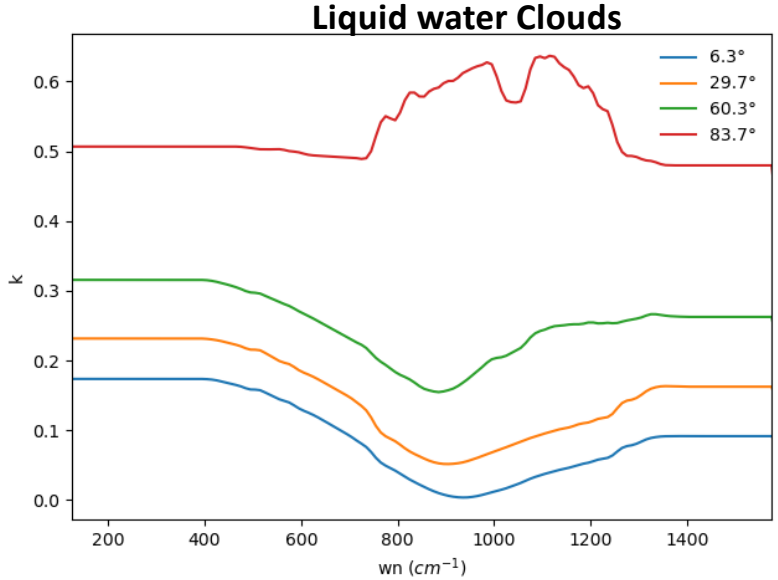
k(μ) for ice and water clouds

Tang's correctional coefficients are provided for 4 gaussian angles after a smoothing filtering

$$k_v(\mu) = F_1\left(\frac{1}{2}\frac{F_2\left(\Delta I_v(\mu)\right)}{F_2\left(I_{tang}(\mu)\right)}\right)$$

Where F_1 and F_2 are 2 filtering functions with Gaussian kernel.



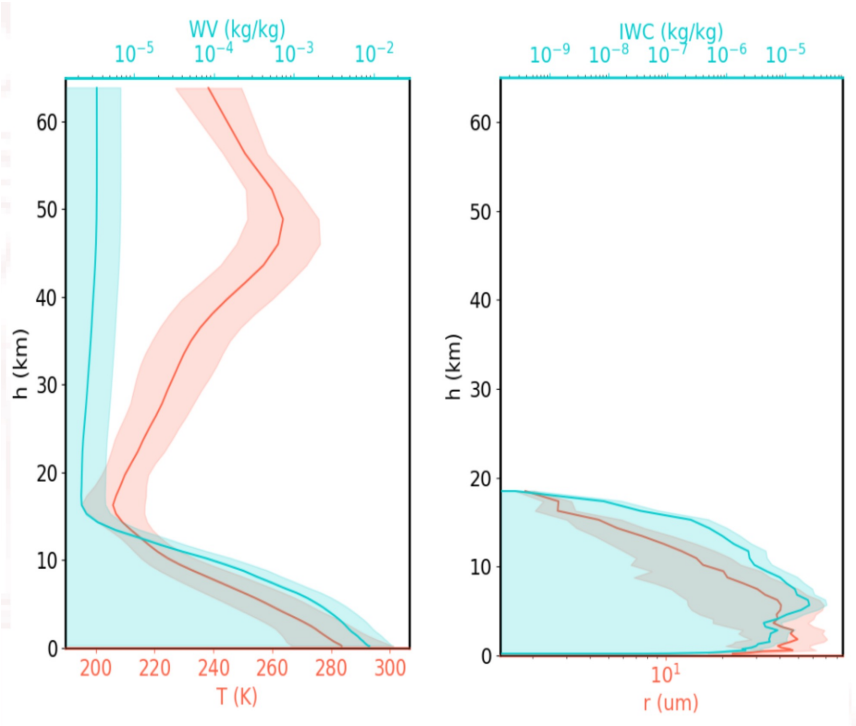


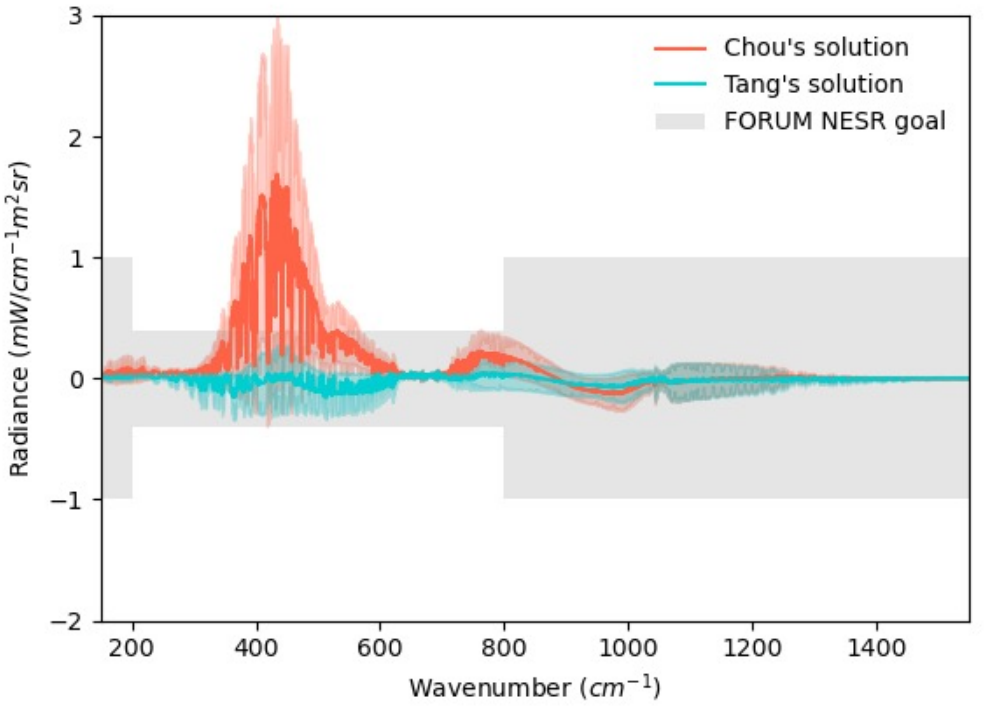
The code allows for compositions of multi-phase layers. Theoretically it is derived that:

$$k_{tot} = \frac{k_{ice}b_{ice}\beta_{ice}^{sca} + k_{wat}b_{wat}\beta_{wat}^{sca}}{b_{ice}\beta_{ice}^{sca} + b_{wat}\beta_{wat}^{sca}}$$

Results on test set

Average differences between approximate methodologies (Chou and Tang) and a reference model (DISORT 32 streams) computed for the EUMETSAT NWP SAF reduced dataset (60 levels).





Only cloudy scenes are considered (54 scenes).
Residuals and standard deviation are within the FORUM nesr at FIR and MIR

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Iota - Inversion model

Iota is an optimal estimation inversion code based on the σ-FORUM fm which minimizes a cost function in a latent space.

Minimization of the cost function in the latent space (LMGN)

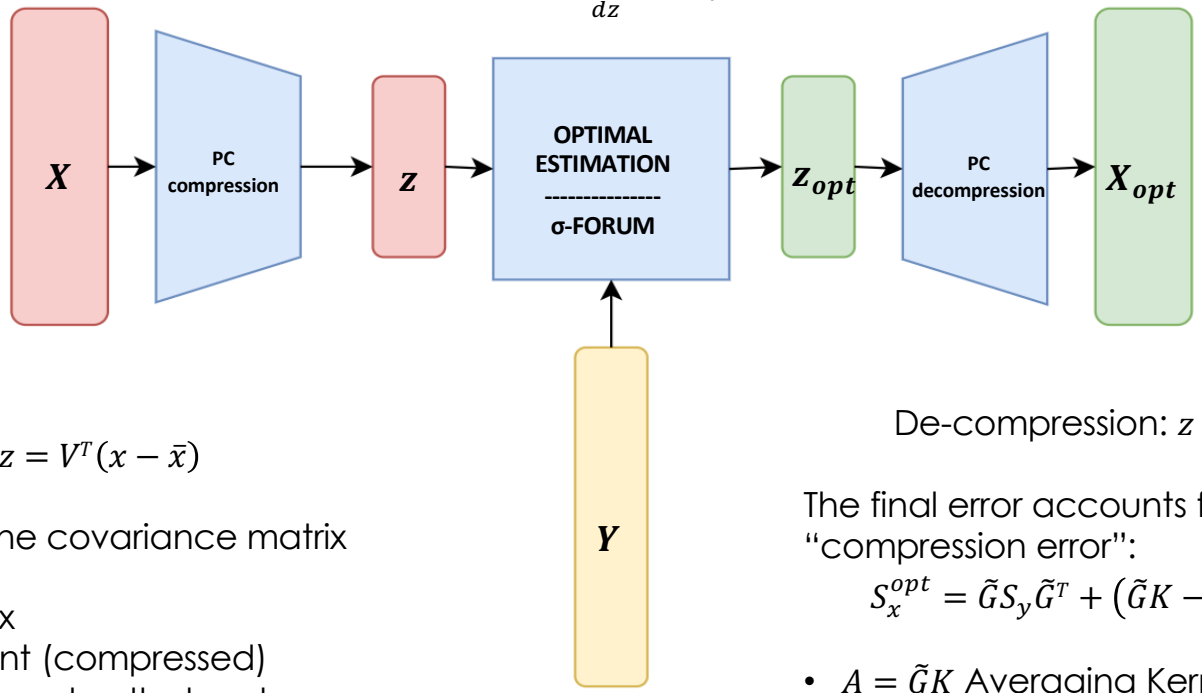
$$\chi^2 = z^T \tilde{S}_x^{-1} z + \left(y - \tilde{F}(z)\right)^T S_y^{-1} \left(y - \tilde{F}(z)\right)$$

$$F(x) \rightarrow \tilde{F}(z) = F(Vz + \bar{x})$$

$$\rightarrow \tilde{K} = \frac{d\tilde{F}(z)}{dz} = KV$$

Atmospheric state: x

- Temperatures
- Emissivity
- gas profile
- cloud concentration
- cloud reff



Compression: $x \rightarrow z = V^T(x - \bar{x})$

- V = the eigenvectors of the covariance matrix (n, q)
- n = original dimension of x
- q = dimension of the latent (compressed) space. It is defined as the value that makes the compression error negligible:

$$\varepsilon_{PC} = K(\mathbb{I} - VV^T)(x - \bar{x})$$

Observation
(IASI, PREFIRE, FORUM, …)

De-compression: $z \rightarrow x = Vz + \bar{x}$

The final error accounts for the "compression error":

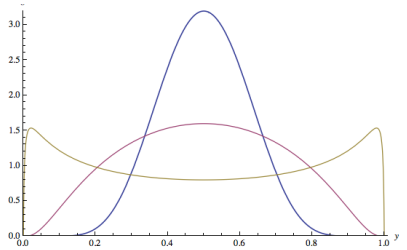
$$S_x^{opt} = \tilde{G} S_y \tilde{G}^T + \left(\tilde{G}K - \mathbb{I}\right) S_a \left(\tilde{G}K - \mathbb{I}\right)^T$$

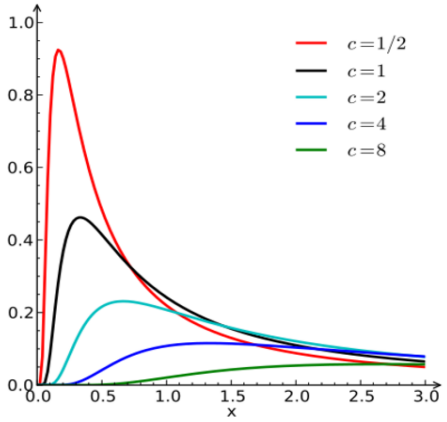
- $A = \tilde{G}K$ Averaging Kernel

Assumptions on the state distributions

The model assumes different types of normal-derived distributions for the a-prior, the likelihood and the posterior:

State	Distribution
Temperature (z)	Normal
Surface Temperature	Normal
Gas profiles (z)	Log-Normal
Emissivity	Logit-Normal
Cloud/Aerosol Reff	Log-Normal
Cloud/Aerosol Conc.	Log-Normal





advantages in using a log-normal distribution (for gas concentration):

- gas concentration range reduced → better numerical representation→ stability
- avoidance of negative values (useful for pca compression)
- realistic for low gas concentrations

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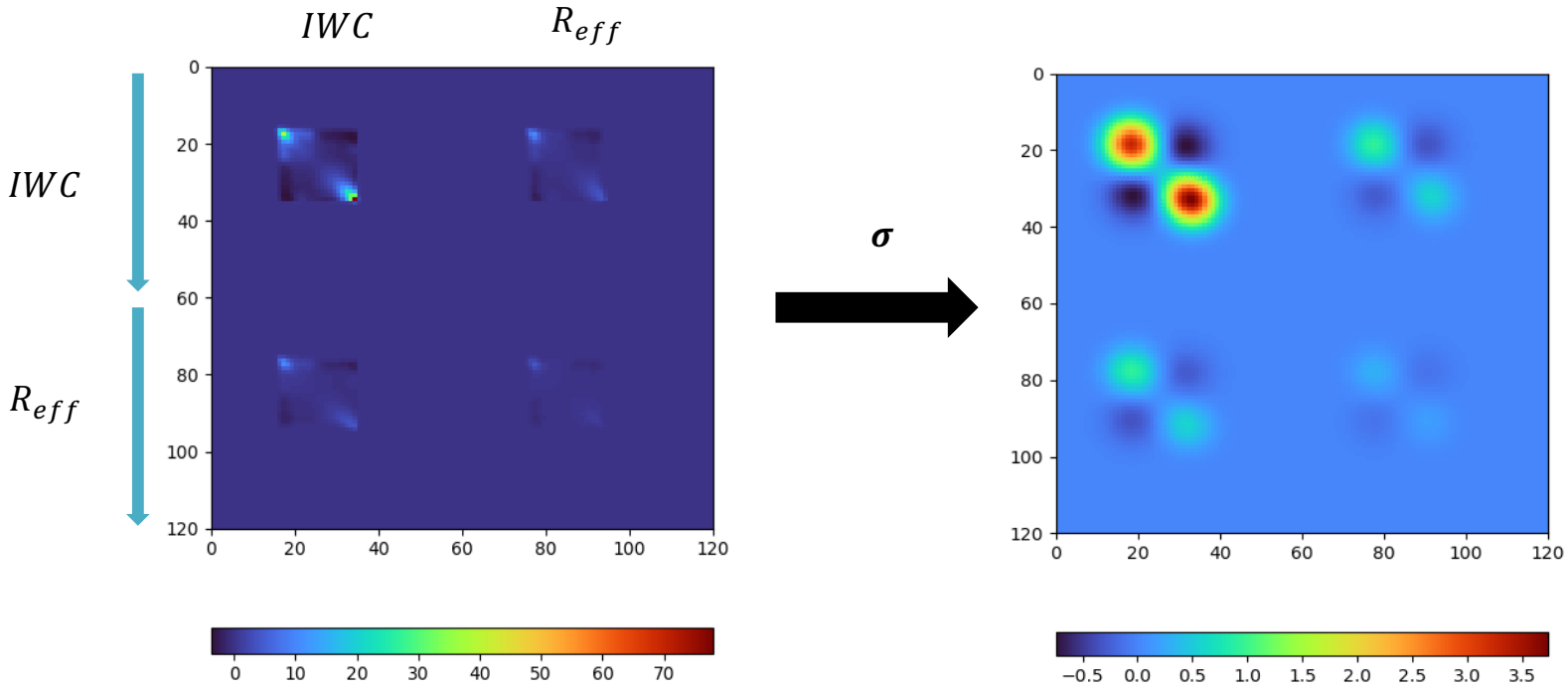
Regularization: tropical Ice clouds (example)

The main regularization is provided by the prior knowledge of the state vector x.
The statistic concerning the clouds is derived from the Eumetsat SAF profiles. A **gaussian filter is applied to the prior covariance matrix**. This is equivalent to require a gaussian smoothing on retrieved profiles. The regularization strength is controlled by the filter standard deviation **σ.**



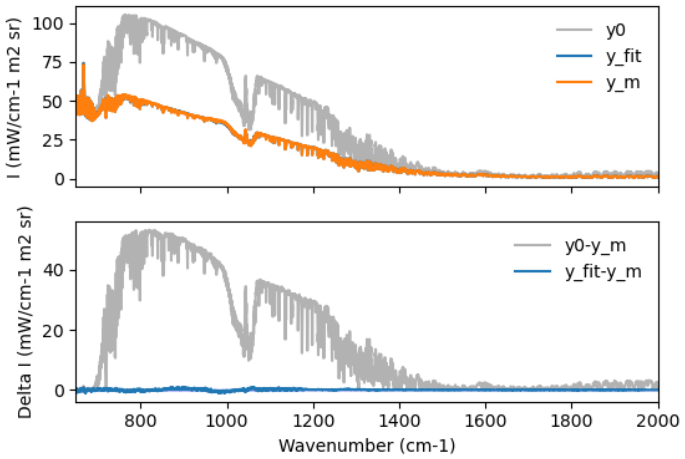
- It allows to exploit smoothed relations concerning the cloud (otherwise difficult to be treated).
- It represents an advancement with respect to using a box representation of the cloud
- The DoFs diminish but important correlations are reinforced by the smoothing.

Results: IASI data (cloudy sky)

IOTA is capable to identify discrepancies in the optical and microphysical properties derived from the analysis

- 30°N over the Atlantic ocean; OZA =17.8°

Analysis
IOTA-FIT
IASI



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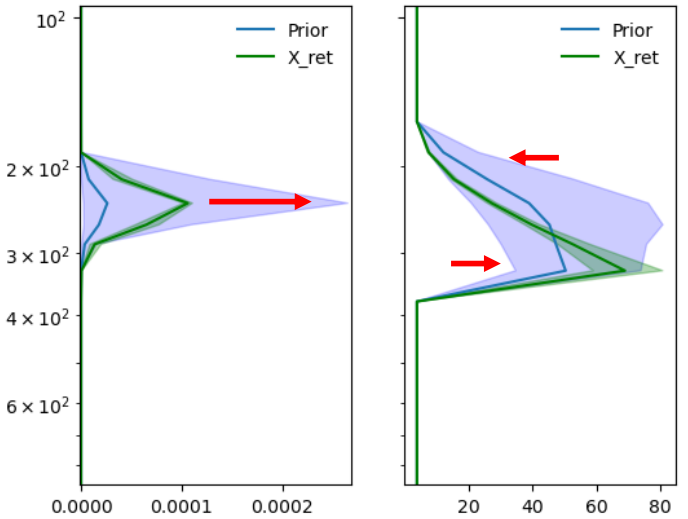
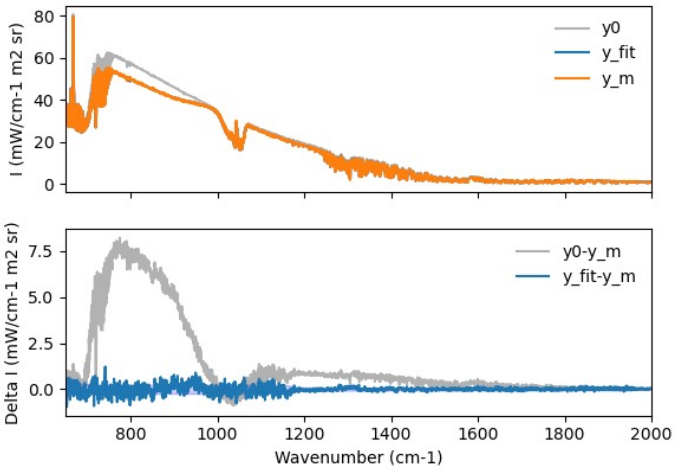


- 68°S Polar region; OZA= 31.6°

Analysis
IOTA-FIT
IASI



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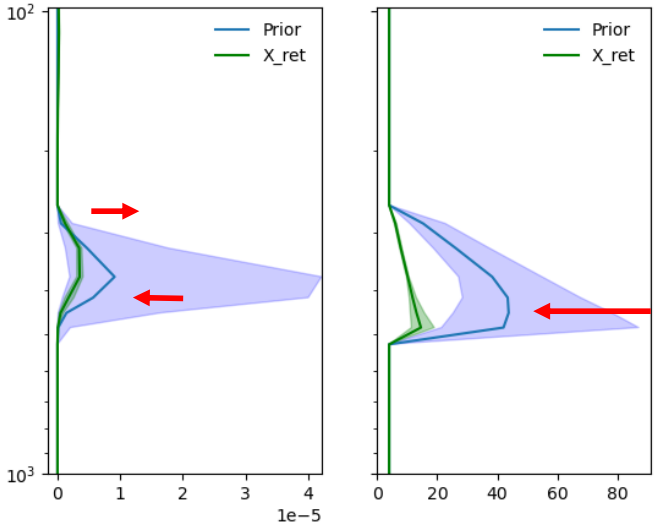

Final Notes

- the code suite (***σ*** and **iota**) is open to ingest new sensors. Already available are: IASI, PREFIRE, FORUM (ideal), GLORIA BB, REFIR-PAD, …
- the ***σ*-FORUM** code is a multi-physics code for the rt solution in the presence of scattering layer: Chou, Chou+Tang, MAMA (to be implemented), 2-stream (to be implemented)
- future work includes the definition of the a-prior statistics on multiple classes of clouds and aerosols
- the code suite is available on request: tiziano.maestri@unibo.it

References

IOTA inversion code: Martinazzo, Maestri et al. 2025 in preparation
σ-IASI all sky retrievals: Serio et al. 2024, https://doi.org/10.1016/j.jqsrt.2024.109211
Tang adjustement in *σ*-IASI: Maestri et al. 2024, https://dx.doi.org/10.1063/5.0183019
σ-IASI fm and IASI comparison: Masiello et al. 2024, https://doi.org/10.1016/j.jqsrt.2023.108814
Chou Scaling method assessment: Martinazzo et al. 2021, https://doi.org/10.1016/j.jqsrt.2021.107739

Acknowledgments

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