UNIVERSITÀ DEGLI STUDI FIRENZE | CNR-INO | Istituto per le Applicazioni del Calcolo | Consiglio Nazionale delle Ricerche Istituto per la BioEconomia

Challenges in emissivity retrieval

Joint FORUM-HAWC Workshop - McGill University, Montreal, Canada - **Oct 15 to Oct 17, 2025**

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Emissivity [ε]: Emissivity is the fraction of incoming energy absorbed by the surface and reemitted according to the Planck function at the surface temperature.

Surface spectral emissivity is a key target for the FORUM instrument.

In the Far-Infrared (FIR) range, emissivity models exist, but no spectrally resolved measurements are yet available. FORUM aims to fill this gap.

Experiment setup: ***FORUM E2E Simulator***, ***CLAIM*** *inversion module* [1]

This poster addresses two main challenges:

Do we have enough sensitivity to retrieve emissivity?
In which spectral bands, under which atmospheric conditions? [2]

If we have enough sensitivy, how do we proceed to obtain reliable results? [3]

Emissivity sensitivity

A measure of the retrievability condition of emissivity is the average retrieval error. This is calculated from the emissivity VCM:

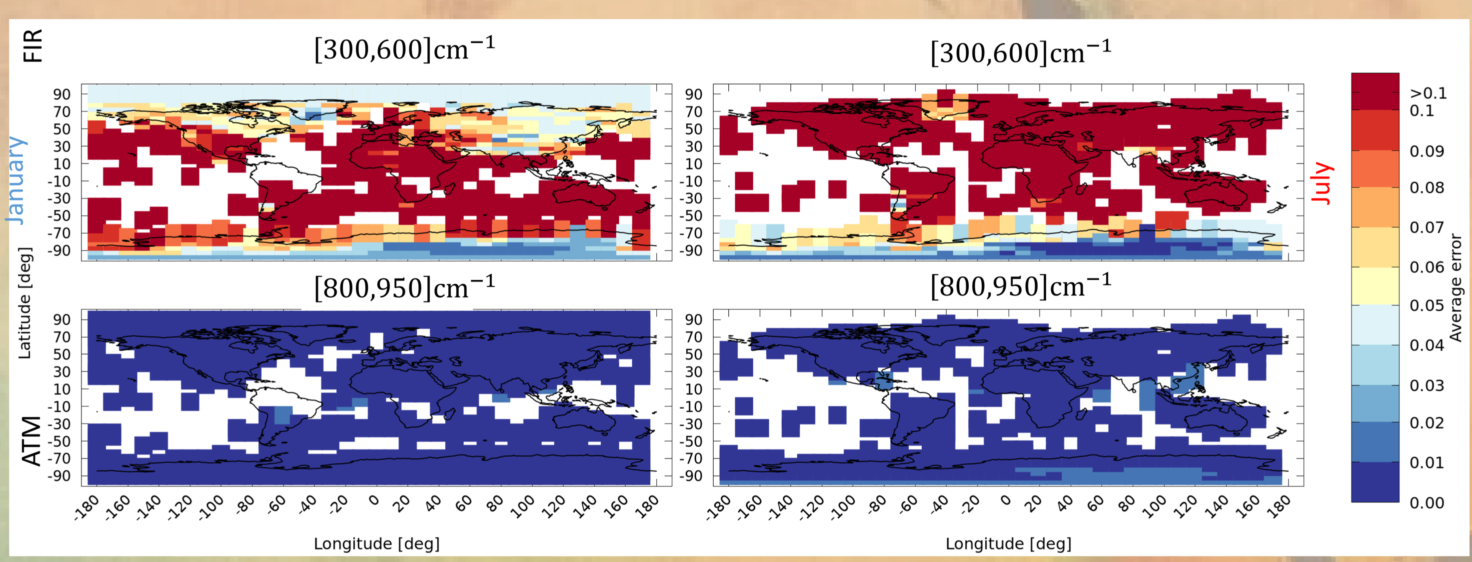
$$\mathbf{S_x} = \left(\mathbf{K}^t\mathbf{S_y}^{-1}\mathbf{K} + \mathbf{S}_a^{-1}\right)^{-1}$$

Given any band $B = [\nu_0, \nu_1]$, the errors of the N_B emissivity values with wavenumbers $w_{i_0} \dots w_{i_1}$ belonging to that band can be averaged to get:

$$\sigma_B = \frac{1}{N_B}\sum_{i=i_0}^{i_1}\sqrt{(\mathbf{S_x})_{ii}}$$

- If there is no sensitivity to emission in value j: $(\mathbf{K}^t\mathbf{S_y}^{-1}\mathbf{K})_{jj} \to 0$, so that $(\mathbf{S_x})_{jj} \to (\mathbf{S}_a)_{jj} \equiv 0.15$ in our tests.
- If there is sensitivity to emission in value j: $(\mathbf{K}^t\mathbf{S_y}^{-1}\mathbf{K})_{jj}$ becomes larger, so that in the limit: $(\mathbf{S_x})_{jj} \to 0$.

Map of emissivity error as a function of geolocation and season

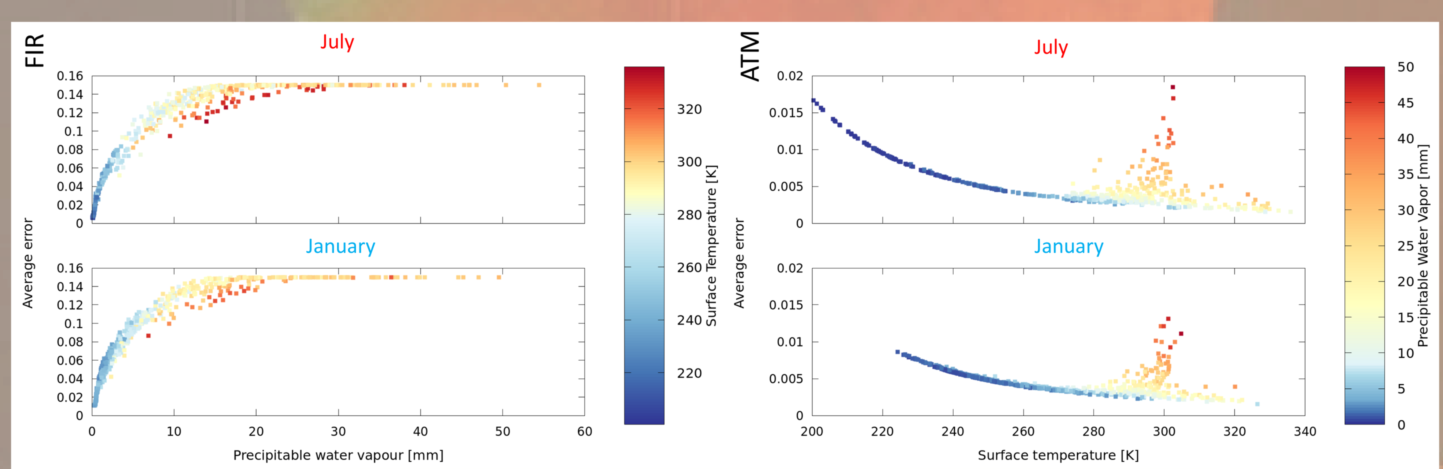


As expected, there is always sensitivity to emissivity in the atmospheric window under clear-sky conditions. In the FIR, retrieval is possible only in very dry scenes — mainly polar, with limited sensitivity over deserts.

Factors driving emissivity sensitivity

There is a correlation between emissivity error, surface temperature, and precipitable water vapor (PWV). However, the main factor driving the error depends on the spectral band: PWV in the FIR, and surface temperature in the atmospheric window.

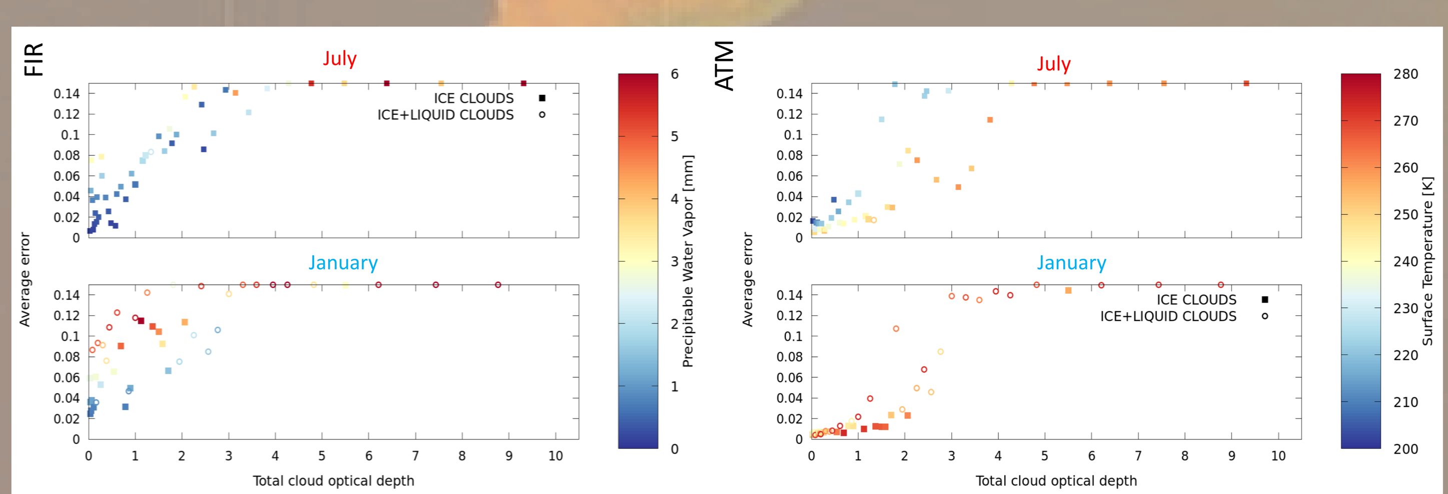
Correlations between emissivity error, surface temperature and precipitable water vapor



Sensitivity in cloudy sky conditions

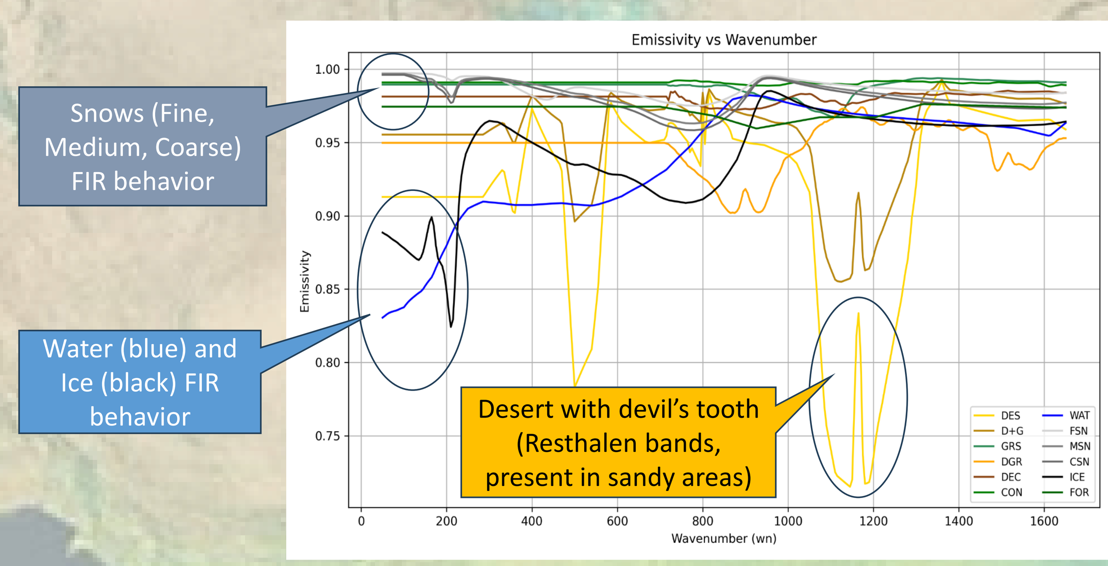
This is only possible at polar latitudes (e.g., Antarctica) when the cloud is thin. The error is mainly correlated with the cloud's total optical depth (at 900 cm⁻¹). A secondary correlation appears with PWV in the FIR and with surface temperature in the MIR.

Correlations between emissivity error, cloud optical depth at 900 cm⁻¹, surface temperature and precipitable water vapor in cloudy scenes



Emissivity profiles

In the MIR there are many good emissivity databases, such as CAMEL (Combined aster modis emissivity over land) [4]. In the FIR there are only the Huang set of profiles [5].



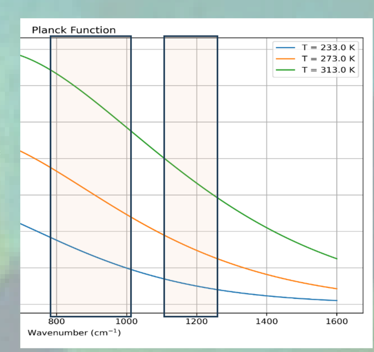
DES: Desert
D+G: 45% desert and 55% grass
GRS: Grass
DGR: Dry grass
DEC: Deciduous
CON: Conifer
WAT: Water
FSN: Fine snow
MSN: Medium snow
CSN: Coarse snow
ICE: Ice
FOR: Tropical Forest

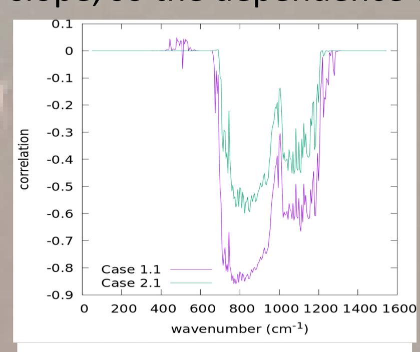
Emissivity retrieval issue

In the radiative trasfer equation: $I_{TOA} = (\varepsilon B(T_E) + (1-\varepsilon)I_d)A + E$

I_{TOA} – Radiation at TOA, ε – Emissivity, T_E – Surface temperature, $B(\cdot)$ – Planck function, I_d – Downwelling radiation, A – Atmospheric attenuation, E – Emission terms

Radiative transfer depends linearly on emissivity ε. It also depends linearly on the Planck function $B(T_E)$, a function of the surface temperature T_E. However, in the MIR, the Planck function for typical surface temperatures is almost linear, with a negative slope, so the dependence of the radiative transfer equation on T_E is almost linear.



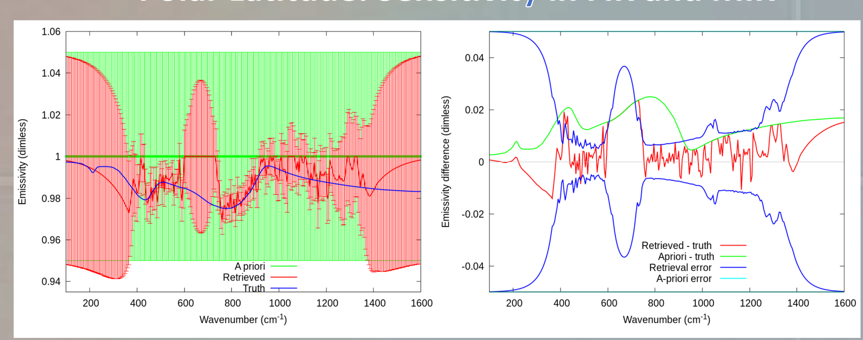


Case 1.1: Desert, Case 2.1: Water

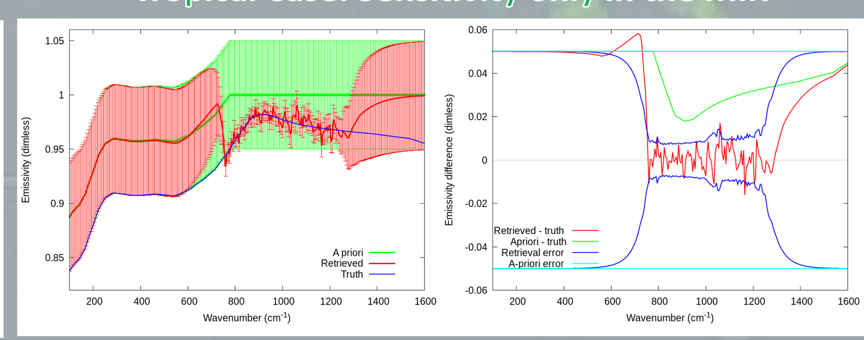
In the retrieval, surface temperature and emissivity are strongly negatively correlated [1]. As a result, the retrieved emissivity and surface temperature can sometimes exhibit opposite-signed biases, even when the spectrum is well reproduced (i.e. reduced chi-square close to 1).

Emissivity in FORUM E2E Retrievals:

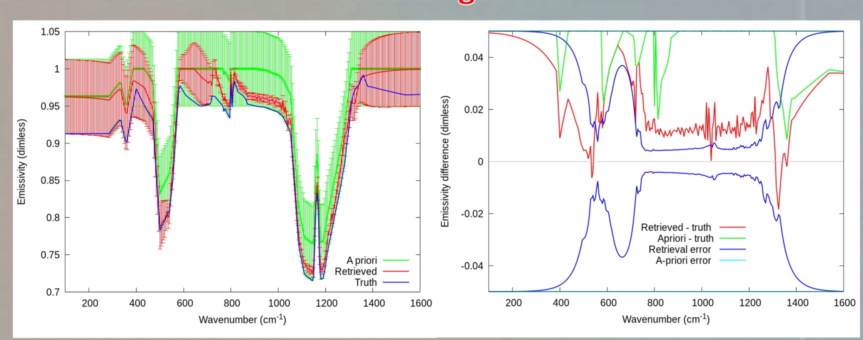
Polar Latitude: Sensitivity in FIR and MIR



Tropical Case: Sensitivity only in the MIR



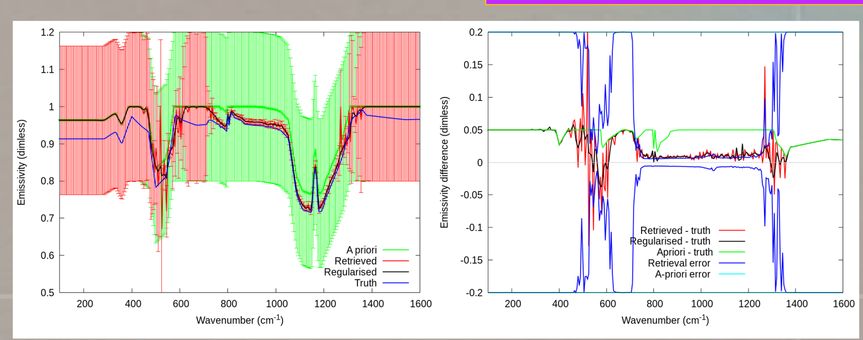
Desert: Case with higher correlation



FORUM E2E Retrieval Conditions (Clear Scenes)
Retrieved Quantities: Surface temperature, spectral emissivity, vertical profiles of temperature, water vapor, and ozone.
Emissivity IG/AP: True values ±0.05, capped at 1; spectral grid 5 cm⁻¹.
Surface Temperature Error (std): ±2 K
Vertical Profile Errors: Background errors from MetOffice IASI assimilation in NWP.
Retrieval Method: Optimal Estimation with Levenberg-Marquardt technique and final a-posteriori IVS regularization [6].

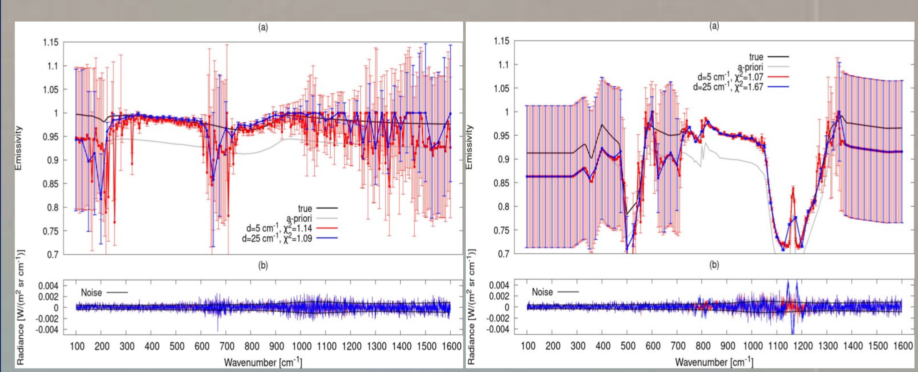
Mitigating strategies

1



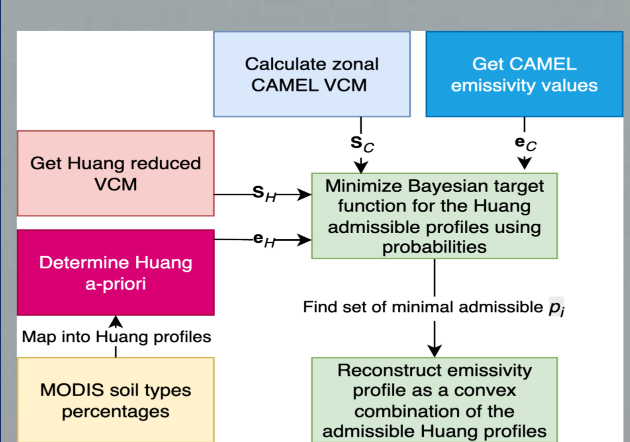
Increase emissivity covariance matrix error to ±0.2 with no correlation length, allowing larger, less constrained variations. Weaker regularization improves overall results but induces oscillations in the retrieved profile (red curve). oscillations in the retrieved profile (red curve). Applying a-posteriori IVS regularization [6] to the emissivity profile reduces the oscillations (black curve).

2



Use a coarser 20 cm⁻¹ grid. The random error is reduced, as each point averages over more measurements.
For smooth emissivity profiles (e.g., polar latitudes, left panel) the reconstruction improves.
For emissivity profiles with fine features (e.g., desert, right panel): smoothing error appears, reducing reconstruction accuracy.

3



Find an emissivity profile (to be used as IG/AP) that is as close as possible to the true one, since a better a-priori improves retrieval accuracy [3,7]. A practical choice is to use the Huang emissivity database [5] that selects profiles that are closest to the CAMEL database [4]. However, CAMEL data are available only in the MIR, so profiles that agree in this range may still differ in the FIR (ice and water regions). To address this, we implemented [3] a slightly more complex method, illustrated in the diagram. The target function is:

$$J(p_{i_1}, \dots, p_{i_l}) = (\mathbf{e}_C(p) - \mathbf{e}_C)^t\mathbf{S}_C^{-1}(\mathbf{e}_C(p) - \mathbf{e}_C) + (\mathbf{e}_H(p) - \mathbf{e}_H)^t\mathbf{S}_H^{-1}(\mathbf{e}_H(p) - \mathbf{e}_H)$$

Where: $\mathbf{e}_C$ - CAMEL a-priori, $\mathbf{e}_H$ - Huang a-priori, $\mathbf{e}_C(p)$ - Emissivity profile on CAMEL wn; $\mathbf{e}_C(p)$ - Emissivity profile on Huang super-channels; $\mathbf{S}_c^{-1}$ inverse of the CAMEL VCM; $\mathbf{S}_H^{-1}$ inverse of the Huang VCM.

Full globe Jan/Jul average emissivity error comparison between:

- CAMEL profiles (linear spline connecting db points)
- HUANG emissivity database
- BAYES approach
- IASI retrieved values

	January	July
BAYES-IASI	0.0264	0.0285
CAMEL-IASI	0.0297	0.0300
HUANG-IASI	0.0333	0.0350
CAMEL-BAYES	0.0191	0.0147

[1] L. Sgheri et al. "The FORUM end-to-end simulator project: architecture and results", Atmospheric Measurement Techniques 15.3 (2022)

[2] C. Sgattoni et al. "Characterization of Surface Spectral Emissivity Retrieved from EE9-FORUM Simulated Measurements". In: Remote Sensing in Earth Systems Sciences 7 (2024)

[3] L. Sgheri, C. Sgattoni, and C. Zugarini. "Determination of emissivity profiles using a Bayesian data-driven approach". In: Mathematics and Computers in Simulation 229 (2025), pages 512–524.

[4] E. Borbas, G. Hulley, M. Feltz, R. Knuteson, S. Hook, The combined aster modis emissivity over land (camel) part 1: Methodology and high spectral resolution application, Remote Sensing 10 (2018).

[5] X. Huang et al. "An Observationally Based Global Band-by-Band Surface Emissivity Dataset for Climate and Weather Simulations". In: Journal of the Atmospheric Sciences 73.9 (2016), pages 3541–3555

[6] C. J. Merchant, S. Saux-Picart, J. Waller, Bias correction and covariance parameters for optimal estimation by exploiting matched in-situreferences, Remote Sensing of Environment 237 (2020).

[7] M. Ridolfi and L. Sgheri. "Iterative approach to self-adapting and altitude-dependent regularization for atmospheric profile retrievals". In: Opt. Express 19.27 (Dec. 2011).