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Retrieval of surface emissivity from FORUM-EE9 simulated measurements: optimization of constraints

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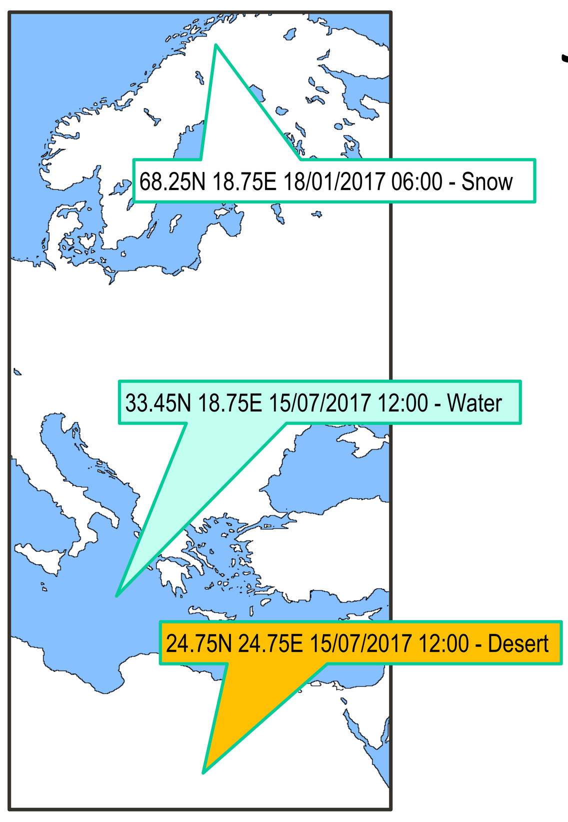
The FORUM Mission:

FORUM (Far-infrared Outgoing Radiation Understanding and Monitoring) is a Fourier Transform Spectrometer (FTS) that will fly as the 9th ESA's Earth Explorer mission. FORUM will sound the atmosphere in the 100-1600 cm^{-1} region, covering the Far Infrared (FIR) and part of the Middle Infrared (MIR), accounting for more than 95% of the outgoing longwave flux lost by our planet. The FORUM data will allow a better insight into the following targets:

- Upper Troposhpere Lower Stratosphere (UTLS) Water Vapour
- **Surface emissivity in polar and dry regions**
- Cirrus cloud characteristics

Joint Retrieval of Tskin, TEM, H2O, Emissivity in Clear Sky: Retrieval Setting



Model:
- EMISSIVITY: Huang database [1]
- TSKIN/TEM/H2O: ERA5 reanalysis [2]
- Other VMR: IG2 database [3]
- Cross Sections: LBLRTM database [4]

Initial guess:
- EMISSIVITY: Model – 0.05
- TSKIN/TEM/H2O: 10-years avg. of ERA5 [5]

A-priori:
- EMISSIVITY: Model – 0.05
- TSKIN: Model, 2K perturbation
- TEM/H2O: Model, perturbed according to a-priori VCM

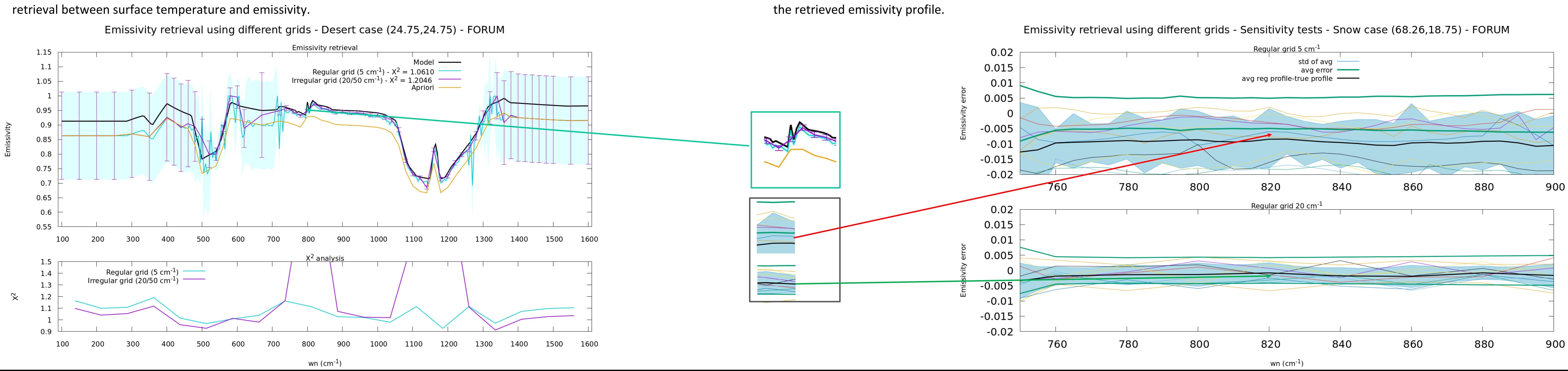
A-priori error:
- EMISSIVITY: 0.15, no correlations
- TSKIN: 2K
- TEM/H2O: UK MET Office IASI assimilation error

Codes:
- Forward Model: LBLRTM, v12.11 [4]
- Retrieval Code: L2M_I , FORUM E2E inversion module [5]
- Retrieval Algorithm: Gauss-Newton (GN), Optimal Estimation (OE), IVS regularization [6,7]
- Instrument Characteristics/Response Function: FORUM project, phase B1 instrument concept

Emissivity grid step: fine vs. coarse

Fine grid (5 cm^{-1}):
- Minimizes smoothing error. The fine grid is able to reproduce sharp features in the emissivity model.
- Reduced precision. The larger random error may produce biases towards the AP. A contributing factor is the negative correlation in the retrieval between surface temperature and emissivity.

Coarse grid (20-50 cm^{-1}):
- May not reproduce sharp features. If the retrieval grid step is larger than the emissivity feature, the feature cannot be reproduced.
- Good precision. Each retrieval point is determined by a large number of measurements. Thus, the random error is smaller and there is no bias in the retrieved emissivity profile.



IVS regularization of emissivity retrieval

Why we need regularization:

- We do not use correlations in the a-priori VCM to avoid cross-talk between spectral ranges with different sensitivity to surface emissivity.
- With this choice, we obtain a better reconstruction in the transition intervals, but there might be oscillations in the retrieved profile, since no constrains are imposed on adjacent emissivity measurements in the a-priori.

IVS (Iterative Variable Strength) regularization:

- Introduced in [6] for ESA MIPAS retrieval and extended [7] to FORUM vertical profile retrievals.
- The optimal estimation $\mathbf{x}_{OE}$ and regularized retrieved solution $\mathbf{x}_\Lambda$ have the form:

$$\mathbf{x}_{OE} = \mathbf{x}_k + \left(\mathbf{K}_k^t\mathbf{S}_y^{-1}\mathbf{K}_k + \mathbf{S}_a^{-1} + \alpha_k\mathbf{M}\right)^{-1}\left[\mathbf{K}_k^t\mathbf{S}_y^{-1}\left(\mathbf{y}-\mathbf{F}(\mathbf{x}_k)\right) + \mathbf{S}_a^{-1}(\mathbf{x}_a - \mathbf{x}_k)\right]$$

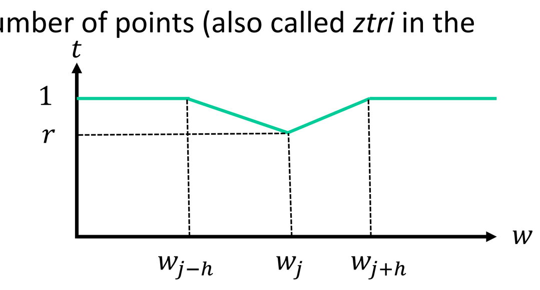
$$\mathbf{x}_\Lambda = \mathbf{x}_k + \left(\mathbf{K}_k^t\mathbf{S}_y^{-1}\mathbf{K}_k + \mathbf{S}_a^{-1} + \alpha_k\mathbf{M} + \mathbf{R}_\Lambda\right)^{-1}\left[\mathbf{K}_k^t\mathbf{S}_y^{-1}\left(\mathbf{y}-\mathbf{F}(\mathbf{x}_k)\right) + \mathbf{S}_a^{-1}(\mathbf{x}_a - \mathbf{x}_k) - \mathbf{R}_\Lambda\mathbf{x}_k\right]$$

Where: $\mathbf{x}$ is the retrieval vector, $\mathbf{F}(\mathbf{x})$ is the forward model, $\mathbf{y}$ is the measurement vector with $\mathbf{S}_y$ VCM, k is the GN iteration index at convergence, $\mathbf{x}_a$ is the apriori with $\mathbf{S}_a$ VCM, $\mathbf{K}_k = \nabla\,\mathbf{F}(\mathbf{x}_k)$, $\alpha_k\mathbf{M}$ is the Levenberg-Marquardt term, and finally the regularization term $\mathbf{R}_\Lambda = \mathbf{L}_i^t\boldsymbol{\Lambda}\mathbf{L}_i$ is such that $\mathbf{L}_i$ is a linear operator approximating the *i*-th derivative: $(\mathbf{L}_i\mathbf{x}_k)_j \cong \frac{d^i}{dw^i}\mathbf{x}_k(w_j)$, and $\boldsymbol{\Lambda}$ is a positive diagonal matrix, so that we may think: $\boldsymbol{\Lambda}_{jj}=\lambda(w_j)$.

The IVS method starts with a large $\boldsymbol{\Lambda}_0 = \lambda_0\mathbf{I}$, and decreases the profile until both conditions below are fulfilled:
- The regularized profile are within a fraction $w_e(w)$ of the error bars of the OE solution.
- The vertical resolution (for profiles) or spectral resolution (for emissivity) of the regularized profile is degraded no more than a multiple $w_r(w)$ of the vertical resolution of the OE solution.

Decreasing the lambda profile:

To decrease the $\lambda(w)$ profile, for each point w_j where the conditions are not satisfied, we multiply by a triangular function $t_j(w)$. We fix $r = 0.99$, the amplitude of the decreasing is set either with the independent variable, or in number of points (also called *ztri* in the plots). For emissivity, sensible choices are: $h = 1$ or $h = 2$.



Retrieval Qualifiers:

- χ^2. Chi-square statistic of the retrieval.
- DOF. Number of degrees of freedom of the solution.
- POQ. Profile Oscillation Quantifier Ω_1. Given any profile $x_i = x(z_i)$, measures the oscillations of the profile.

$$\Omega_1 = \frac{1}{n-2}\sum_{i=2}^{n-1}\frac{\left|x_i - x_{i-1} - \frac{x_{i+1}-x_{i-1}}{z_{i+1}-z_{i-1}}(z_i - z_{i-1})\right|}{\sqrt{(x_{i+1}-x_{i-1})^2 + (z_{i+1}-z_{i-1})^2}}$$

Three test scenarios

Sensitivity to emissivity in the FIR depends on the Precipitable Water Vapour (PWV) of the atmosphere.

Water: Control case. Retrieval over sea. Large water vapour atmospheric content. No sensitivity to emissivity in FIR.

Snow: Retrieval over fine snow in winter. Dry atmosphere. Good sensitivity to emissivity in FIR.

Desert: Retrieval over desert in summer. Fairly dry atmosphere. Some sensitivity to emissivity in FIR.

WATER CASE PVW: 36.33 mm

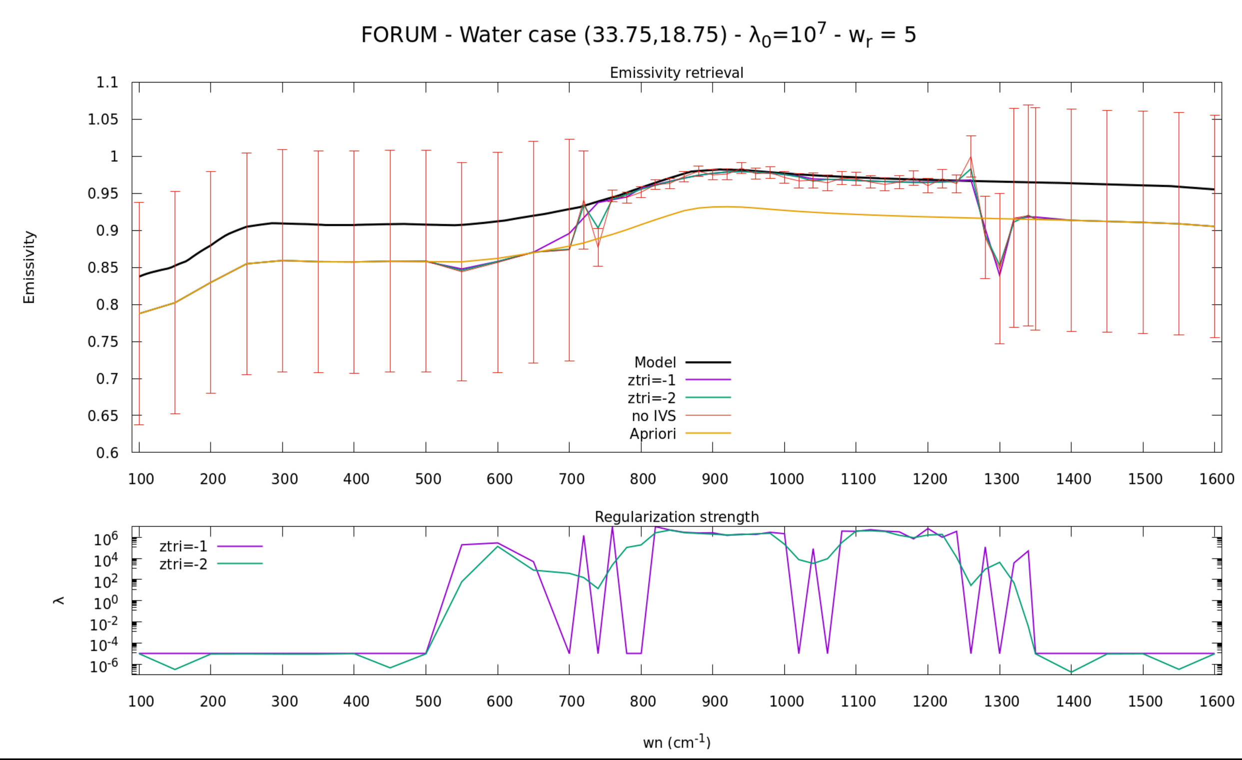
	BEFORE IVS	AFTER IVS ($\lambda_0 = 10^7$, $w_e = 1$, $w_r = 5$) h = 1	h = 2
DOF	29.167	9.524	11.048
POQ	271E-6	97E-6	165E-6
χ^2	1.0287	1.0365	1.0356

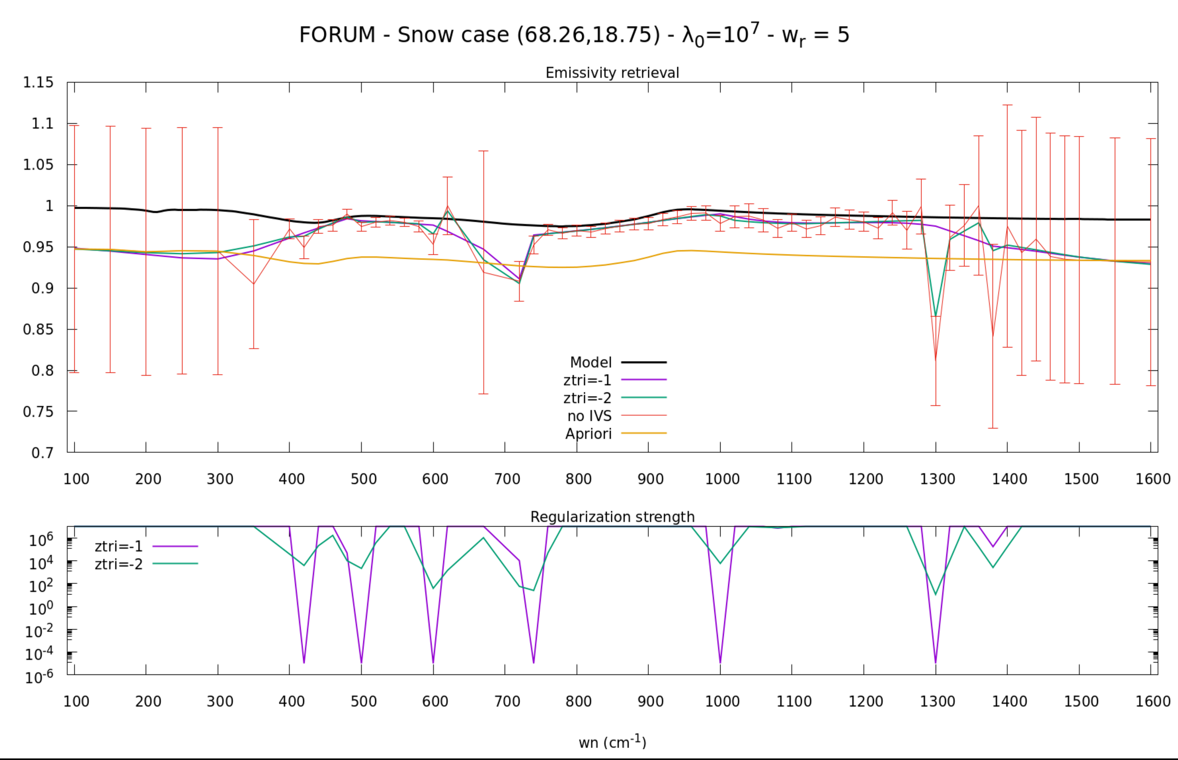
SNOW CASE PVW: 3.31 mm

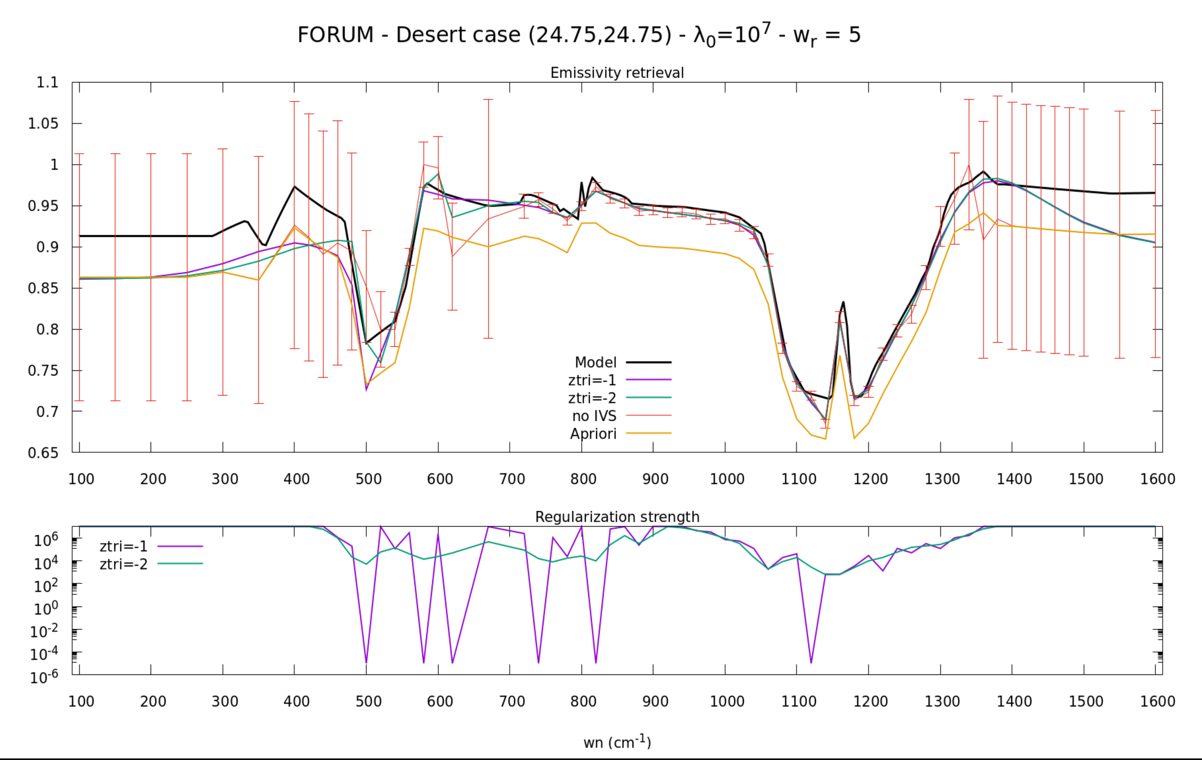
	BEFORE IVS	AFTER IVS ($\lambda_0 = 10^7$, $w_e = 1$, $w_r = 5$) h = 1	h = 2
DOF	45.343	10.920	14.809
POQ	473E-6	34E-6	166E-6
χ^2	1.0262	1.0376	1.0341

DESERT CASE PVW: 23.14 mm

	BEFORE IVS	AFTER IVS ($\lambda_0 = 10^7$, $w_e = 1$, $w_r = 5$) h = 1	h = 2
DOF	38.403	17.605	19.535
POQ	422E-6	254E-6	283E-6
χ^2	1.2046	1.2506	1.2409







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