A Fast Retrieval Model for Synergistic Inversion of FORUM and IASI-NG Measurements

Marco Ridolfi (1), Claudio Belotti (1), Samuele Del Bianco (2), Stefano Della Fera (2,3), Gianluca Di Natale (1), Guido Masiello (4), Piera Raspollini (2), Carmine Serio (4), Luca Palchetti (1)

(1) Istituto Nazionale di Ottica - Consiglio Nazionale delle Ricerche (INO - CNR), Sesto Fiorentino, IT
(2) Istituto di Fisica Applicata "Carrara" – Consiglio Nazionale delle Ricerche (IFAC – CNR), Sesto Fiorentino, IT
(3) Dip. di Fisica e Astronomia, Univ. di Bologna, Bologna, IT
(4) Scuola di Ingegneria, Università degli Studi della Basilicata, Potenza, IT

Background

FORUM (Far-infrared Outgoing Radiation Understanding and Monitoring) will be the ESA Earth Explorer 9 mission, planned for launch in the time frame 2026 - 2027. The core FORUM instrument will be a FT spectrometer measuring, for the first time from space, the outgoing spectral radiance from the FAR- to the MID- infrared spectral regions, namely, from 100 to 1600 cm^{-1}.

FORUM will fly in loose formation with the MetOp-SG-1A satellite, hosting the Infrared Atmospheric Sounding Interferometer - New Generation (IASI-NG). The MIR (645 to 2760 cm^{-1}) upwelling atmospheric spectrum measured by IASI-NG will complement the FORUM FIR spectrum, providing an unprecedented spectral coverage, from 100 to 2760 cm^{-1} (see figure on the right).

The joint inversion of tightly matching of FORUM and IASI-NG measurements will permit to obtain high quality Level 2 products thanks to the fact that, while the FIR part of the spectrum measured by FORUM is the most sensitive to the water vapour content in the UTLS and to cloud microphysical parameters, the atmospheric windows in the MIR are measured by IASI-NG with a very high signal-to-noise ratio, thus supplying very precise information on the surface temperature and on the temperature profile, which are essential to constrain the retrieval parameters.
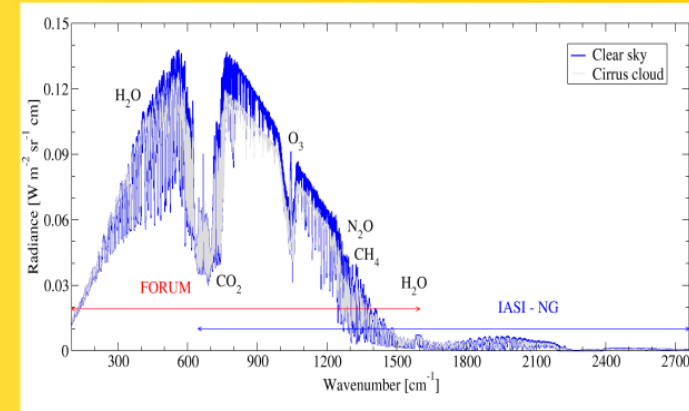
Inversion model

Bayesian [1] inversion of FORUM and / or IASI-NG measurements.
Cost function:

$$\xi^2(\mathbf{x}) = \sum_{i=1}^{2} (\mathbf{y}_i - \mathbf{F}_i(\mathbf{x}))^t \mathbf{S}_{yi}^{-1} (\mathbf{y}_i - \mathbf{F}_i(\mathbf{x})) + (\mathbf{x}_a - \mathbf{x})^t \mathbf{S}_a^{-1} (\mathbf{x}_a - \mathbf{x})$$

Iterative Gauss – Newton solution:

$$\mathbf{x}_k = \mathbf{x}_{k-1} + \left[\sum_{i=1}^{2} \mathbf{K}_{i,k-1}^t \mathbf{S}_{yi}^{-1} \mathbf{K}_{i,k-1} + \mathbf{S}_a^{-1} \right]^{-1}$$

$$\left[\sum_{i=1}^{2} \mathbf{K}_{i,k-1}^t \mathbf{S}_{yi}^{-1} (\mathbf{y}_i - \mathbf{F}_i(\mathbf{x}_{k-1})) + \mathbf{S}_a^{-1} (\mathbf{x}_a - \mathbf{x}_{k-1}) \right]$$

Diagnostics

The retrieval error is estimated with the error covariance matrix:

$$\mathbf{S} = \left[\sum_{i=1}^{2} \mathbf{K}_i^t \mathbf{S}_{yi}^{-1} \mathbf{K}_i + \mathbf{S}_a^{-1} \right]^{-1}$$

The averaging kernels (AKs) are computed as:

$$\mathbf{A} = \left[\sum_{i=1}^{2} \mathbf{K}_i^t \mathbf{S}_{yi}^{-1} \mathbf{K}_i + \mathbf{S}_a^{-1} \right]^{-1} \sum_{i=1}^{2} \mathbf{K}_i^t \mathbf{S}_{yi}^{-1} \mathbf{K}_i$$

$\mathbf{K}_1$ and $\mathbf{K}_2$ are Jacobians of FORUM and IASI-NG simulated measurements, $\mathbf{S}_{y1}$ and $\mathbf{S}_{y2}$ their error covariance matrices.

The state vector includes

Temperature, H_2O and O_3 vertical profiles
Surface Temperature
Surface spectral emissivity
Still to be implemented: cloud parameter and other gases retrieval

The fast forward model

The inversion model includes the **σ-FORUM** fast parametric radiative transfer code [2, 3]. Advantages:

A) Being monochromatic, this model can be easily exploited to simulate measurements from several instruments by convolving high-resolution (0.01 cm⁻¹) simulated radiance with the related instrument spectral response functions.

B) The radiance can be simulated assuming instrument line of sight with given zenith angle, thus making easier the calculation of outgoing spectral / total fluxes via angular integration e.g. with the Gauss quadrature.

References

[1] Rodgers, C. D.: Inverse methods for atmospheric sounding: theory and practice, World Scientific, Singapore, 2000.

[2] Amato, U., Masiello, G., Serio, C., and Viggiano, M.: The σ-IASI code for the calculation of infrared atmospheric radiance and its derivatives, Environmental Modeling & Software, 17, 651 - 667, 2002.

[3] Liuzzi, G., Masiello, G., Serio, C., Meloni, D., Di Biagio, C., and Formenti, P.: Consistency of dimensional distributions and refractive indices of desert dust measured over Lampedusa with IASI radiances, Atm. Meas. Tech., 10, 599 - 615, 2017.

Instrument parameters assumed

	• IASI-NG	FORUM
Spectral coverage	645 - 2760 cm⁻¹	100 - 1600 cm⁻¹
Spectral sampling	0.125 cm⁻¹	0.36 cm⁻¹
Spectral resolution	0.25 cm⁻¹	0.5 cm⁻¹
Measurement mode	Step and stare (azimuth scanning)	Step and stare (no azimuth scanning)
Ground pixel (diameter at nadir)	12 km	15 km

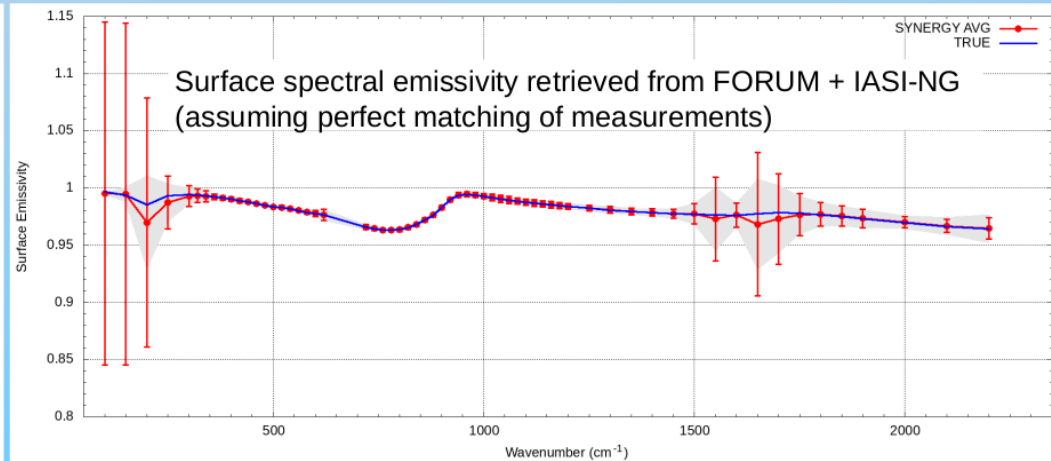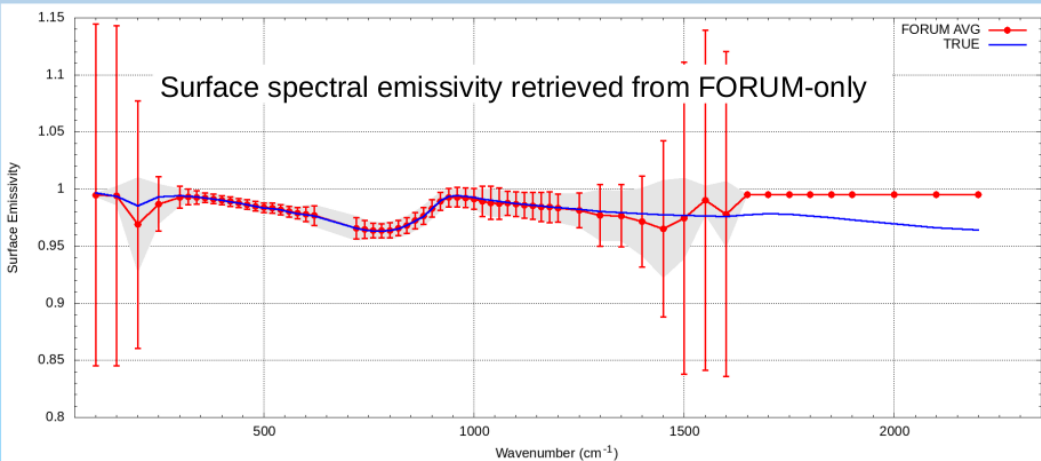NESR and Absolute Radiometric Accuracy (ARA)
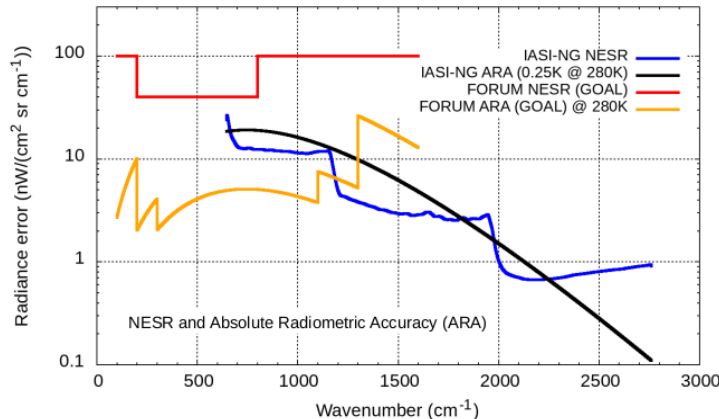
Example results for FORUM-only retrieval, Antarctic Winter atmosphere
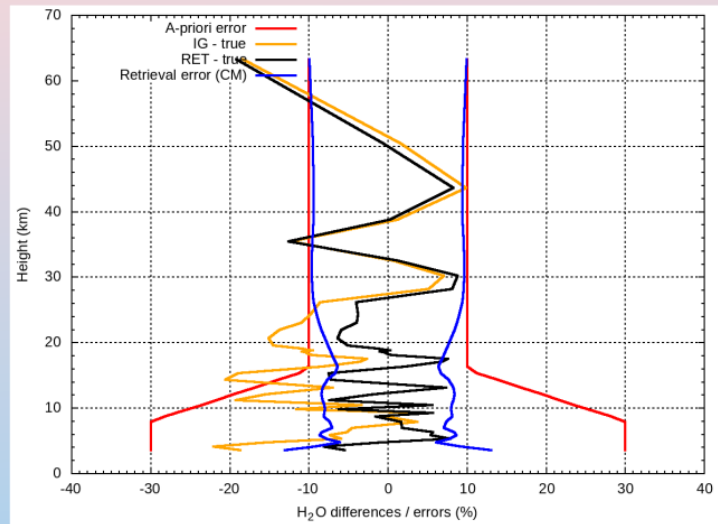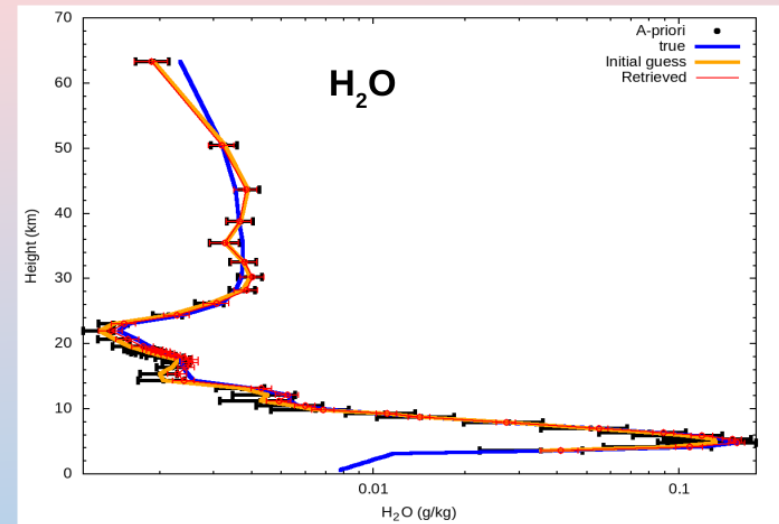
Left plot: Retrieved (red), a-priori (black), initial guess (orange) and true (blue) water vapour profiles for a test retrieval from FORUM synthetic radiance based on Antarctic Winter atmosphere observation scenario.

The right plot shows the percentage profile differences for retrieval minus true (black) and initial guess minus true (orange) profiles, as well as the retrieval (blue) and the a-priori (red) errors as estimated by the covariance matrices S and S_a.

Bottom plots: emissivity retrieved from FORUM-only (left) and from FORUM + IASI-NG (right). Error bars are evaluated from the retrieval covariance S. Shadowed areas represent the st. dev. of the differences retrieved minus true, thus is an ex-post estimate of the retrieval error.

Surface spectral emissivity retrieved from FORUM-only

Surface spectral emissivity retrieved from FORUM + IASI-NG (assuming perfect matching of measurements)

Summary / conclusions

The retrieval algorithm developed is self consistent, i.e. as the measurement noise vanishes, the retrieval converges to the true atmosphere / surface state used to generate the synthetic measurements.

The inversion system was used to assess the performance of FORUM retrievals in clear sky: the key clear-sky Level 2 FORUM products will be the water vapour profile, with a retrieval error of less than 10 % in the UTLS region, and surface spectral emissivity with an error smaller than 0.01 in the $300 - 600$ cm^{-1} range, in Polar regions.

The synergistic exploitation of FORUM and IASI-NG measurements permits to reduce significantly the retrieval errors, especially for tightly matching measurements.