All-sky Far-Infrared Deep Learning based Observation Operator

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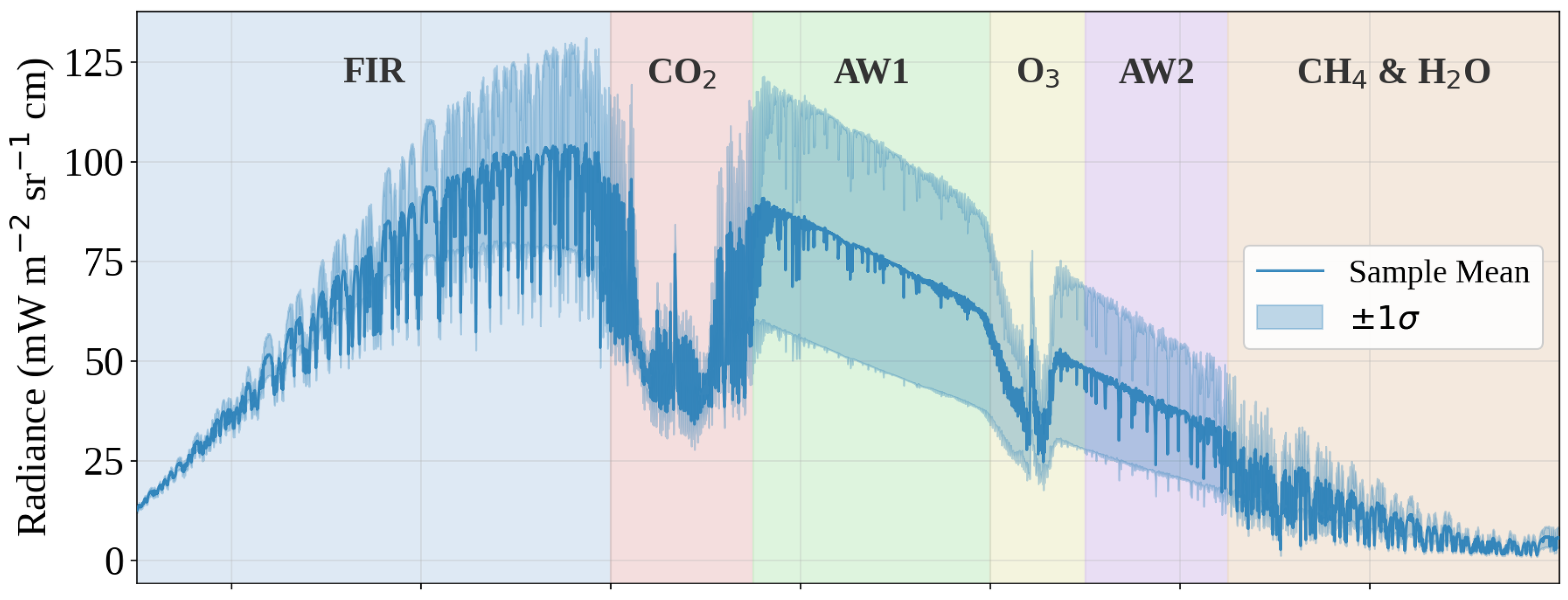
Introduction

Deep learning emulators offer a fast alternative to physics-based radiative transfer models. The top-of-atmosphere upwelling radiance simulated by them is:

$$I_\nu = \varepsilon_\nu B_\nu(T_s)\,\mathcal{T}_\nu(0, z_\infty) + \int_0^{z_\infty} B_\nu(T(z))\,\frac{d\mathcal{T}_\nu}{dz}\,dz + \text{scattering}$$

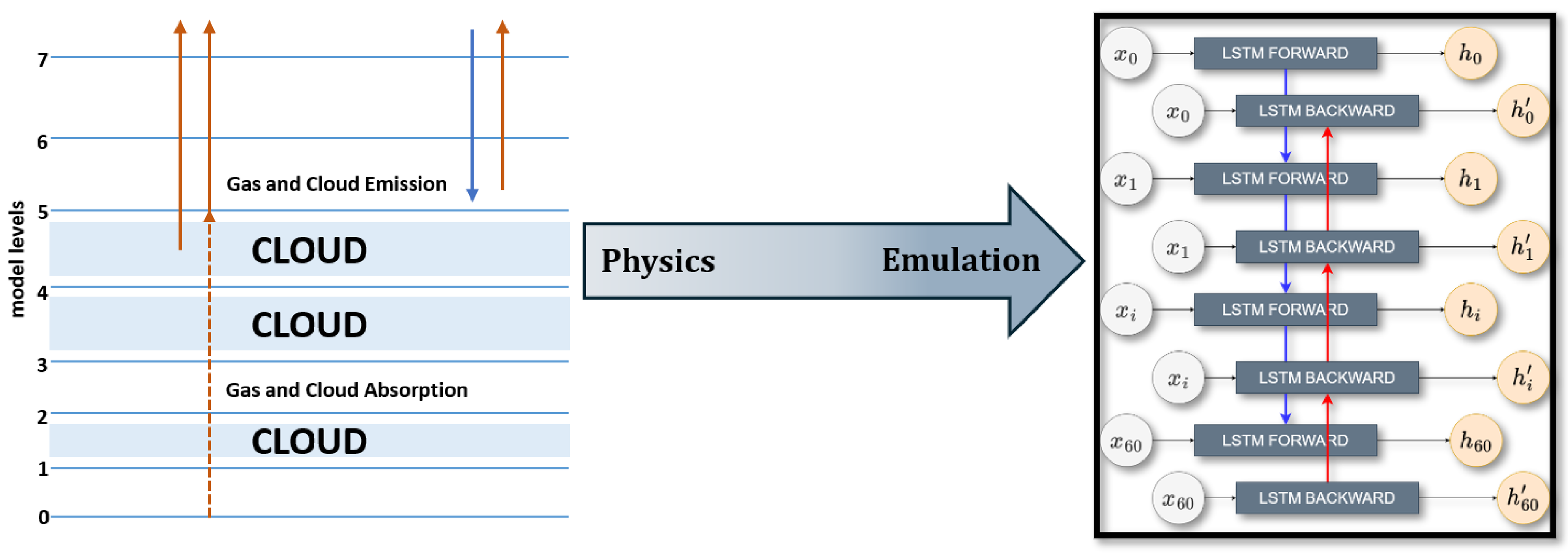
Solving this over fine discretized atmosphere and thousands of spectral channels is computationally demanding. We present a neural network emulator of RTM σ-***FORUM***, targeting the top-of-atmosphere spectra of the **FORUM** instrument — ESA's 9th Earth Explorer — which uniquely covers the infrared (100–1600 cm^{-1}), providing a tool for infrared satellite data assimilation, very important for NWP [1].



Deep Learning Modeling

Architecture: Mirroring the two-stream Radiative Trasfer

Atmospheric radiative transfer has an intrinsic two-stream structure, with radiation propagating both upward and downward through the atmospheric column. A **Bidirectional LSTM** (BiLSTM) naturally mirrors this physics [3], processing each layer sequence in both directions simultaneously.

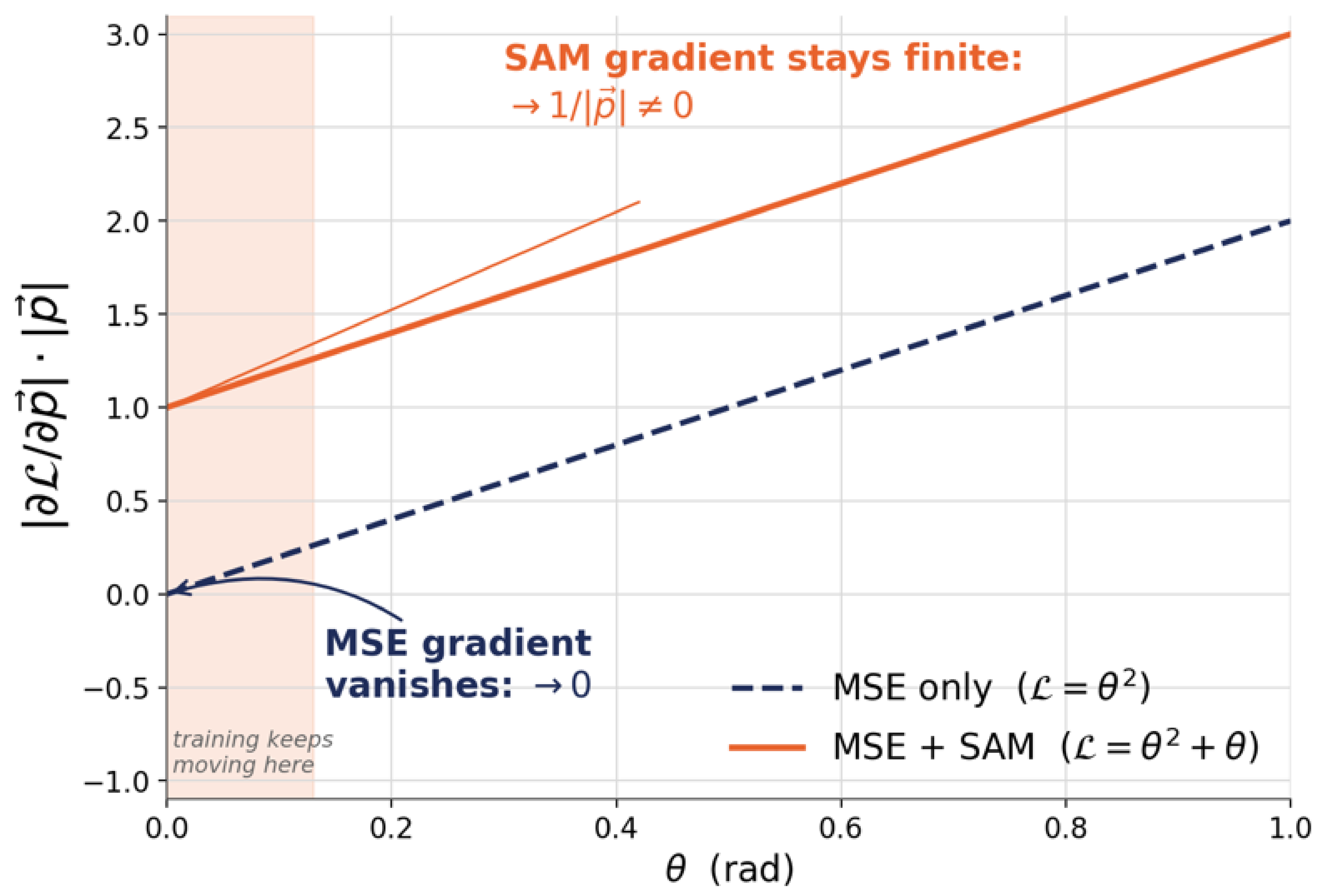


A Cross-Attention mechanism was implemented in order to capture the cross-correlation between the vertical atmospheric layer and the different absorption/emission problem for each spectral channel [2].

Loss function: Spectral Angle Constraintment

To enforce spectral shape fidelity, we augment the loss with the **Spectral Angle Mapper** (SAM), which measures the angle between predicted and target spectra in the C-dimensional radiance space, independently of their magnitude.

$$\mathcal{L} = \mathcal{L}_{\text{MSE}} + \alpha\,\mathcal{L}_{\text{SAM}} = \mathbb{E}\left[(\mathbf{p}-\mathbf{t})^2\right] + \alpha\,\mathbb{E}\left[\arccos\frac{\mathbf{p}\cdot\mathbf{t}}{\|\mathbf{p}\|\|\mathbf{t}\|}\right].$$



Although MSE already contain the angular information, this term during the training is able to give further contribution in small angles limit case. MSE instead has a vanishing gradient for this case.

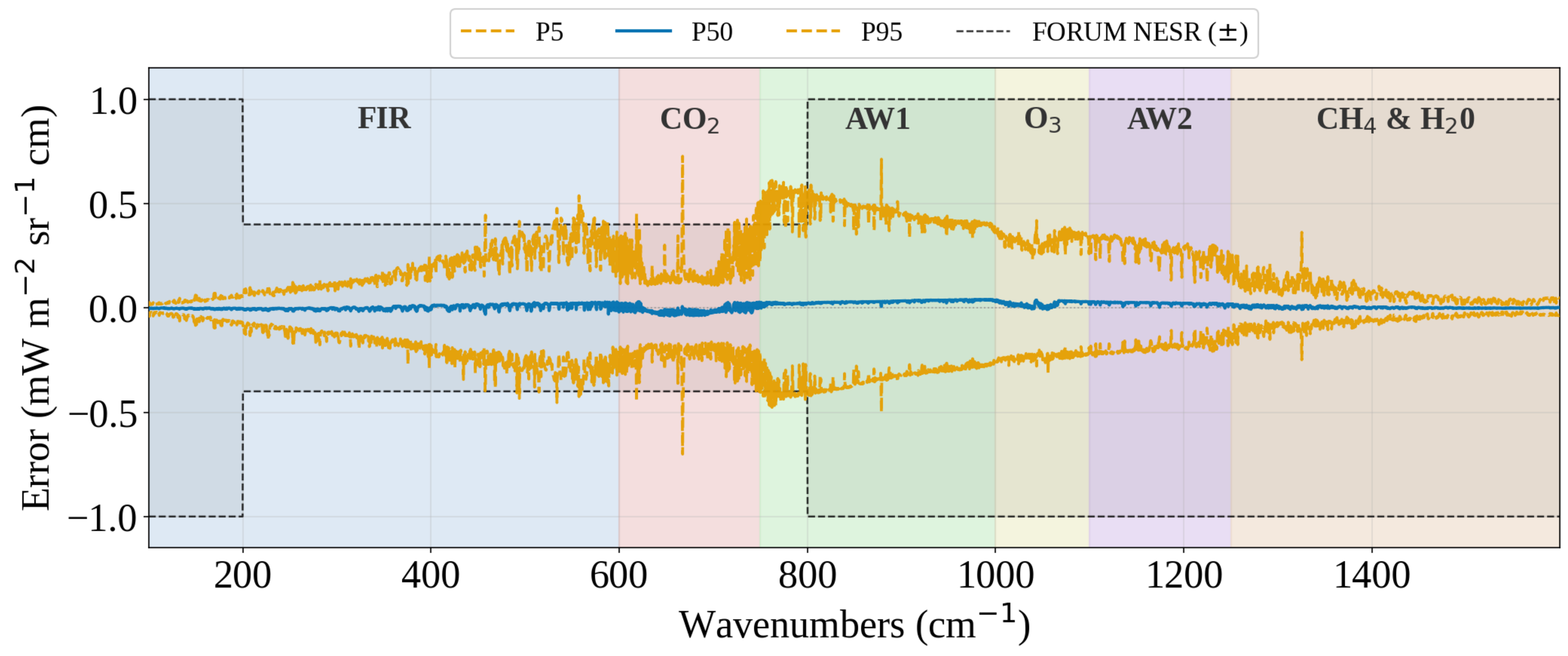
Results

On the independent test set the model was applied and evaluated, with error metric:

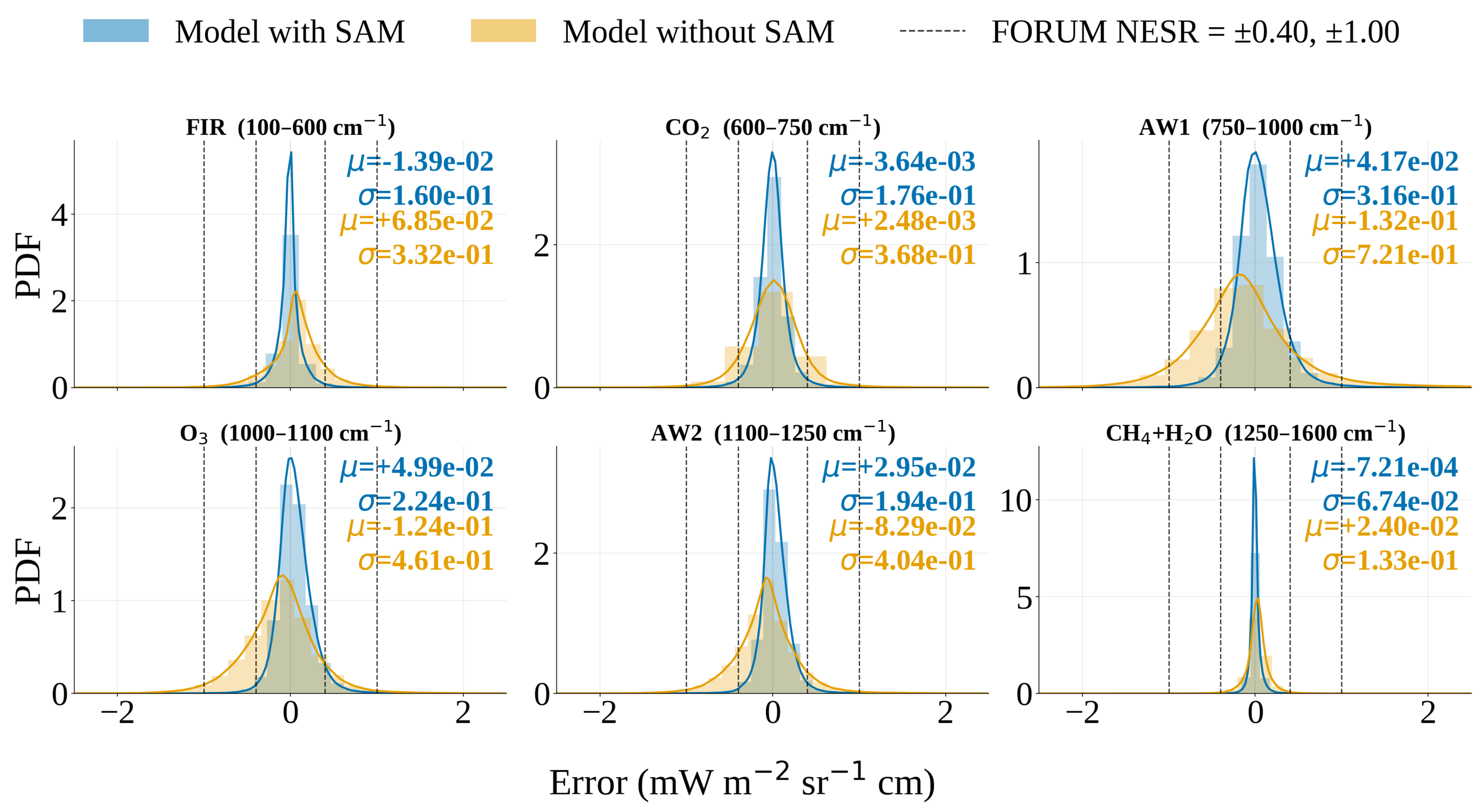
$$E = R_{pred} - R_{true}$$

In particular, the yellow lines represent the 5_{th} and 90_{th} percentiles, showing that the 90 $\%$ of errors is included in the NESR of instrumentation. This result confirms that the residual error introduced by the emulator remains below the noise floor of the FORUM instrument across the whole spectral range, from the far-infrared up to the mid-infrared channels.

As a consequence, the errors propagated through the emulator can be considered negligible for retrieval purposes, and the network can be safely exploited as a fast forward operator within an operational data assimilation framework, replacing the computationally expensive physics-based radiative transfer model without degrading the quality of the retrieved atmospheric and surface parameters.



In order to investigate how much contribute the penalty term to the errors, a further emulator trained with only the Mean Square Error was trained. The main impact of SAM is the shrinking of pdf, reducing bias and spread.



The following table shows the computational times (tested on a GPU NVIDIA RTX A4000, with 16 GB VRAM) of the models:

Model	Norm. inference time per channel (adim.)
σ-FORUM	1
Full-spectrum emulator	1.4×10^{-2}
8-channel emulator	7.5

Future Work

- **Data Assimilation:**
  Computation of Emulator Jacobian and integration as observation operator within DA schemes to assimilate already orbiting satellites (e.g. IASI-NG).
- **Polarized Radiance Assimiation:**
  What's the impact of assimilate polarized radiance on the atmospheric state reconstruction? Toward emulation of 3D radiative transfer solvers.

References

[1] A. J. Geer et al. All-sky assimilation of infrared radiances sensitive to mid- and upper-tropospheric moisture and cloud. *AMT*, 2019.
[2] Z. Li et al. All-sky microwave radiance observation operator based on deep learning with physical constraints. *JGR: Atmospheres*, 2024.
[3] P. Ukkonen. Exploring pathways to more accurate machine learning emulation of atmospheric radiative transfer. *JAMES*, 14(4):e2021MS002875, 2022.