Towards A Joint Retrieval Of Aerosols And CO2 From Space-based Hyperspectral Imager Data

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Greenhouse gas emissions from anthropogenic activities are the main driver of current global climate change. Emission monitoring is essential the verification of emission reduction efforts and a feasible way for attaining global coverage are satellite observations. Recent developments in space-based hyperspectral cameras open up new possibilities for greenhouse gas emission monitoring also on a smaller scale.

Most of the anthropogenic greenhouse gas emissions originate from urban areas. Urban areas are also sources of co-emitted atmospheric aerosols, which decrease the local air quality and complicate the atmospheric radiative transfer. Even slight concentrations of atmospheric aerosols can cause considerable inaccuracies in space-based remote sensing observations of carbon dioxide (CO2).

In this work, we present a novel retrieval method for a co-emitted CO2 and aerosol emission plume content originating from a point source observed from a satellite. We plan to test the method for a joint CO2 and aerosol retrieval and emission rate estimation from satellite-based hyperspectral imaging data, such as imagery obtained using PRISMA or EMIT. The solar and viewing angle dependent radiative coupling of adjacent camera pixels and co-emission of aerosols are investigated as means to improve the CO2 retrieval process.

Additionally, the prospect of optimizing radiative transfer (RT) calculations by preliminary wavelength pruning is examined. The presented approach reduced the amount of needed wavelengths in the calculation by 15 – 45 % in the tested cases and generalizes to arbitrary spectral observations.

As part of this work, a space-based hyperspectral imaging simulator is developed. The GPU-based simulator outputs top-of-the-atmosphere radiances in near- to shortwave-infrared wavelengths and thus enables a rapid retrieval of atmospheric constituents in a 3D atmosphere.

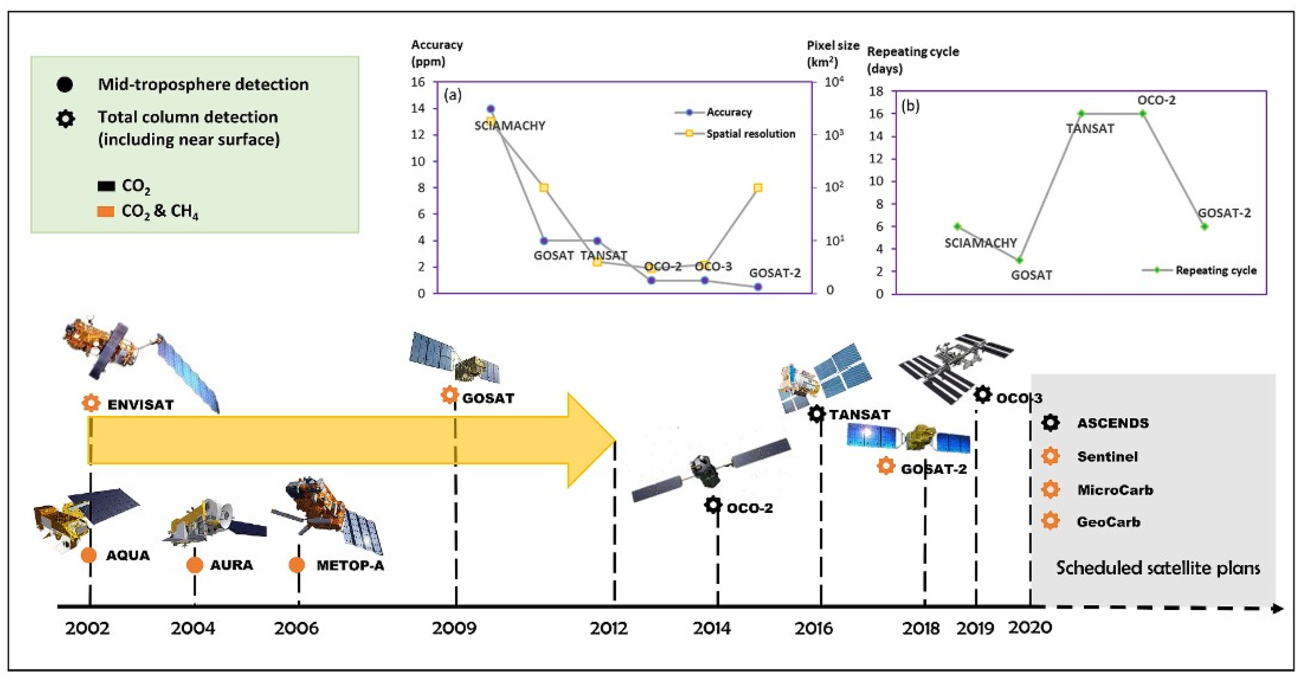
Greenhouse gas observations from satellites

Anthropogenic greenhouse gas (GHG) emissions are the main driver of the on-going climate change. Rapid and global reduction of GHG emissions is necessary to mitigate the effects of the climate change and satellite instruments are a vital aid in monitoring and verification efforts.

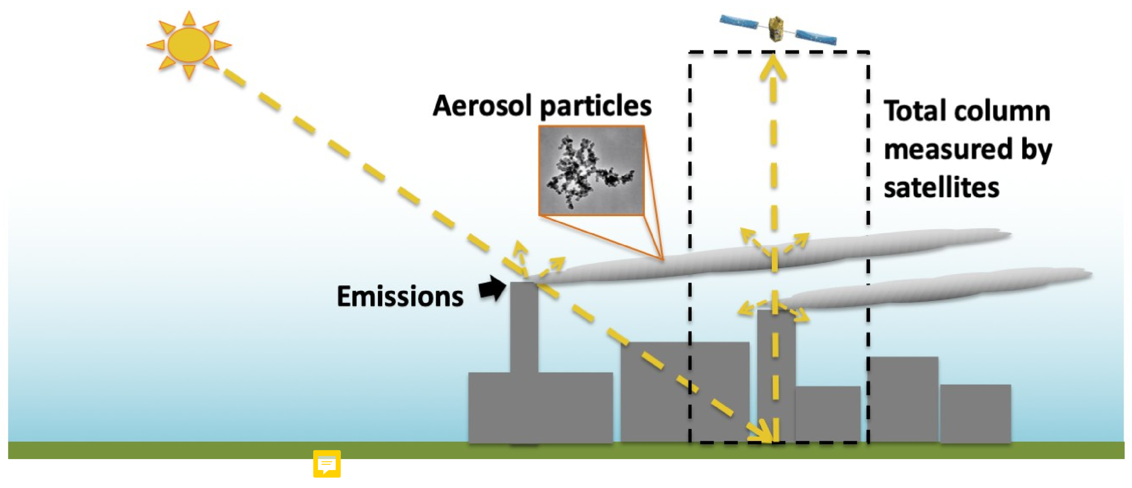
Space-based observations of atmospheric CO2 and methane (CH4) are based on measuring the solar radiation reflected from the Earth's surface in the near- and shortwave infrared wavelength region. The process to infer CO2 and CH4 content from the radiation spectrum is an inverse problem, which requires accurate modeling of the measurement and sophisticated numerical methods (Boesch et al. 2021).

Current GHG observing missions providing global coverage are Nasa's OCO-2/3, JAXA's GOSAT(-2) and MOST's TANSAT. However, their imaging capabilities are limited. Upcoming missions, such as ESA's CO2M, aim to extend these observational capabilities with even larger footprint to observe entire emission plumes. In addition, space-based hyperspectral cameras could also provide point source estimates in the future.

Boesch et al.: Monitoring Greenhouse Gases from Space, Remote Sensing, **13**, 2700, 2021, doi:doi.org/10.3390/rs13142700



Greenhouse-gas observing satellite missions (Pan et al.: The potential of CO2 satellite monitoring for climate governance: A review, *Journal of Environmental Management* 277 (2021) 111423, doi:10.1016/j.jenvman.2020.111423)



Takeaways

- 3D effects of the atmosphere become more pronounced with smaller ground pixel sizes.
- The basis function approach to atmospheric discretization can boost the computational efficiency of RT in 3D atmospheres.

Future work

- A realistic emission plume model with appropriate CO2 and aerosol content with more retrieval parameters.
- Test the effect of wavelength pruning on the retrieval results.
- Optimization of the RT model
  - Automatic wavelength pruning within the RT model.
  - Large hyperspectral scenes impose memory and performance restrictions, which can be tackled with GPUs.

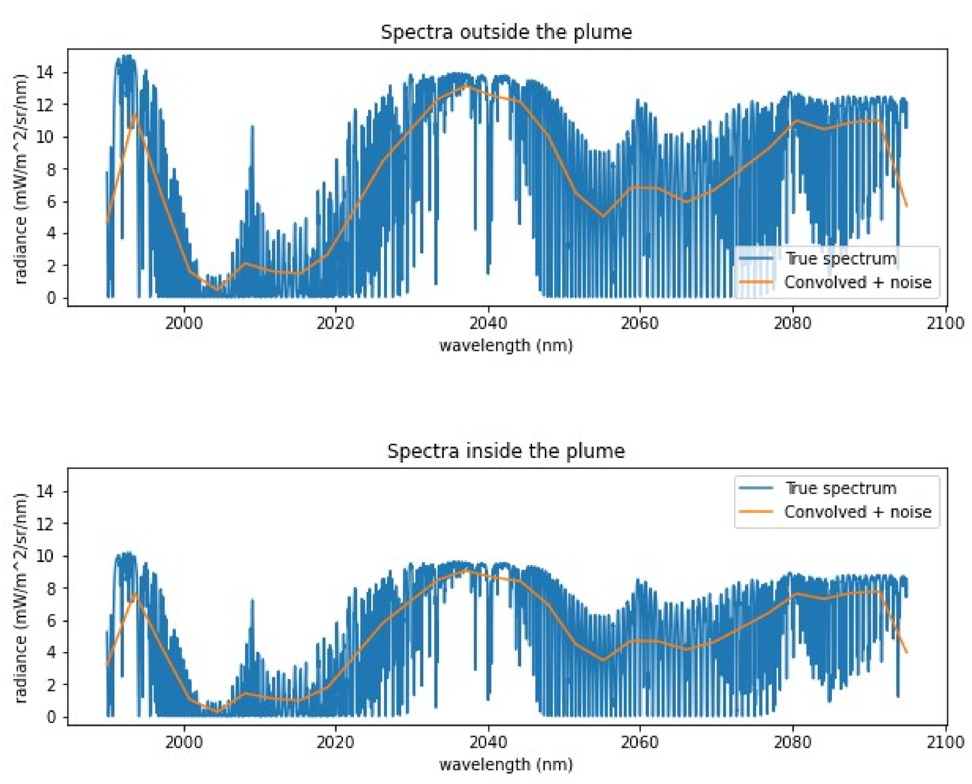
Simulation of co-emitted CO2 and aerosols.

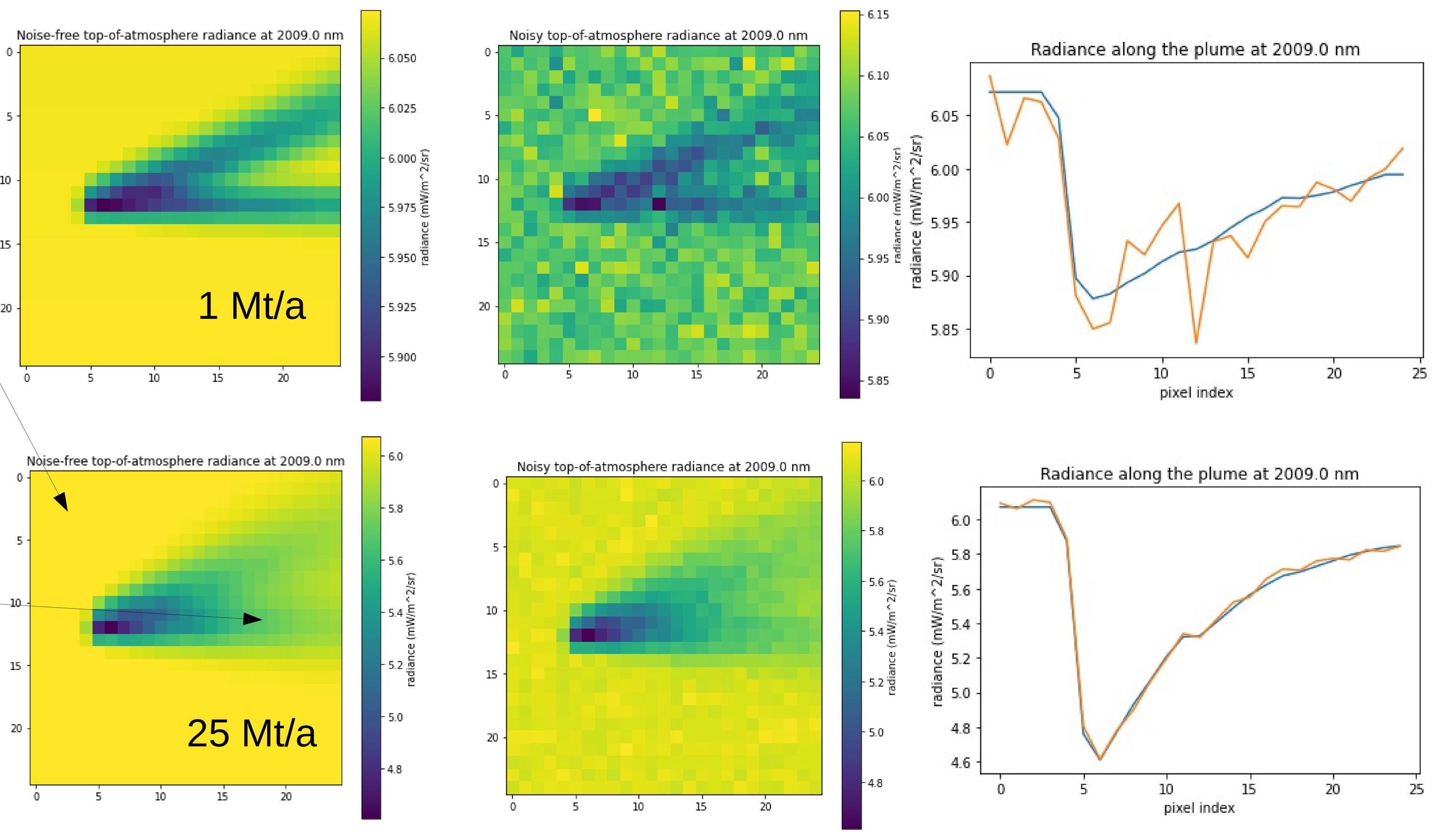
A hyperspectral camera imaging scene with a CO2 and aerosol emitter was simulated. The plume, composed of 30 Gaussian basis functions with different positions and standard deviations is carried by the wind directly eastwards. The altitude of the basis functions is also slightly increased the more east we are. Please note that this just a representative model of an emission plume and it is not based on measurements or transport equation solutions. The solar zenith angle is 50 degrees and the incident radiation comes directly from the south. Observe the shadow cast by the plume on the north side of it.

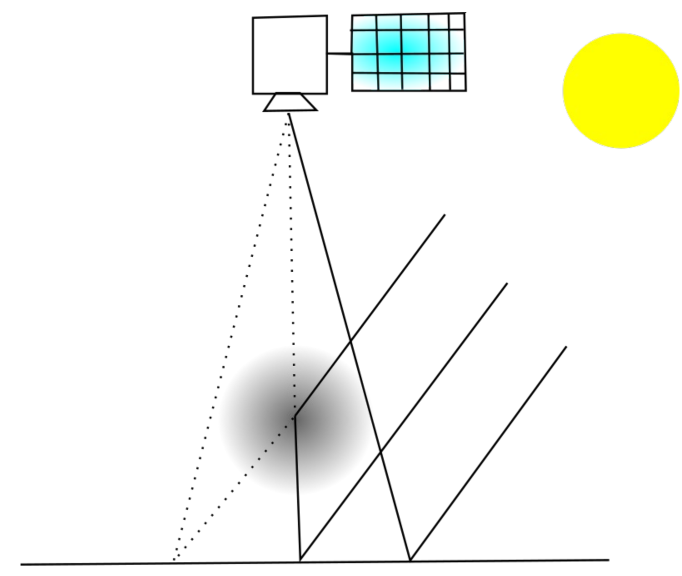
The camera image was 25 x 25 pixels with a ground resolution of 100 m in the nadir. The imaging instrument was at an altitude of 500 km and pointing to nadir. In the wavelength band from 1.99 - 2.095 µm, we simulated 12595 discrete wavelength. The dense spectra were convolved using a Gaussian slit instrument function with standard deviation of 3 nm and resampled, resulting in 30 wavelengths. To create our simulated measurement data, Gaussian noise using a signal-to-noise ratio of 300 was added to the convolved spectra. Black carbon (BC) aerosol and atmospheric Rayleigh extinction were taken into account, but signal increase due to scattering was neglected in this initial experiment. Additionally, background atmosphere and surface reflectivity of the scene were assumed to be known.

These simulations were carried out using Raysca (Mikkonen et al. 2023) RT model. Using a Gaussian prior distribution for CO2 and BC emission rates, we can do optimal estimation. The CO2 and BC emission rate were retrieved with maximal error of 0.02% from the true value, which indicates that there is lots of space for complicating the retrieval method further.

Mikkonen A, Lindqvist H, Peltoniemi J, Tamminen J: The non-Lambertian snow surface reflection models for simulated atmospheric transmittances in the NIR and SWIR wavelengths, JQSRT, (2023, in review)







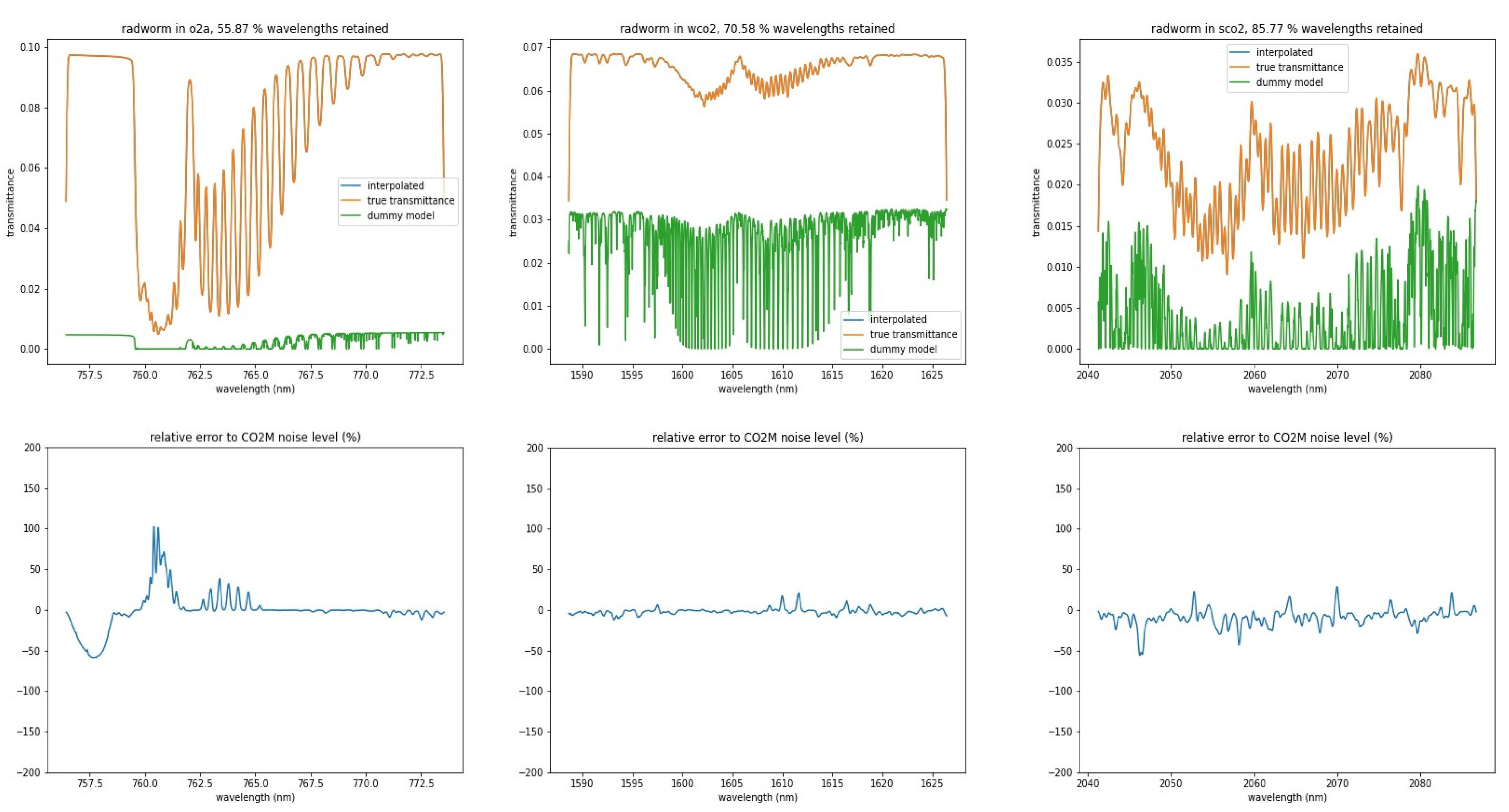
Optimizing radiative transfer models by preliminary wavelength pruning

New satellite instruments generate orders of magnitude more data than previous ones, which require optimization in data processing and modelling. One way to boost RT simulation efficiency is to select which wavelengths are most informative and which can be interpolated in the final result spectrum. A recent example of the developments in this field is by Mauceri et al. 2022. We created a method to select the important wavelengths case-by-case using a simplified RT model and analyzing its output spectrum. The actual RT model is then run using only the important wavelengths. Depending on the spectroscopy, this results in about 10 – 50% reduction in the needed wavelengths. The degree of acceptable interpolation errors is tied to the expected instrument measurement noise. These interpolation errors are reduced dramatically when smoothing the spectrum with the instrument function.

Here are simulated spectral observations from the CO2M mission and their corresponding interpolation errors compared to the instrument noise level. Each of the band has tens of thousands of wavelengths and in this case reductions of 15 – 45 % was reached. Future work includes testing errors on CO2M retrievals and with other instruments and algorithm specifications.

Mauceri S, O'Dell C, McGarragh G, Natraj V: Radiative Transfer Speed-Up Combining Optimal Spectral Sampling With a Machine Learning Approach, Front. Remote Sens. Sec. Multi- and Hyper-Spectral Imaging Volume 3, 2022, doi:https://doi.org/10.3389/frsen.2022.932548

Convolved with instrument function



RT model output