# Integrated instrument simulator suites for Earth Science

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## ABSTRACT

The NASA Earth Observing System Simulators Suite (NEOS$^3$) is a modular framework of forward simulations tools for remote sensing of Earth's Atmosphere from space. It was initiated as the Instrument Simulator Suite for Atmospheric Remote Sensing (ISSARS) under the NASA Advanced Information Systems Technology (AIST) program of the Earth Science Technology Office (ESTO) to enable science users to perform simulations based on advanced atmospheric and simple land surface models, and to rapidly integrate in a broad framework any experimental or innovative tools that they may have developed in this context. The name was changed to NEOS$^3$ when the project was expanded to include more advanced modeling tools for the surface contributions, accounting for scattering and emission properties of layered surface (e.g., soil moisture, vegetation, snow and ice, subsurface layers). NEOS$^3$ relies on a web-based graphic user interface, and a three-stage processing strategy to generate simulated measurements. The user has full control over a wide range of customizations both in terms of a priori assumptions and in terms of specific solvers or models used to calculate the measured signals.This presentation will demonstrate the general architecture, the configuration procedures and illustrate some sample products and the fundamental interface requirements for modules candidate for integration.

**Keywords:** Forward modeling, radiative transfer, scattering, emission.

## 1. INTRODUCTION

The first release of the NASA Earth Observing System Simulators Suite (NEOS$^3$.1) is an integrated set of tools to simulate active and passive instruments aiming at the remote sensing of the atmosphere. The concept of NEOS$^3$ is that of providing a modular framework to enable the creation of a 'universal' instrument simulator (for real-aperture instruments). All the modules necessary to simulate the instruments considered for deployment on the Aerosol/Cloud/Ecosystems mission (ACE, [1] p. 4-5) and those to be deployed on the Global Precipitation Measurement mission (GPM, [1] p.11-9) are implemented by incorporating state-of-the-art forward models from the microwave to the UV range, and integrating them so that a common input from atmospheric models is treated with consistent assumptions across the simulated instruments. The modularity of this approach has been tested and its range of applicability is being further expanded under a follow-on project to satisfy also the needs of instruments aiming at the observation of Earth surface (limitedly to real-aperture instruments). As such the name of the tool has been changed to NASA Earth Observing System Simulator Suite (NEOS$^3$), with ISSARS being version 1 and the follow on with additional capabilities version 2. In the remainder of this document we will use NEOS$^3_{.1}$ to indicate ISSARS specific items, and NEOS$^3$ when referring to features that are common to the overarching architecture.

The quality and accuracy of the simulations is determined by the capabilities of the state-of-the-art, ranging from very reliable and validated (i.e., adequate for inclusion in refined quantitative retrievals of various properties) to experimental or admittedly overly simplified (i.e., adequate only to obtain non-quantitative depictions of the observed quantities). One key property of NEOS$^3$ is that of being able to integrate new algorithms and forward models in a modular fashion and without the need of recompiling the entire suite. NEOS$^3$ allows also online custom instrument configuration definition (e.g., orbit, scanning strategy, beamwidth, frequency) to facilitate mission design trade studies. These features were first

implemented in the Matlab prototype of NEOS$^3$: a Doppler Simulator 3-D (DS3, [2]) focusing on radar observations and including very simple passive microwave – Eddington 1D approximation - and IR module.
NEOS$^3_{.1}$ includes modules for scattering, emission and absorption, including Doppler and polarimetric quantities, from atmospheric constituents (gas, hydrometeors and aerosol) and surface characteristics.
The overarching goal of NEOS$^3$ is to fill a specific existing gap: in general, each instrument, or at the most each mission, developed its own set of simulators, some empirical, some based on arbitrary assumptions applied to the output of atmospheric models (e.g., scattering properties of frozen hydrometeors and particle size distributions). The end result is that specific 'knobs' are used to match relatively small subsets of observables, and often they perform poorly when applied to other instruments. NEOS$^3_{.1}$ accepts as input fields generated by commonly used models (Weather Research Forecasting, WRF model [3], and NASA-Unified WRF [4] are the standard input), and handles all assumptions on microphysics and scattering calculations consistently among all instruments to allow:
A) immediate and accurate verification of achievability of desired scientific requirements by planned missions, in various configurations; use of NEOS$^3_{.1}$ will greatly benefit mission design and reduce mission costs.
B) integration in Observing System Simulation Experiments (OSSE) as provider of simulated observations for quantitative assessment of measurements impact and mission design optimization. Most importantly, NEOS$^3$ will enable the efficient implementation of multi-instrument, multi-platform OSSEs.
C) consistent, and statistically robust validation of forward model formulations and atmospheric model outputs by reanalysis of data products from existing satellite missions (e.g., TRMM, A-Train [5] , etc.). In fact, it is widely accepted that some of the current forward models need improvement. Significant efforts by the scientific community aim at developing new advanced models or at improving existing ones: NEOS$^3_{.1}$ will allow rapid integration of new models and will accelerate their validation and transition to higher technology readiness levels.
D) efficient and accurate performance assessment of on-board or at-ground processing methods aiming at the achievement of scientific requirements and goals given the available hardware and financial resources.
NEOS$^3_{.1}$ hinges upon the contributions of several scattering calculations and databases, Radiative Transfer Models (RTM), and simulators developed by the community in the last decades. In particular, the structure and approach adopted in DS3 and described in the next section is generalized and applied to preexisting codes to implement the modules.
The collaboration with the precursor multi-instrument simulator projects EarthCARE SIMulator (ECSIM, [6]) and Goddard Satellite Data Simulation Unit (G-SDSU, [7]) provides further guidance in the definition of candidate approaches and enriches the library of available modules.

## 2. ARCHITECTURE AND USER INTERFACE

The overall NEOS$^3$ software architecture was designed provide web-based job configuration, submission, and monitoring, independent of job processing which occurs off-line. Using a standard web browser on any Internet-connected computer, a scientist may request registration as a new user, login, view their job history, configure a new job via the Geophysics/Electromagnetics/Instrument (GEI) interface, submit a job for processing, and monitor progress.
A separate daemon process on the server checks periodically the job queue and assigns jobs to the workflow manager for processing. There is no need to keep the web server connection open during computation-intensive batch processing, which eliminates the possibility of web server time outs. The user may submit a job and return at any convenient time, even from a different computer, to check job status or retrieve results.
The NEOS$^3_{.1}$ off-line processor has a linear, pipelined dataflow divided in three main stages. The workflow manager (WM) is custom built in the Python programming language to ensure that the NEOS$^3$ infrastructure is portable, lightweight, flexible, and not bound to the data model implemented by generic workflow software. Nevertheless, the NEOS$^3$ computational components are modular and compatible with alternative workflow methodologies, for easy transition to these alternative tools as the need arises. Most modules are implemented as *plugins*, they are compiled as dynamic libraries and can be hot-swapped or upgraded with no need to recompile the entire suite.
The three stages of off-line processing are the Input Reconditioning Module (IRM), the Scattering/ Emission/ Absorption/ Modules (SEAM), and the Instrument Simulator Modules (ISM). A general description of the functions and capabilities of each stage is provided in [8]. This paper provides more detail on the user interface and updates on the modules integrated in the third stage (the ISM).
The parameters defining the requested operations at each stage are set in the main page of the GEI, called the 'Treeview' (Figure 1). The main Treeview area is divided in 4 sections (or *tabs*), the first one is relative to the functions and assumptions needed by the IRM stage, the second to those relative to the SEAM stage, and the third and fourth to the ISM stage (and indirectly affecting the SEAM stage). If a job is at a status where one or more stages have completed already, the corresponding tabs are greyed-out: the user can still see the selected options but not change them (since they

have been already used). There are two ways to change those choices: one can 'rewind' the job to the desired status (via the 'back' button in the Job Manager) to unlock the corresponding tabs, or 'save as new' the current job, exit and access the new job which will have the same identical selections, but will be in 'Draft' status. The former approach is recommended only to rectify errors, the latter is recommended for sensitivity studies or other trade-off analyses. Inside each tab the parameters are organized in a file-system-like hierarchical tree, where selected branches can be cloned to produce various options (most notably in the instrument section).

The most important functions covered by each of the trees in the four tabs are as follows:

Geophysics (see Figure 2)– selection of the input datasets, selection of the rules to assign a priori assumptions for particle size distributions, particle shapes and orientation angles, and selection of parameters describing multiple layers of the surface (the latter is functional at the IRM stage in $NEOS^3_{.1}$ but its output is not actually used in the following stages, which rely only on single-layer descriptions of the surface; integration of multi-layer surface scattering models is one of the main objectives of $NEOS^3_{.2}$).

Electromagnetics (see Figure 2) – selection of the scattering models for the surface and for the particles, and absorption models for gaseous species.

Instruments and Orbit – selection of the parameters describing the geometry (i.e., spacecraft trajectory sampled at each time of observation, velocity, viewing angle, etc., see Figure 4) and the instrument characteristics. Each *instrument* is described by an identical tree structure, and it can therefore be cloned, it can be copied and pasted into another to generate multiple instruments off of the same one by changing only a subset of parameters. The next level of the hierarchical structure of an instrument is the *channel* (one instrument can have one or more channels, each described by the same structure, channels are clonable), and each channel is composed of 4 sections: frequency, scanning geometry,

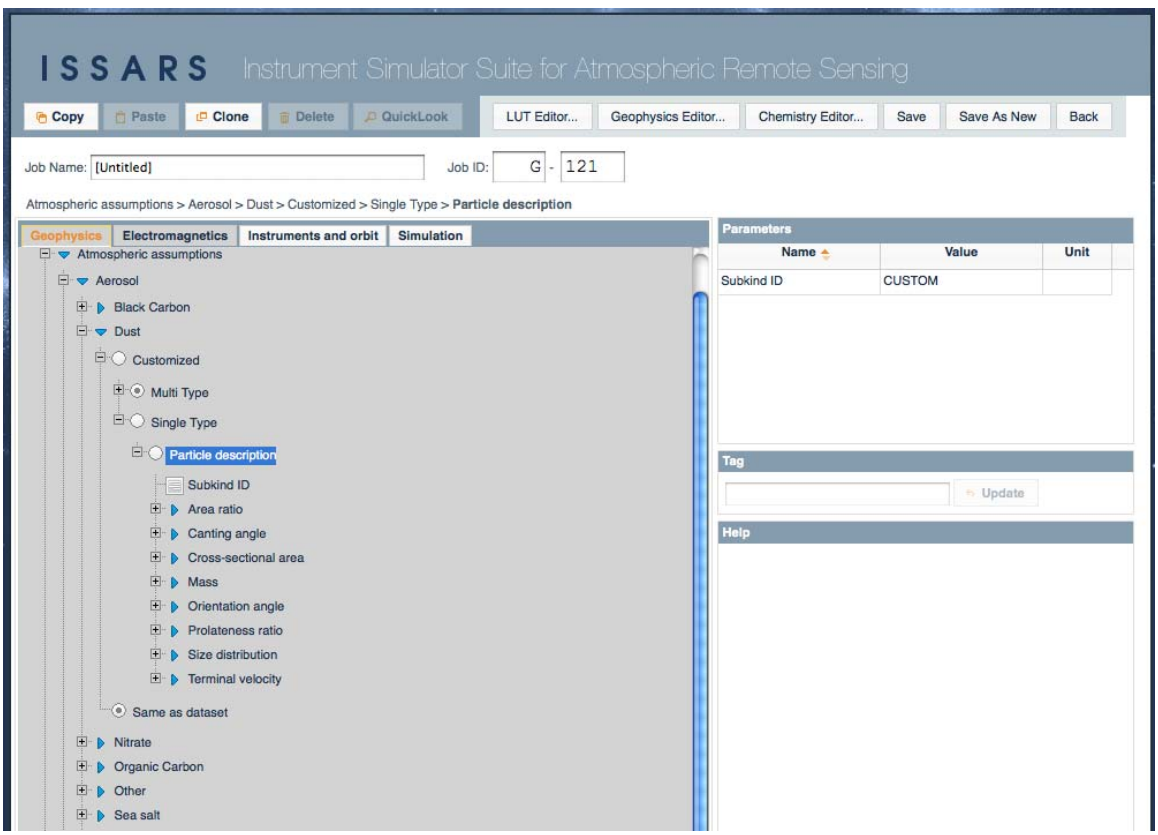


Figure 1- The Treeview interface. Top left: action buttons to copy, paste, clone and delete branches of the tree (e.g., clone an instrument to create a second one identical to be edited in some aspects) and to visualize the Quicklook of input data from cloud resolving models. Top right: access buttons to other editors, and to save the current configuration or exit the Treeview. Lower left: the main treeview area is divided in 4 tabs, each one containing a tree of options for the geophysical data and assumptions (it affects the IRM), the scattering and absorption models and assumptions (it affects the SEAM), the instrument characteristics (it affects the SEAM and ISM), and the parameters specific to the simulation strategies (it affects SEAM and ISM). In this particular snapshot the two leftmost tab sections are greyed out because the corresponding stages have been executed already: a user can only inspect the selections in the greyed out areas, but not change them. Lower right: dialogue panels, inclusive of editing and information only areas, their content changes based on the selected item in the treeview to the left.

receive path parameters, transmit path parameters (these options will be accessible only to authorized instrument scientists).

Simulation (see Figure 4) – this section includes the parameters that affect the process of simulating but do not describe instrument characteristics. For example, the antenna beamwidth is in the Instrument and Orbit section, but how many sub-beam directions are used to sample the pattern in the most sophisticated 3-D simulators is in the simulations section. Selection of the Radiative Transfer Model (RTM) to be used for a given category of instruments (radar, lidar, microwave/sub-mm passive, IR/VIS/UV passive) is also in this section.

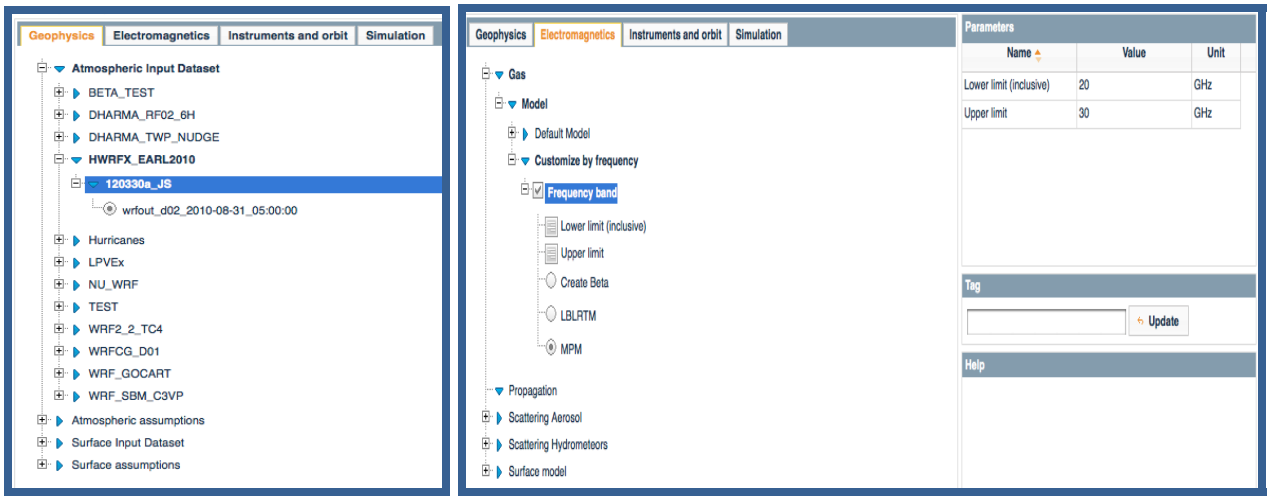


Figure 2 - Details of the Geophysics and Electromagnetics sections of Treeview. In the left example the user selected as input dataset an HWRF (Hurricane WRF) run of hurricane Earl, the only file available in that directory (the 'Atmospheric Input Dataset' tree updates automatically as new files are placed in the input data section of the system). In the right hand example the user is indicating that specifically in the range between 20 and 30 GHz the Millimeter wave Propagation Model should be used to calculate gaseous absorption instead of the Default, which is selected in a separate branch. Aspect ratio not preserved.

Other interfaces accessible from the Treeview are the editors of the Look-Up-Tables of scattering properties, of the microphysical assumptions, and the Quicklook tool to visualize intermediate products (see Figure 4).

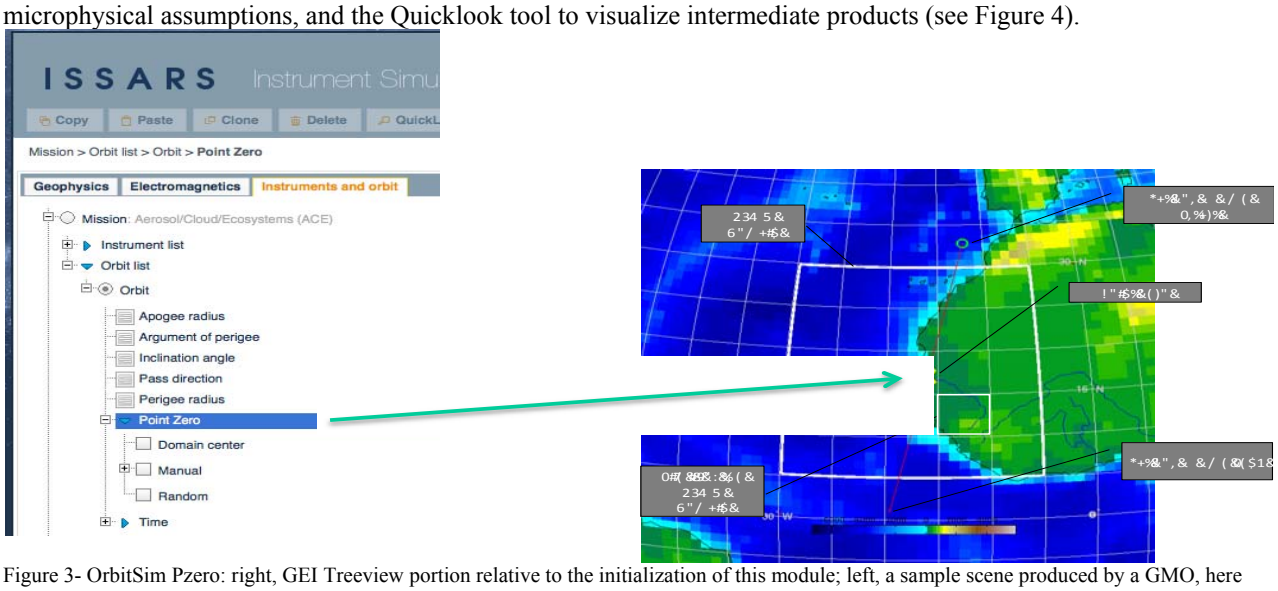


Figure 3- OrbitSim Pzero: right, GEI Treeview portion relative to the initialization of this module; left, a sample scene produced by a GMO, here divided in tiles. In this example the user chose a Pzero close to the center of the domain, an 82° inclination orbit at 705 km and requested a descending pass from 20 seconds prior to time zero, to 20 seconds after. Some of the positions so generated fall outside of the domain and will be discarded by the Beam Downselection module.

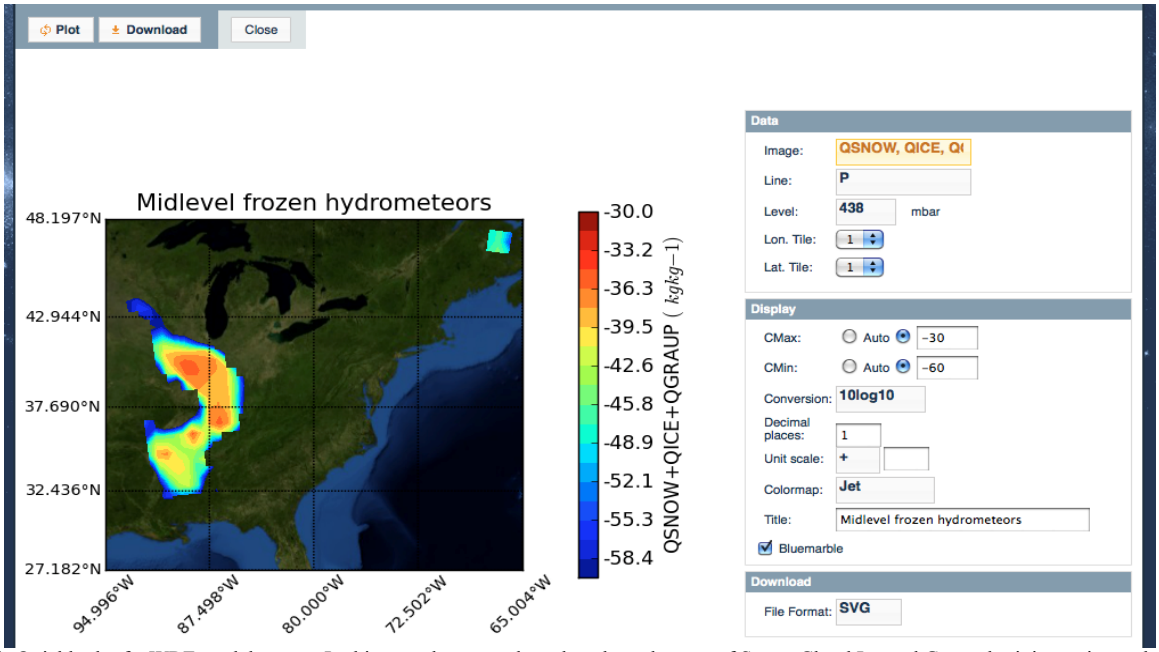


Figure 4- Quicklook of a WRF model output. In this case the user selected to show the sum of Snow, Cloud Ice and Graupel mixing ratios at the 438 mbar layer, show them in log scale with one decimal point precision, and name the plot 'Midlevel frozen hydrometeors'. These images can be saved in svg, eps or pdf file formats, or cut and pasted directly from screen. Images are rendered on-demand usually in a few seconds, directly from the data file.

# 3. RADIATIVE TRANSFER MODELS

The Radiative Transfer Models (RTM) are integrated in NEOS3 as *ism_beam plugin* modules. The work necessary to integrate an RTM is twofold: a) the main code must be converted into a subroutine or function, to be embedded in a wrapper that presents always the same interface to the WM; and b) inside the code, all the routines that were used to calculate particle size distributions, surface temperatures, scattering property calculations or other assumptions adopted to derive the single scattering, absorption and emission properties must be disabled and replaced by calls to a gateway function that will place the desired scattering and emission properties at the desired points by interrogating the memory area pre-allocated with the results of the SEAM stage.

In order to demonstrate the effectiveness of the NEOS$^3$ approach we integrated (at the time of writing) nine RTM: five Time Dependent RTM (TD-RTM) for active instruments, and four Time-Independent RTM (TI-RTM) for passive instruments. They were selected to span the entire range of complexity and diversity of approach.

## 3.1 Time-Dependent Radiative Transfer Models

The first RTM integrated in NEOS$^3$ has been the Doppler Multiple Scattering radar simulator (DOMUS, [9]). This RTM was selected because of its high level of sophistication that requires a comprehensive set of pieces of information to be used successfully. Namely, DOMUS accounts for the full antenna pattern shape and the 3-D distribution of particles inside the beam, it resolves in fast time (i.e., it resolves in range), and accounts for Doppler broadening and shifts at all interactions (i.e., it captures the process spectrum in slow time); it is fully polarimetric (i.e., it operates on Stokes vectors), it accounts for scattering in all directions (i.e., it requires the entire Phase Matrix sampled at sufficiently fine resolution) and it accounts for surface-particle interactions and gaseous absorption. While it certainly is not the fastest tool (probably one of the most 'expensive' active instrument simulators), it is a solid test-bed to define and put to a critical test all the interfaces.

DOMUS was then upgraded to account also for molecular scattering in order to simulate HSRL measurements, the resulting RTM has been integrated as DOMUS2 (see Figure 5 for example products of DOMUS2).

Two 1-D models have been integrated they represent the opposite class of radar and lidar simulators: extremely simple and fast. They are implementations of the basic radar/lidar equation with 1-D propagation, no Doppler information, no Antenna Pattern information, no multiple scattering and parametrized polarimetric return. It covers the functions of simulators such as the QuickBeam , the Radar or Lidar modules included in G-SDSU (version 2009), the radar module included in ECSIM first release (the latest ECSIM release uses DOMUS), and many others. One is labeled QUICK1D, it operates on the line-of-sight defined by the Orbit and instrument viewing geometry parameters ; the second is labeled

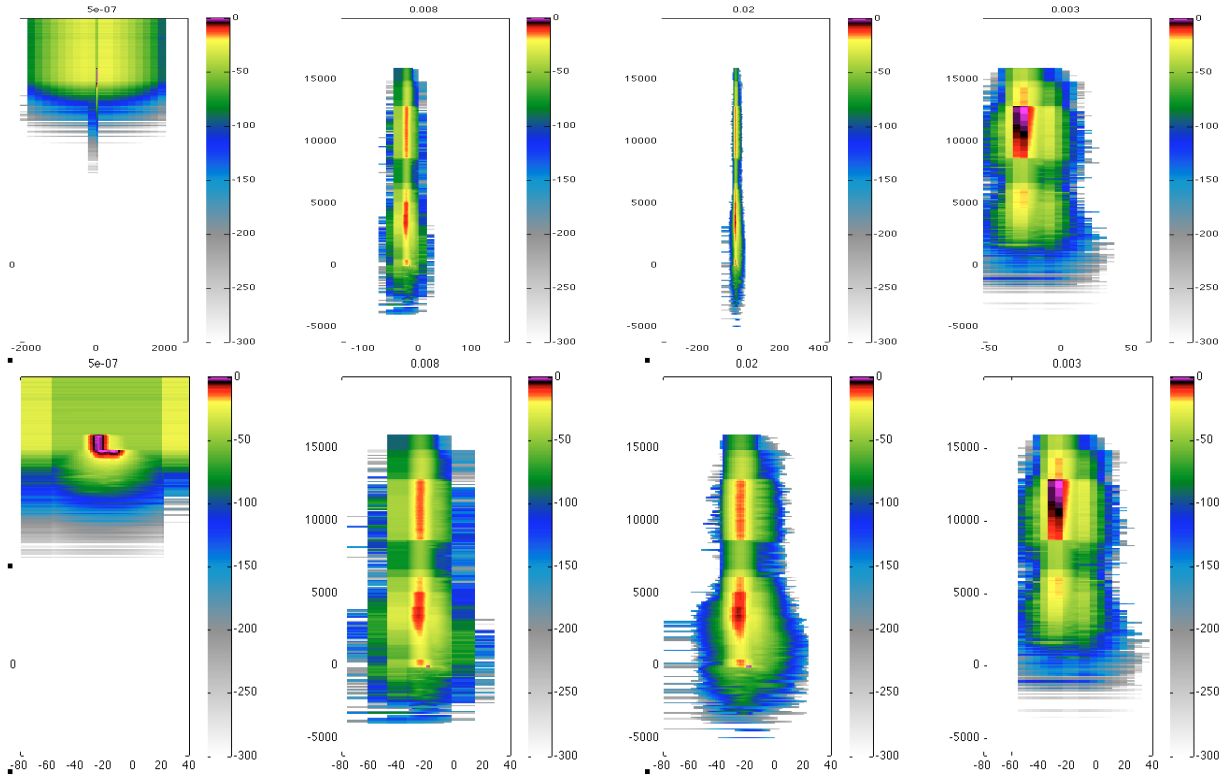


Figure 5 Vertical stack of Doppler spectra generated by DOMUS2 (one profile of the same simulation shown in Figure 6 but using DOMUS2 as RTM for four frequencies). The y-axis is altitude in m, the x-axis is relative Doppler velocity. From left to right: Green (532 nm), Ka-band (8.5 mm), Ku-band (22 mm) and W-band (3.2 mm) all assuming the same beamwidth and geometry. The lower row is the same data zoomed between -80 and +40 m/s in the Doppler axis. Power spectral densities are shown in a normalized dB colorscale: power spectral densities in the blue and grey ranges are likely outside of the dynamic range of most instruments.

VERT1D and it adopts the same implementation of the radar/lidar equation but it operates on each column of the input dataset, irrespective of the orbit and instrument viewing geometry. One example of the output of QUICK1D is shown in Figure 6. These modules are 2-3 orders of magnitude faster than DOMUS.

The last TD-RTM is is a middle-ground solution, and it is the actual simulator that was integrated in the Matlab prototype of NEOS[3]. This is a discrete ordinate, pseudo 3-D model [2] (that is, with 1-D propagation and with the 3-D distribution inside the beam resolved by sampling the antenna pattern at a fine scale and combining all the 1-D results accordingly). It includes simulation of the Doppler spectra but not polarimetric measurements. This TD-RTM has been designed and tested only in the microwave range, but its use as lidar simulator is possible with minor upgrades similar to the ones applied to DOMUS. Execution time is between QUICK1D and DOMUS.

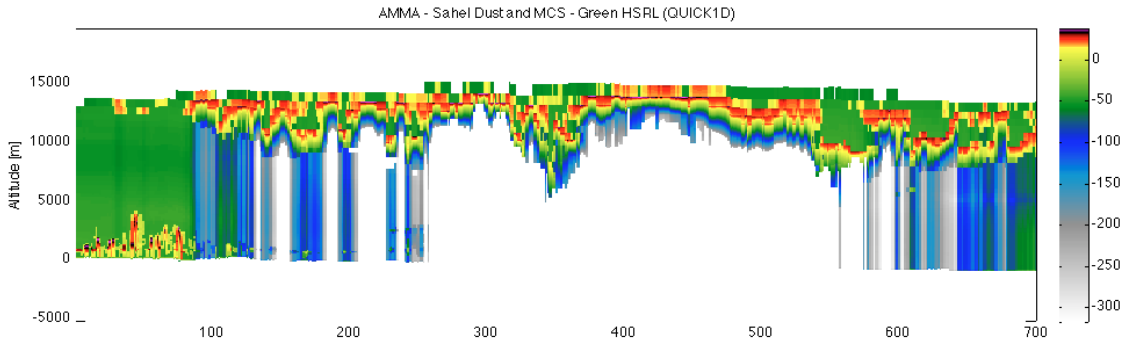


Figure 6 Example of QUICK1D product: Green backscatter (total) from a simulation over the AMMA domain: Sahel dust signature is visible in the first 100 beams, whith molecular scattering background visible above it. After beam# 100, the thick cirrus anvil obscures almost completely the lower troposphere.

### 3.2 Time-Independent Radiative Transfer Models

Successive-Order-of-Interaction (SOI) [10] is an iterative method for solving radiative transfer problem for 3D atmosphere. The method is based on the Successive-Order-of-Scattering (SOS) [11] technique that also uses an iterative approach to compute the overall scattering effect of multiple layers of atmosphere. For SOS, every layer of atmosphere has to be optically thin so that multiple scattering within a layer can be neglected. SOI method overcomes this limitation by utilizing a doubling method [12] to compute the scattering effect of an individual layer allowing the individual layer of atmosphere to be optically thick.
SOI method, however, has one limitation that the scattering atmosphere is assumed to have azimuthally symmetric radiation properties. For this reason, SOI is not appropriate for the application in visible wavelength where the directional contribution from the solar beam can no longer be neglected.
In SOI, the physical properties of the atmosphere are described in 3D grid where an extinction coefficient, a single scattering albedo and coefficients of the Legendre phase function can be described at each grid point. The particles are assumed to be spherical or randomly oriented. The brightness temperatures and radiances for horizontal and vertical polarization are the main output of the original SOI code. The SOI algorithm as integrated in NEOS$^3$ includes an algorithm that performs integration of brightness temperature over the pattern of the receiving antenna (i.e., this is a pseudo-3D approach as in DS3).

Spherical Harmonics Discrete Ordinate Method (SHDOM) [13] is an alternative radiative transfer solver integrated in NEOS$^3$. The method uses spherical harmonics to represent the source function in the integral equation while discrete ordinates are used to integrate the radiative transfer equation spatially. In contrast to the SOI approach, the method allows contribution from the solar beam to be included. Additionally, SHDOM uses adaptive gridding algorithm where finer resolution grids are to be added at run-time only when they needed. A limitation of the SHDOM method is, however, un-polarized radiative transfer is assumed.
For SHDOM, physical properties of the atmosphere can be specified per grid point similar to the SOI method. In the original code the choices to specify the contribution of the surface scattering are limited to a few built-in models. As SHDOM was integrated to NEOS$^3$, the code was modified to accommodate arbitrary BRDF (Bidirectional Reflectance Distribution Function) input provided by the SEAM stage. Antenna pattern integration functionality was also added to obtain a true 3-D module.

Despite the fact that it is computationally expensive, Monte Carlo approach remains an important method for solving radiative transfer problem because of its wide range of applicability. For instance, unlike SOI method, azimuthal symmetry of the radiation is no longer a requirement. The Monte Carlo algorithm [14] is integrated in NEOS$^3$. This method also allows the polarization of the wave to be tracked throughout every scattering event inside the domain. In the current version emission from gaseous species, particles, Earth Surface and cosmic background are accounted for. The extension to include Solar Emission will be implemented in the near future.

The most recently integrated TI-RTM is the 1-D polarimetric SOS [21], [22] model.

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## REFERENCES

[1] NRC (Nat. Research Council), "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," (2007)

[2] Tanelli S., E. Im, S. L. Durden, L. Facheris, D. Giuli, "The Effects of Nonuniform Beam Filling on Vertical Rainfall Velocity Measurements with a Spaceborne Doppler Radar," *J. Atmos. and Oceanic Technol.,* vol. 19, p. 1019-1034. (2002)

[3] Skamarock, W.C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, J. G. Powers, "A Description of the Advanced Research WRF Version 2," NCAR Tech Note, NCAR/TN-468+STR, 88 pp. (2005)

[4] https://modelingguru.nasa.gov/community/atmospheric/nuwrf/

[5] L'Ecuyer T. S. and J. Jiang, "Touring the Atmosphere Aboard the A-Train," Physics Today 39, 36-41. (2010)

[6] Voors, R., Donovan D., Acarreta J., Eisinger M., Franco, R., Lajas D., Moyano R., Pirondini F., Ramos J., Wehr T., "ECSIM: The simulator framework for EarthCARE," *Proceedings of SPIE*, Florence, Italy,vol. 6744, p 67441Y. (2007)

[7] Masunaga, Hirohiko, and Coauthors, “Satellite Data Simulator Unit: A Multisensor, Multispectral Satellite Simulator Package”. *Bull. Amer. Meteor. Soc.*, 91, 1625–1632. doi: 10.1175/2010BAMS2809.1. (2010)

[8] Tanelli S., N. Niamsuwan, M. P. Johnson, A. Battaglia, P. Li, J. C. Jacob, W. Tao, T. Matsui, C. A. Hostetler, K. Kuo, S. L. Durden, D. J. Diner, T. Y. Nakajima, T. S. L’Ecuyer, G. L. Stephens, A. Heymsfield, D. Donovan, J. T. Johnson, N. Majurec, “Instrument Simulator Suite for Atmospheric Remote Sensing (ISSARS)”, Earth Science and Technology Forum 2011, Pasadena CA, June 20-22, 2011. Available online at: esto.nasa.gov/conferences/estf2011/papers/Tanelli_ESTF2011.pdf. (2011)

[9] Battaglia, A. , S. Tanelli, “DOMUS: DOppler MUltiple-Scattering Simulator,” *IEEE Trans. Geo. Rem. Sens.*, 49(1), 442-450. (2010)

[10] A. K. Heidinger, C. O’Dell, R. Bennartz, and T. Greenwald, “The successive-order-of-interaction radiative transfer model, Part I: Model development,” *Journal of Applied Meteorology and Climatology*, 45(10): 1388–1402, (2006).

[11] Greenwald, T., R. Bennartz, C. W. O’Dell, and A. Heidinger, “Fast computation of microwave radiances for data as- similation using the successive order of scattering approximation,” *J. Appl. Meteor*, 44, 960–966, (2005).

[12] Hansen, J. E., “Radiative transfer by doubling very thin layers,” *Astrophys. J.*, 155, 565–573, (1969)

[13] K. F. Evans, “The spherical harmonics discrete ordinate method for three-dimensional atmospheric radiative transfer,” *Journal of the Atmospheric Sciences*, 55(3): 429–446, 2, (1998).

[14] A. Battaglia, S. Mantovani, “Forward Monte Carlo computations of fully polarized microwave radiation in non-isotropic media,” *Journal of Quantitative Spectroscopy and Radiative Transfer*, Volume 95, Issue 3, Pages 285-308. (2005)

[15] English, S., and T. Hewison, “A fast generic millimeter-wave emissivity model”, Proceedings of SPIE, 3503, 288-300. (1998)

[16] Weng, F., B. Yan, and N. C. Grody, “A microwave land emissivity model,” Journal of Geophysical Research, Vol. 106, No. D17, pp. 20,115-20,123, (2001)

[17] Rahman, H., B. Pinty, and M. M. Verstraete, “Coupled surface-atmosphere reflectance (CSAR) model 2: Semi-empirical surface model usable with NOAA Advanced Very High Resolution Radiometer data,” *Journal of Geophysical Research*, 98, 20,791-20,801. (1993)

[18] L. Tsang, J. A. Kong, and R. Shin, “Theory of Microwave Remote Sensing,” Wiley-Interscience, New York, (1985)

[19] L. Tsang and J.A. Kong, “Scattering of Electromagnetic Waves, Vol. 3: Advanced Topics,” Wiley Interscience, 413 pages. (2001)

[20] Read, W.G., Z. Shippony, M.J. Schwartz, N.J. Livesey, and W.V. Snyder, "The clear-sky unpolarized forward model for the EOS Microwave Limb Sounder (MLS)," IEEE Trans. Geosci. Remote Sensing 44, no. 5, 1367-1379, (2006)

[21] P. Zhai, Y. Hu, J. Chowdhary, C. R. Trepte, P. L. Lucker, D. B. Josset, “A vector radiative transfer model for coupled atmosphere and ocean systems with a rough interface,” J Quant Spectrosc Radiat Transf, **111**, 1025-1040 (w2010).

[22] P. Zhai, Y. Hu, C. R. Trepte, and P. L. Lucker, "A vector radiative transfer model for coupled atmosphere and ocean systems based on successive order of scattering method," Optics Express **17**, 2057-2079 (2009).