NASA's integrated Instrument Simulator Suite for Atmospheric Remote Sensing from spaceborne platforms (ISSARS) and its role for the ACE and GPM missions

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Abstract — **Forward simulation is an indispensable tool for evaluation of precipitation retrieval algorithms as well as for studying snow/ice microphysics and their radiative properties. The main challenge of the implementation arises due to the size of the problem domain. To overcome this hurdle, assumptions need to be made to simplify complex cloud microphysics. It is important that these assumptions are applied consistently throughout the simulation process. ISSARS addresses this issue by providing a computationally efficient and modular framework that can integrate currently existing models and is also capable of expanding for future development. ISSARS is designed to accommodate the simulation needs of the Aerosol/ Clouds/ Ecosystems (ACE) mission and the Global Precipitation Measurement (GPM) mission: radars, microwave radiometers, and optical instruments such as lidars and polarimeters.**

ISSARS's computation is performed in three stages: input reconditioning (IRM), electromagnetic properties (scattering/ emission/ absorption) calculation (SEAM), and instrument simulation (ISM). The computation is implemented as a web service while its configuration can be accessed through a web-based interface.

I. INTRODUCTION

The Instruments Simulator Suite for Atmospheric Remote Sensing (ISSARS) will be capable of simulating active and passive instruments aiming at the remote sensing of the atmosphere. The concept of ISSARS 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) will be 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. Indeed, 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 ISSARS 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. ISSARS allows also online custom instrument configuration definition (e.g., orbit, scanning strategy, beamwidth, frequency) to facilitate mission design trade studies. These features are implemented in the prototype Doppler Simulator 3-D (DS3, [2]) which focuses on radar observations (DS3 includes simple

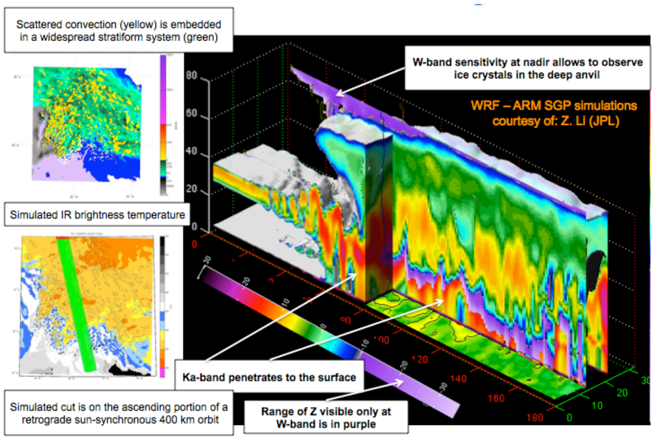

Figure 1. a) precipitation intensity and classification map from a 'truth' run generated by WRF; b) corresponding simulation of IR brightness temperature and swath of a notional ACE scanning radar on a polar orbiter; c) 3-D depiction of the radar reflectivity field at Ka- and W-band observed by the notional radar.

passive microwave and IR modules) and was used to generate data as shown in Figure 1.

ISSARS includes modules for scattering, emission and absorption, including Doppler and polarimetric quantities, from atmospheric constituents (gas, hydrometeors, aerosol and dust) and surface characteristics.

The overarching goal of ISSARS 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. ISSARS 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 ISSARS will greatly benefit mission design and reduce mission costs.

B) integration in Observing System Simulation Experiments (OSSE), made possible by optimizing the parallelization structure of the code, for quantitative assessment of measurements impact and mission design optimization. Most importantly, ISSARS 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: ISSARS 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.

ISSARS hinges upon the contributions of several scattering calculations and databases, radiative transfer models, 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 ECSIM [6] and SDSU [7] provides further guidance in the definition of candidate approaches and enriches the library of available modules.

II. ISSARS ARCHITECTURE

The overall ISSARS software architecture was designed to be compliant with the following guiding principles.

Web-based job configuration, submission, and monitoring are independent of job processing. Using a standard web browser on any Internet-connected computer, a scientist may register 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 periodically checks 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 ISSARS off-line processor has a linear, pipelined dataflow divided in three main stages, and a single-server architecture (at least for the current implementation). The workflow manager (WM) is custom built in the Python programming language to ensure that the ISSARS infrastructure is portable, lightweight, flexible, and not bound to the data model implemented by generic workflow software. Nevertheless, the ISSARS computational components are

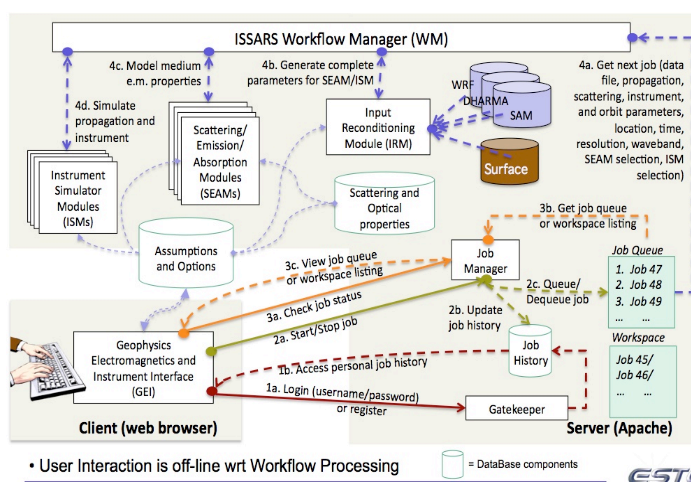

Figure 2. ISSARS architecture and its three main stages.

modular and compatible with alternative workflow methodologies, for easy transition to these alternative tools as the need arises.

Where appropriate data parallelism is applied with data partitioned among processing cores either by grid point (this is a typical 'embarrassingly parallel' problem, managed in an embarrassingly simple domain pre-partition approach called 'tiler') or by propagation path (e.g., in Monte Carlo based simulators such as DOMUS [8] planned for integration in ISSARS).

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). Data is passed between successive computational modules in memory for small datasets, or via files on disk for large datasets. The user may allow the WM proceed according to a default processing sequence, or take full control and run just a subset of the workflow.

A. User Interface

The web-based user interface is divided in a job management interface and the Geophysics/ Electromagnetics/ Instrument interface (GEI). GEI allows selection of either pre-packaged sets of rules and parameters representing existing models and instruments, or a fully customizable selection of options. The outputs of GEI are *job descriptor* files that include all parameter settings necessary for the execution of a job: they are parsed by the WM and by the modules. The parameter lists are saved as XML files and they can be used to run ISSARS in batch mode. GEI includes ancillary user interfaces for quick visualization of the input and intermediate data files (Quicklook tool), and for editing the library of geophysical properties of the species and materials assumed in each simulation (Species Editor and Chemistry Editor).

B. Input Reconditioning Module (IRM)

The IRM converts an Atmospheric Model Output (AMO) and a Land Model Output (LMO) into an intermediate data product sampled at the same grid points (space and time locations) but explicitly including all the parameters necessary to perform calculations of scattering and optical properties.

AMO is in general a 4-D (3-D plus time) array of collocated fields representing the state of the atmosphere and the characteristics of the underlying surface. ISSARS is being integrated and tested primarily with WRF and NU-WRF; it is designed to accept in input also other cloud resolving models (e.g., DHARMA [9] , SAM [10], [11], WRF-SBM [12] and UW-NMS [13]), and general circulation models after pre-processing for data format compatibility.

The *job descriptor* determines the rules by which the IRM associates to each species provided by the AMO one or more entries from the database of ISSARS species (where specific assumptions in regards to its physical characteristics are defined). For example, any single-moment atmospheric model will not provide the Particle Size Distribution (PSD) for a specific class of scatterers. Three possible options are to: 1) adopt the same exact parameterization of PSD used in the atmospheric model itself, 2) adopt a different parameterization according to pre-defined rules, 3) adopt a binned representation from in-situ measurements or climatological data. IRM's output is complete for all the variables needed by the next stage, reported at each point of the native AMO grid.

C. The Scattering/Emission/Absorption Modules (SEAM)

The IRM is followed by Scattering/Emission/Absorption Modules (SEAM). Scattering modules include the existing Rayleigh, Mie, T-Matrix [14], Discrete Dipole Approximation (DDA, [15]) and other libraries (e.g., [16], [17] , [18], [19] , [20]) which include calculated scattering properties for complex-shape particles. Also included in the libraries are the values of refractive index which describes the scattering and absorption capacity of the particles; appropriate numbers can be selected according to model assumptions or numbers published in literature, (e.g., for aerosol [21]). ISSARS is also contributing to the expansion of these libraries with a focused effort employing DDSCAT [22], [23]. The two most notable groups of such scatterers are: ice/snow crystals and their aggregates, and some types of aerosol/dust. Realistic snow/ice crystals and aggregates are generated with the 3-D version of Snowfake [24], a model capable of generating realistic crystals with the fine features found in nature. Such particles are converted into "shape" as input to DDSCAT for single scattering calculations. To create non-spherical aerosols, we use an open-source subdivision surface modeler: Wings3D. In 3-D computer graphics, a subdivision surface is a method of representing a smooth surface using a piecewise linear polygon mesh. Converter programs that convert the structure generated by Wings3D to input for DDSCAT are available.

Also included are millimeter wave propagation models (e.g., [25]) and HITRAN [26] database for Emission/Absorption by gaseous species. Surface scattering and emission modules will include the sea surface, and simple modules for snowpack and other land covers (e.g., [27], [28]).

SEAM options to calculate scattering and optical properties can be auto-selected based on particle size vs. wavelength ranges of applicability, or manually by the user. The output of the SEAM is still sampled on the AMO native grid, but the set of variables at each point is now replaced by the scattering and absorption properties relevant to each selected wavelength (plus the three components of air motion, necessary for Doppler calculations). The geophysical variables are processed by the instrument simulator (if so selected) in order to produce 'truth' values at the instruments' resolution and sampling positions (as done in DS3); however, they are kept separate from the main data stream for better memory management.

D. The Instrument Simulator Modules (ISM)

The final stage of ISSARS is that of the Instrument Simulator Modules (ISM) themselves, this stage will be implemented during the third year of this project. Here the observing geometry (defined by orbit propagator, scanning strategy, acquisition times, instrument beamwidths and range resolutions, etc.), and instrument characteristics (e.g., noise floor, pulse repetition frequency, etc.) are coupled by two submodules: first, a Propagator Module (PM) constructs from the viewing geometry and the electromagnetic grid input the expectation of the signal to be received, second an Acquisition Module (AM) processes the expected signal to include a realistic simulation of the output data from the instrument given the instrument characteristics. This approach guarantees very high efficiency if ISSARS is used to study instrument configurations, since one can reuse the intermediate product generated by the PM (not shown in figure) multiple times, bypassing all prior stages (see e.g., [29]). The PMs that will be included in ISSARS are: Doppler polarimetric radar modules (discrete ordinates [2], with and without a Monte Carlo scheme for multiple scattering [8]), a Lidar module (both the module from SDSU and LaRC's new module implementing standard backscatter, HSRL backscatter, and depolarization channels with and without Monte Carlo for multiple scattering), 1-D and 3-D Radiative Transfer (RT) models inclusive of surface characterization (e.g., [30], [31], [32], [33], [34], [35]) , and a Monte Carlo 3-D RTE solver [36]. Development of a new 3-D polarized RT model will be included when/if completed by collaborating projects. ISSARS modules will retain a certain level of customizability to accommodate variations upon a baseline configuration. For example, one of the polarimeter concepts has several non-contiguous narrow-band channels, starting from the UV (355 nm) down to the SWIR (2130 nm), with some of those channels having polarimetric sensitivity, and viewing angles ranging from -70 to +70 degrees fore/aft.

The AM that will be included in the open version of ISSARS will only include the basic instrument characteristics that usually characterize an instrument's performance at the 'marketing level' and are sufficient to reproduce L0/L1 products; however, team members from NASA institutions will be able to implement/access more complete AMs that reflect their own instrument characteristics in greater detail. Any portion of the code of modules containing proprietary information will not be shared; the executable binary versions could still be employed as black boxes by the other investigators, according to the specific licenses and agreements.

III. ISSARS ROLE FOR THE ACE AND GPM MISSIONS

ISSARS output is expected to facilitate a) development and validation of new algorithms for calculation of the scattering and radiative properties of cloud and aerosol particles, and surfaces; b) development and validation of retrieval algorithms, especially in the case of multi-instrument algorithms; c) assessment of instrument performance and mission impact, and therefore mission configuration.

Synthetic datasets have been already produced both for the GPM algorithm development team (with DS3 and SDSU) and for the ACE Science Working Group (see e.g., Figure 1). A significant effort has been dedicated towards the production of many relevant and validated model runs. ISSARS is expected to augment such efforts by providing the means to rapidly and efficiently explore the sensitivity of retrieval algorithms and instrument configurations to realistic atmospheric and surface scenes. For GPM some of the ongoing studies pertain impact of non-uniformities in rain pattern, algorithm sensitivity to assumptions in PSD and cloud liquid water content, melting layer characterization, beam mismatching and sampling, and use of surface reference techniques. For ACE a broader set of sensitivity studies is ongoing to assess the impact of potential instrument configurations.

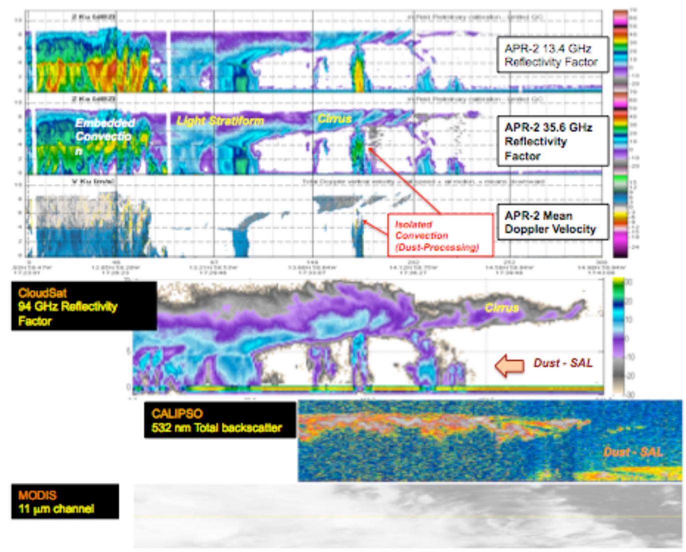

Figure 3. September 21, 2010 NASA GRIP – A-Train Underflight ~ 13.5N 58.5W. Top to bottom: Ku-band radar reflectivity (APR-2 on NASA DC-8), Ka-band reflectivity (APR-2), Ku-band mean Doppler velocity (APR-2), W-band reflectivity (CPR on CloudSat), lidar backscatter (CALIOP on Calipso), and infrared brightness temperature (MODIS on AQUA).

ISSARS will also allow expanding the possible combinations of instruments simulated to facilitate multi instrument retrievals of cloud/precipitation/aerosol properties from scenarios like the one depicted as an example in Figure 3.

IV. ACKNOWLEDGMENTS

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