JCSDA Developments Supporting Polarimetric Radio Occultation Simulation for Data Assimilation Applications

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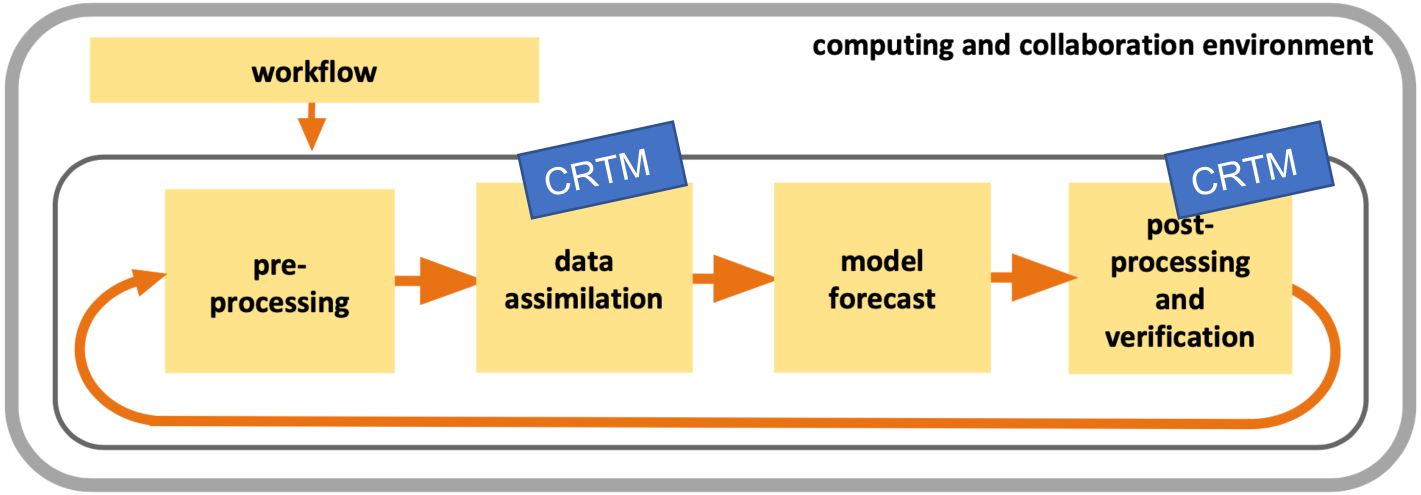
Overview

- CRTM Introduction
- Scope / Context
- Hydrometeor Modeling
- Polarimetric RO simulation requirements
- Data Assimilation activities and requirements to support PRO

CRTM: the critical enabling component

- Enables DA in US systems
  - UFS, GFS, RRFS, UPP, etc.
  - JEDI/UFO, MPAS-JEDI, WRF-DA, etc.
  - GEOS, MERRA
  - Navy / Air Force

Parts of a UFS Application



Pre-processing and data assimilation	• Stages inputs, performs observation processing, and prepares an analysis
Model forecast	• Integrates the model or ensemble of models forward
Post-processing and verification	• Assesses skill and diagnoses deficiencies in the model by comparing to observations
Workflow	• Executes a specified sequence of jobs
Computing and collaboration environment	• May be different for research (experiment focus) and operations (forecast focus) • Provides actual or virtualized hardware, databases, and support

CRTM

Inputs:

Atmospheric & Surface state (x)

Outputs:

TOA Radiance, Jacobian(x)

Support for Polarized **UV, VIS/near-IR, IR, sub-MM, MW** – future: far IR.

Instrument specific (center frequency, bandwidth, side bands, viewing geometry, polarization basis, spectral response)

Clouds: multi-species / habits supporting clouds / precipitation from VIS -> MW, microphysics-model specific LUTs (Thompson, GFDL, WSM-6)

Aerosols (detailed later)

Gaseous species available in CRTM: H_2O, CO_2, O_3, N_2O, CO, CH_4, O_2, NO, SO_2, NO_2, HNO_3, N_2, OCS, and CFCs – *many others available from LBLRTM, not yet used in CRTM.*

Surface properties: land (soil moisture, vegetated), ocean (wind, foam,), sea-ice, snow cover (land, sea-ice, depth) --- primarily tested in IR/MW.

Active sensor: space-based radar (v3.1) / lidar (backscat, extinct.)

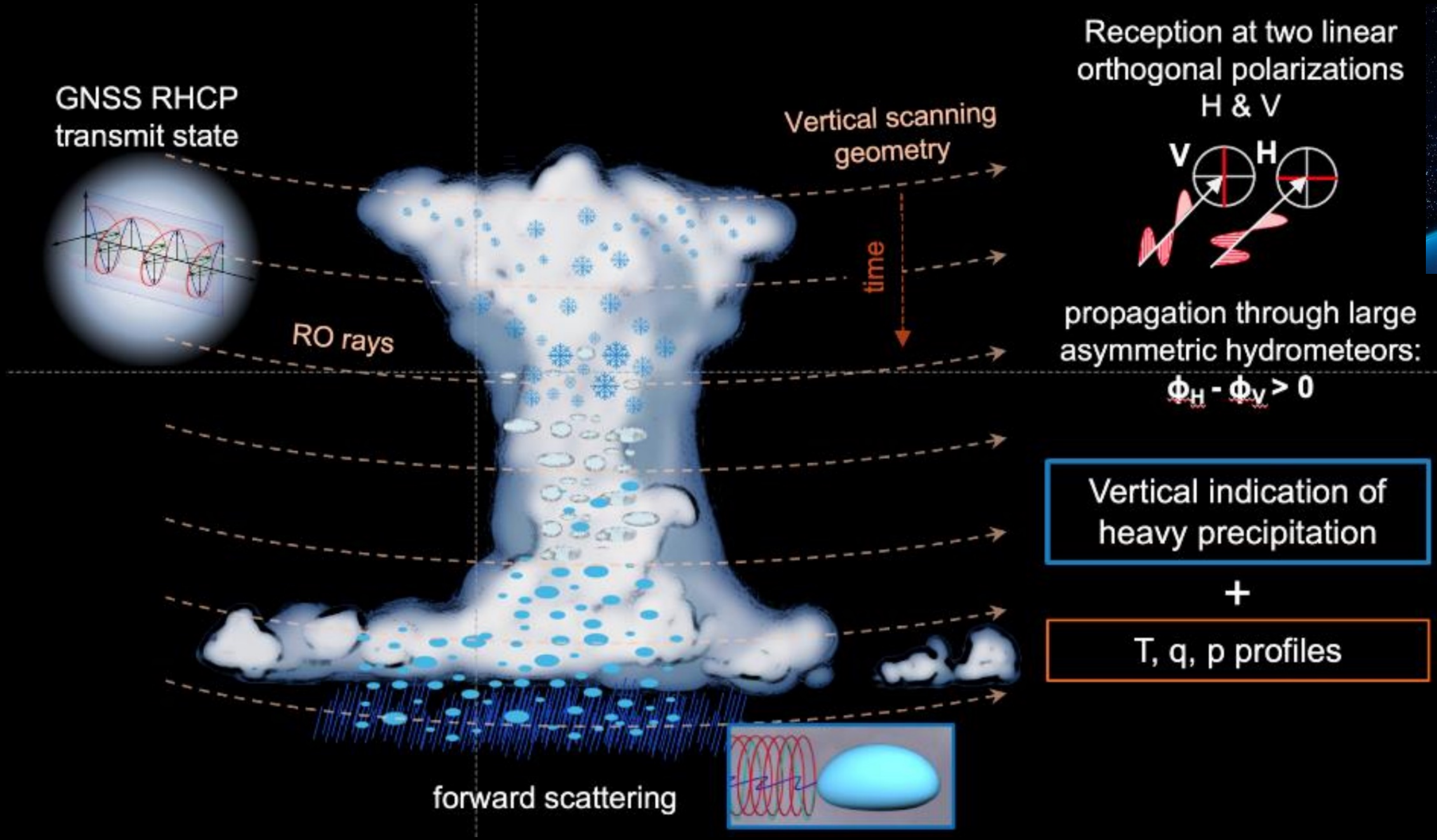
Non-LTE (daytime) and Zeeman effects; Aircraft-based simulation

CRTM Modeling Drawbacks

CRTM assumes randomly oriented hydrometeors (solver)

- This substantially reduces the sensitivity to the polarizability of hydrometeors (particularly at L-band)
- CRTM relies on pre-computed LUT of particle size distribution (PSD)-integrated optical properties.
- New LUTs could be created with oriented hydrometeor properties to “force” phase delay calculations.

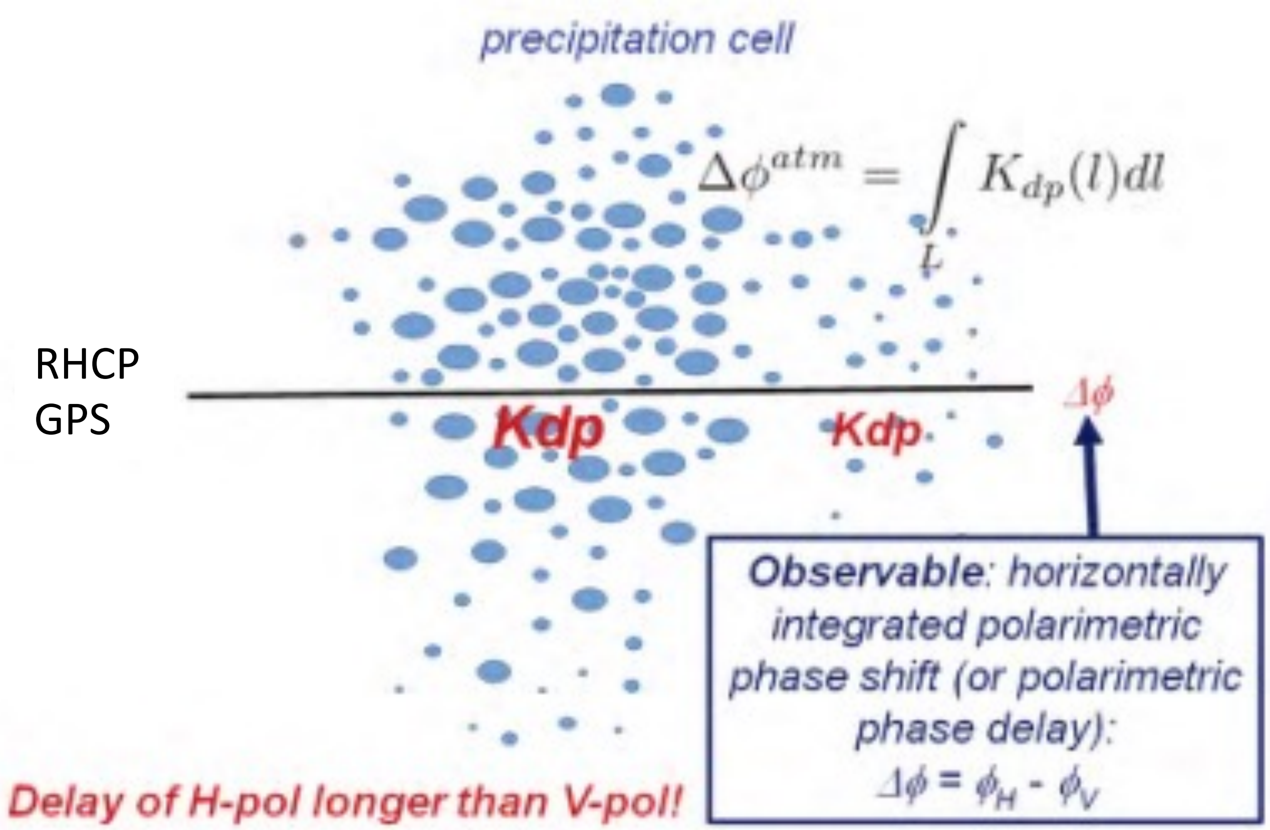
Scope / Context : ”Input / Output” (1/2)

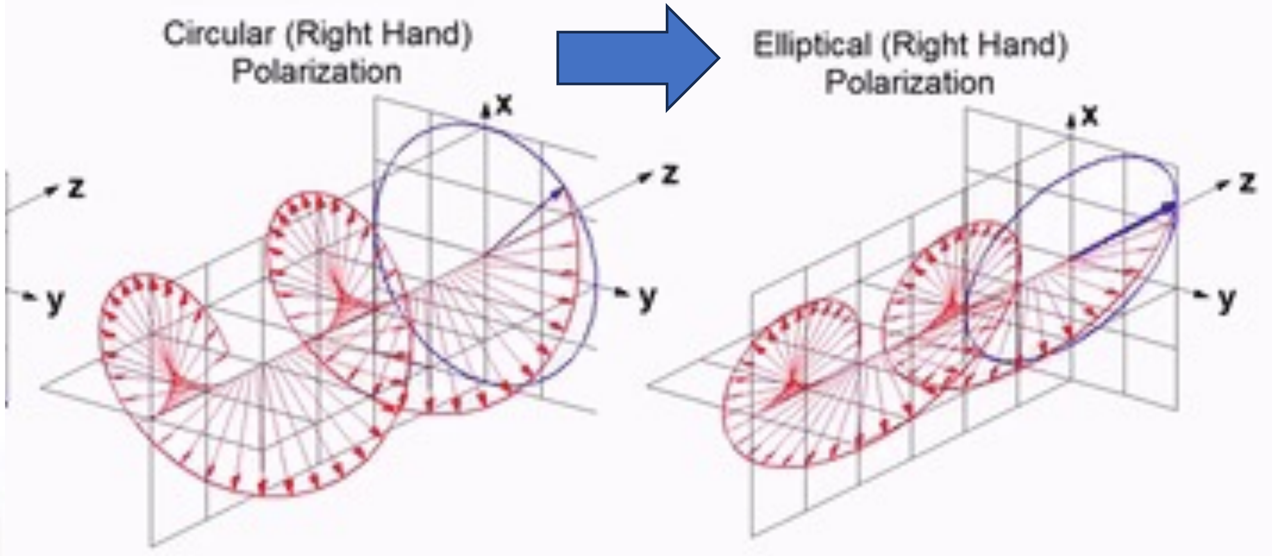


Turk, F.J., Padullés, R., Ao, C.O., Juárez, M.D.L.T., Wang, K.N., Franklin, G.W., Lowe, S.T., Hristova-Veleva, S.M., Fetzer, E.J., Cardellach, E. and Kuo, Y.H., 2019. Benefits of a closely-spaced satellite constellation of atmospheric polarimetric radio occultation measurements. *Remote Sensing*, *11*(20), p.2399.

Scope / Context: ”Input / Output” (2/2)

- GNSS systems transmit / receive right-hand circular-polarized (RHCP) signals.
- Hydrometeors modify the polarization state, depending on shape, size, orientation, and composition.





Cardellach, IEEC Spain

Hydrometeor Modeling

Goal: Accurate optical properties of realistic hydrometeors at L-band (~1.5 GHz)

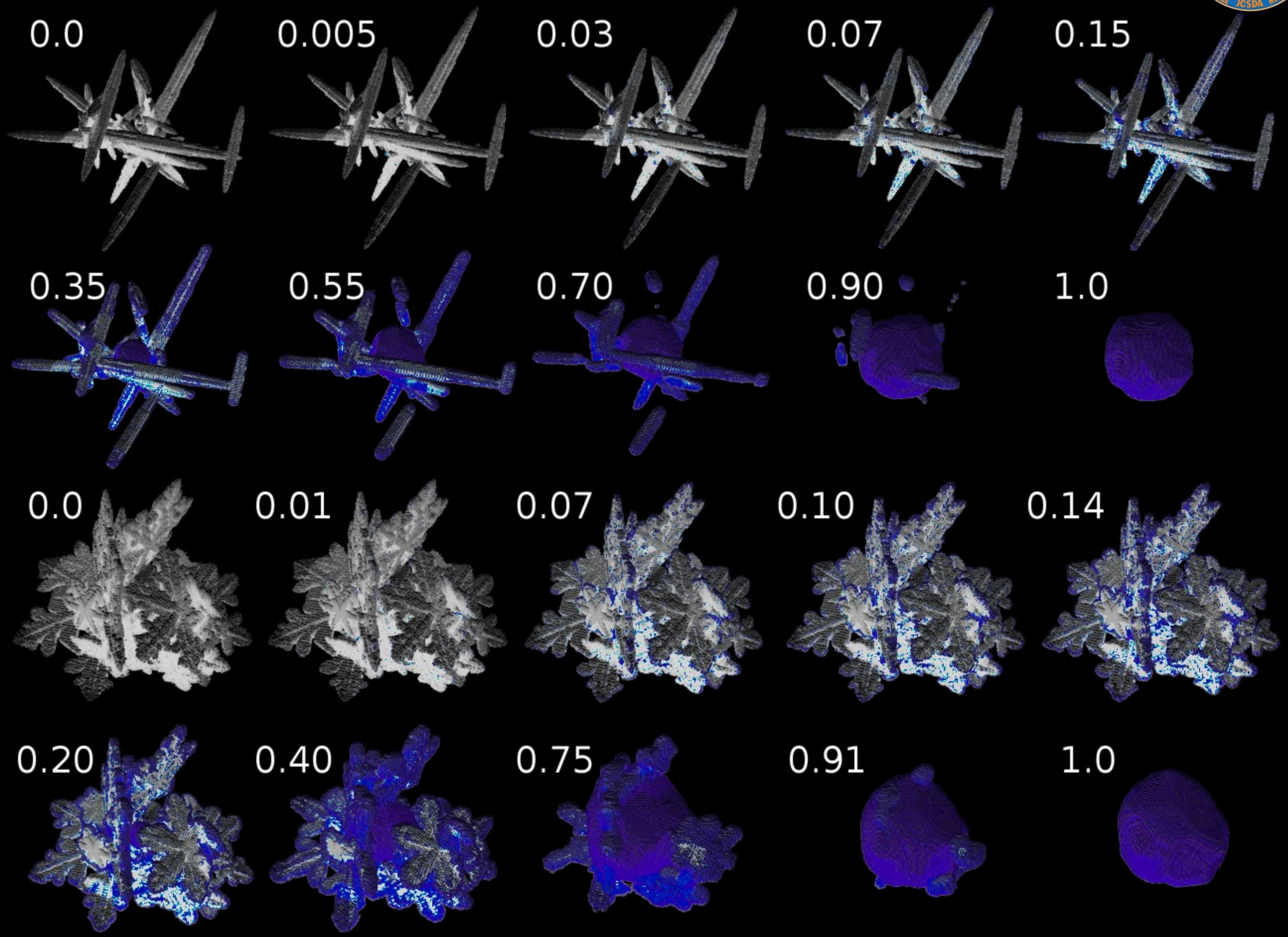
- Key challenges for CRTM simulations of PRO
  - Signal primarily forward scattered, and primarily Rayleigh regime
  - Hydrometeor physical properties are not known a priori
  - Dielectric properties of ice / water are temperature and "density" dependent
  - Accurately simulating Phase Delay requires knowledge of the atmospheric state along the path (i.e., the integrated optical properties, atmospheric thermodynamic properties, ionospheric effects, GNSS-RO doppler effects, etc.)
- Hydrometeor challenges to be considered
  - **Ice-phase**
    - confounding characteristics: wide range of possible shapes/densities, orientations, temperatures, ray-path variability
  - **Liquid-phase**
    - characteristics: non-spherical (large drops), temperature dependence, canting angles, ray-path variability
  - **Mixed-phase**
    - Melting layers present unique challenges due to rapid shift in dielectric properties from ice to liquid

Optical Properties at L-band

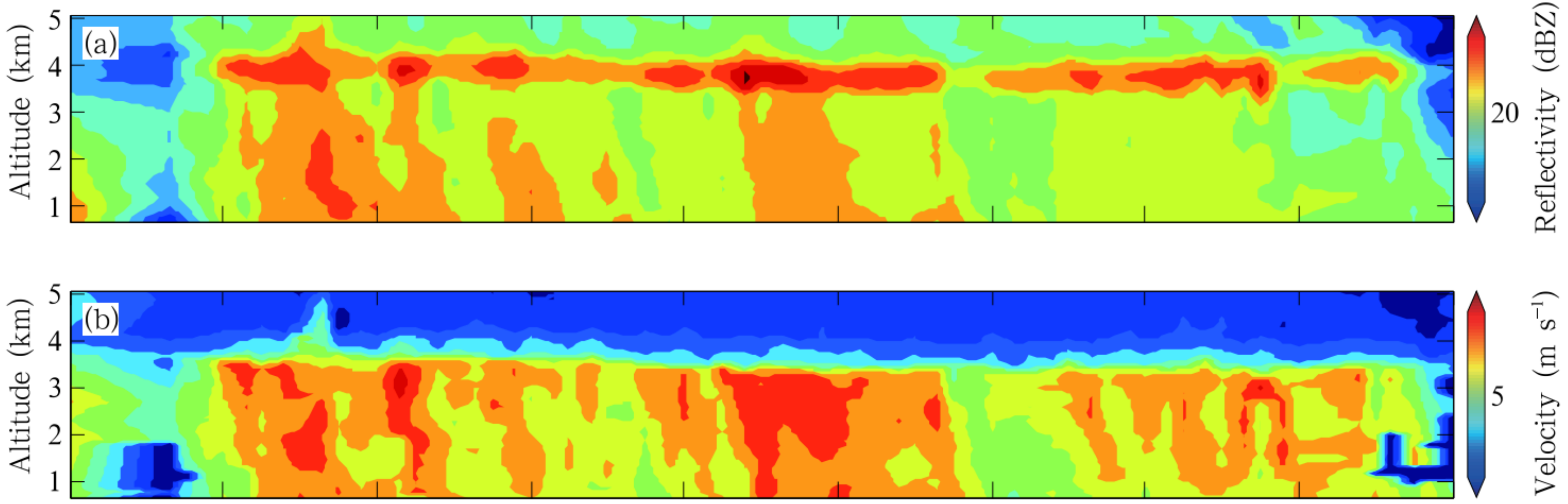
- Very few optical properties databases (if any) for snowflake aggregates / graupel / melting particles go down to 1.5 GHz, since most were developed for TRMM/GPM at 6.93 GHz and higher. *please let me know if you’re aware of any existing DDA databases that are suitable*
- Due to the stringent polarizability requirements and the sensitivity of DDA to polarizability assignment, a database needs to be carefully constructed specifically for PRO requirements.
- The transition from ice to liquid (melting) is expected to have a substantial impact on attenuation, and most likely phase delay/polarizability.

Melting Simulations

Johnson, B.T., Olson, W.S. and Skofronick-Jackson, G., 2016. The microwave properties of simulated melting precipitation particles: Sensitivity to initial melting. Atmospheric Measurement Techniques, 9(1), pp.9-21.



Observed L-band Radar Melting layer



Ruan, Z., Ming, H., Ma, J., Ge, R. and Bian, L., 2014. Analysis of the microphysical properties of a stratiform rain event using an L-Band profiler radar. *Journal of Meteorological Research*, *28*(2), pp.268-280

Toward PRO Implementation in JEDI/UFO:

- **Existing Infrastructure**: JEDI/UFO currently supports a range of forward operators for various satellite observation types, including standard GNSS-RO. These operators are designed to simulate satellite observations from model states. (examples next slides)
- **PRO Data Processing**: As of now, the standard GNSS-RO forward operators in JEDI/UFO are primarily focused on bending angle calculations and do not explicitly account for the polarimetric characteristics unique to PRO. This includes the differential phase delay between orthogonal polarizations caused by anisotropic hydrometeors.

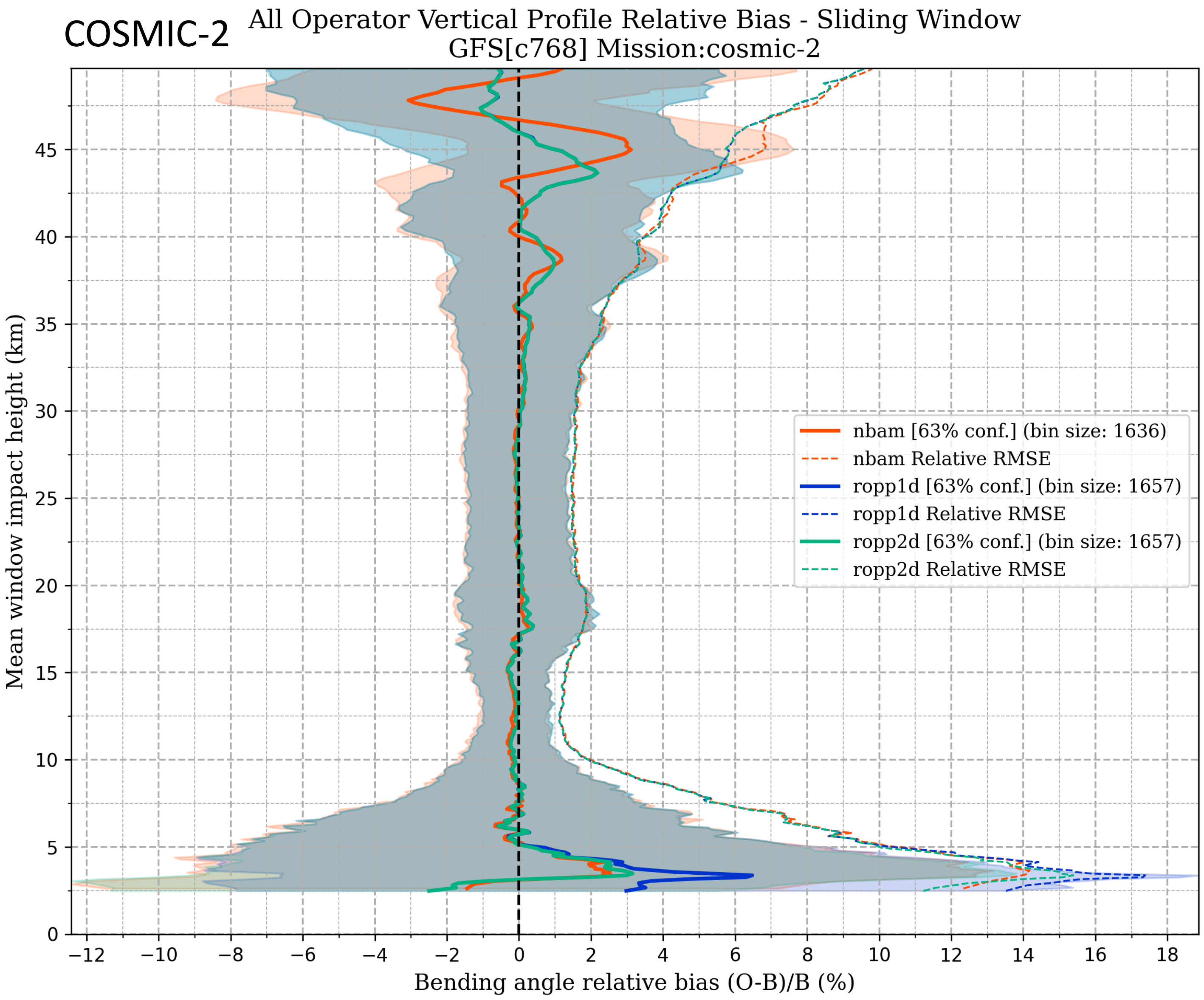
JEDI Unified Forward Operator (UFO) for GNSS-RO

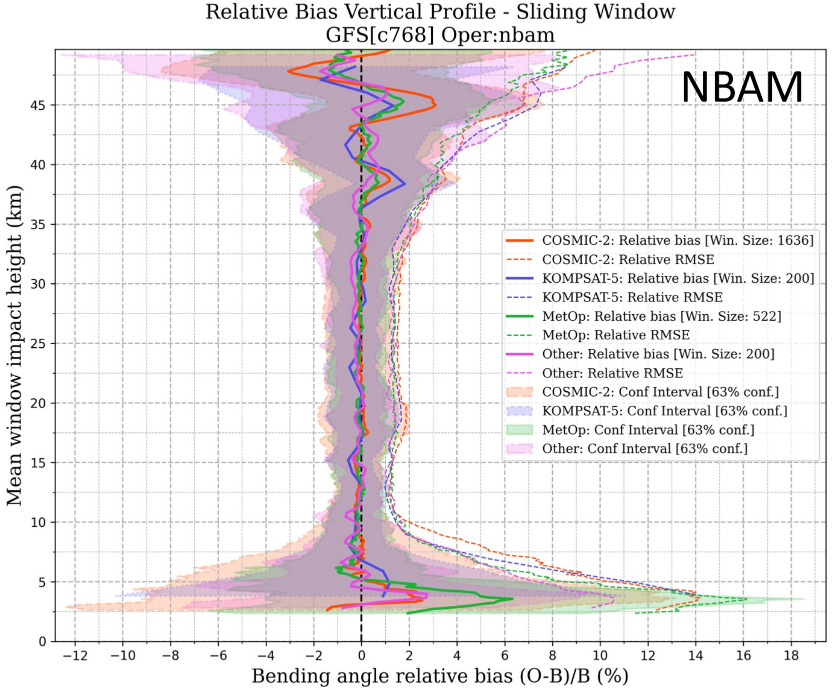
Operators:

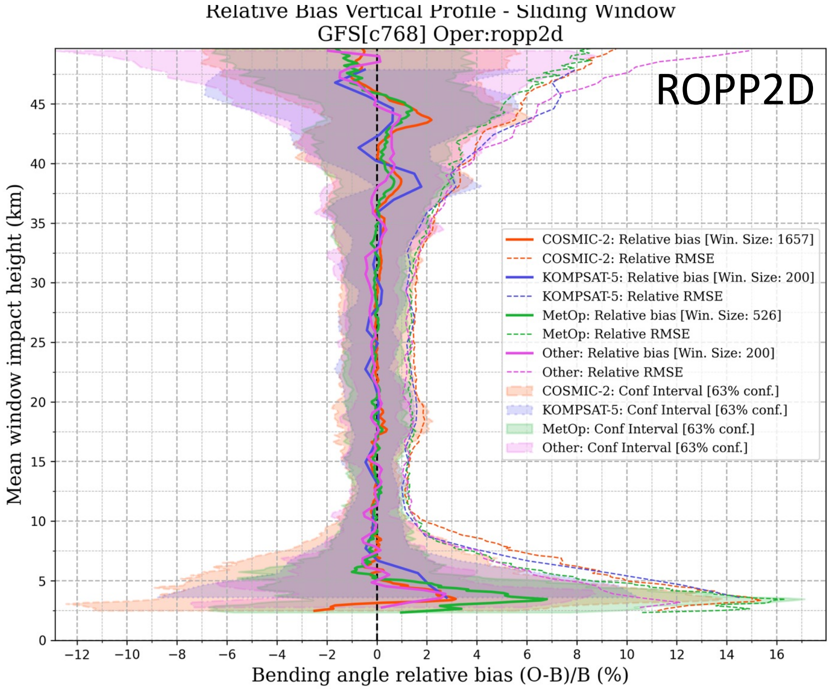
	BndGSI	BndROPP1D	BndMetOffice	BndROPP2D	RefNCEP	RefMetOffice
Operation	NCEP	NRL	Met Office	ECMWF	NCEP	Met Office
Assimilated Observable	Bending angle				refractivity	
	Vertical integral			take account of the real limb nature of the measurement; solve a set of ray path equations	Local refractivity operator	
Equation(s)	$\alpha(a) = -2a\int_a^\infty \frac{d\ln n/dx}{\sqrt{x^2-a^2}}dx$			$\frac{dr}{ds} = \cos\phi$ $\frac{d\theta}{ds} = \frac{\sin\phi}{r}$ $\frac{d\phi}{ds} \approx -\sin\phi\left[\frac{1}{r} + \left(\frac{\partial n}{\partial r}\right)_\theta\right]$	$N = 77.6\left(\frac{P}{T}\right) + 3.73\times 10^5\left(\frac{P_v}{T^2}\right)$	
Reference	Cucurull et al. 2013	Healy and Thepaut 2006	Burrows et a. 2014	Healy et al. 2007	Cucurull et al. 2007	Buontempo et al. 2008

Observation error model and QC

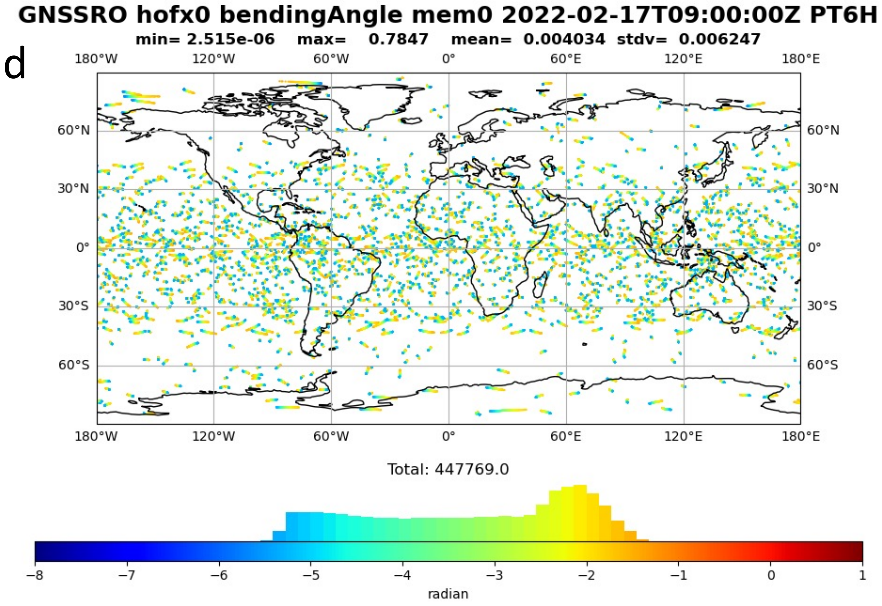
		option1	option2	option3	option4	option5
operator	Bending angle	BndNBAM	BndROPP1D	BndROPP2D	BendMetOffice	
	refractivity	RefNCEP	RefMetOffice			
quality control	Background departure	Generic	RONBAM			
	Super refraction	NBAM	ECMWF	CDAAC observation-based (to be added)		
	Profile QC	LSW	1DVar			
Observation error	In obs file	NBAM	NRL	ECMWF	Read in from file	Read in from any observation error file (e.g., 3CH)
Observation filter	Mission id/ gnss id	Height/lat	rising/setting	Processing_center	and more	


COSMIC-2
All Operator Vertical Profile Relative Bias - Sliding Window
GFS[c768] Mission:cosmic-2
nbam [63% conf.] (bin size: 1636)
nbam Relative RMSE
ropp1d [63% conf.] (bin size: 1657)
ropp1d Relative RMSE
ropp2d [63% conf.] (bin size: 1657)
ropp2d Relative RMSE
Mean window impact height (km)
Bending angle relative bias (O-B)/B (%)

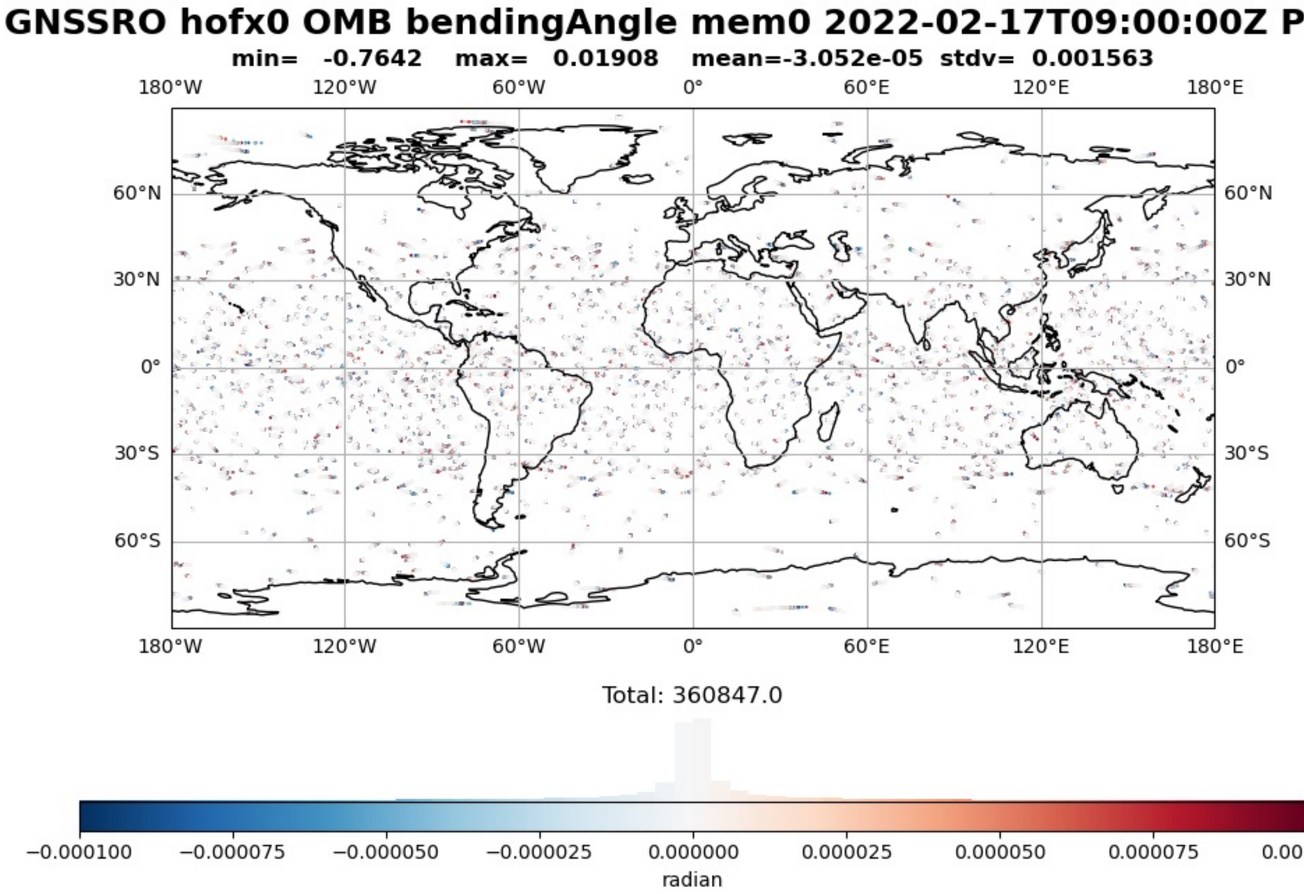

Relative Bias Vertical Profile - Sliding Window
GFS[c768] Oper:nbam
NBAM
COSMIC-2: Relative bias [Win. Size: 1636]
COSMIC-2: Relative RMSE
KOMPSAT-5: Relative bias [Win. Size: 200]
KOMPSAT-5: Relative RMSE
MetOp: Relative bias [Win. Size: 522]
MetOp: Relative RMSE
Other: Relative bias [Win. Size: 200]
Other: Relative RMSE
COSMIC-2: Conf Interval [63% conf.]
KOMPSAT-5: Conf Interval [63% conf.]
MetOp: Conf Interval [63% conf.]
Other: Conf Interval [63% conf.]
Mean window impact height (km)
Bending angle relative bias (O-B)/B (%)


Relative Bias Vertical Profile - Sliding Window
GFS[c768] Oper:ropp2d
ROPP2D
COSMIC-2: Relative bias [Win. Size: 1657]
COSMIC-2: Relative RMSE
KOMPSAT-5: Relative bias [Win. Size: 200]
KOMPSAT-5: Relative RMSE
MetOp: Relative bias [Win. Size: 526]
MetOp: Relative RMSE
Other: Relative bias [Win. Size: 200]
Other: Relative RMSE
COSMIC-2: Conf Interval [63% conf.]
KOMPSAT-5: Conf Interval [63% conf.]
MetOp: Conf Interval [63% conf.]
Other: Conf Interval [63% conf.]
Mean window impact height (km)
Bending angle relative bias (O-B)/B (%)

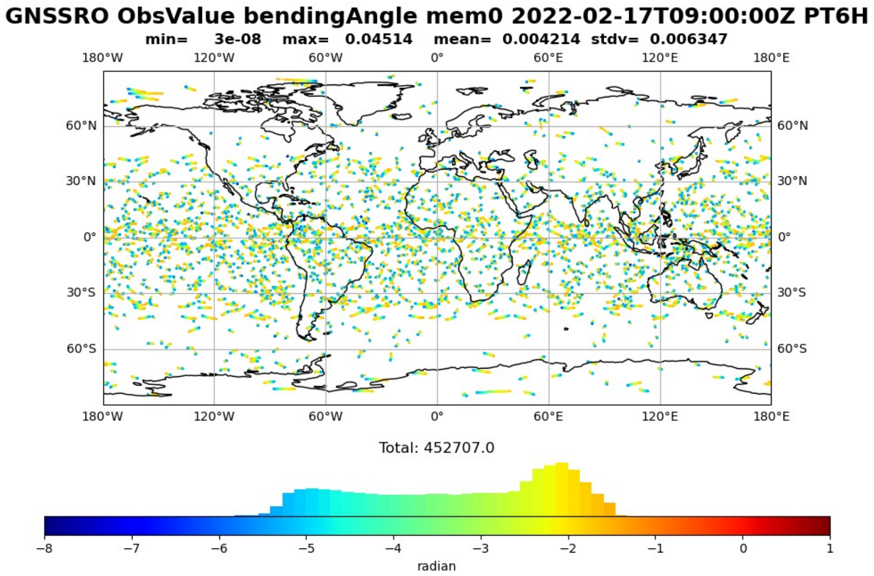
Simulated
Bending
Angle



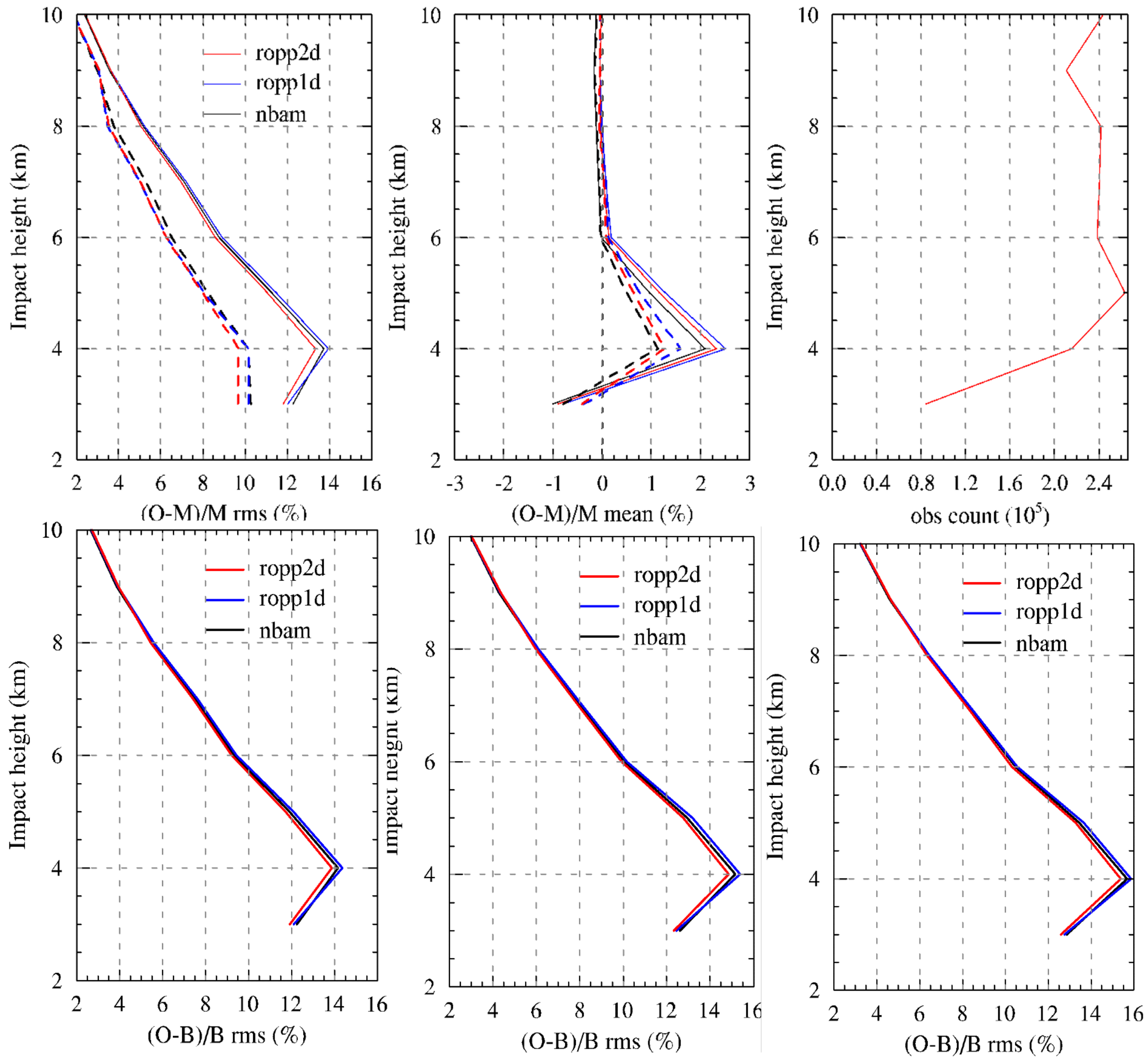
see https://skylab.jcsda.org



OBS
Bending
Angle



2D RO Ray-tracing Operator vs 1D Operator



DASHED – OMA

SOLID – OMB

ROPP2D fits RO data better at all lead times

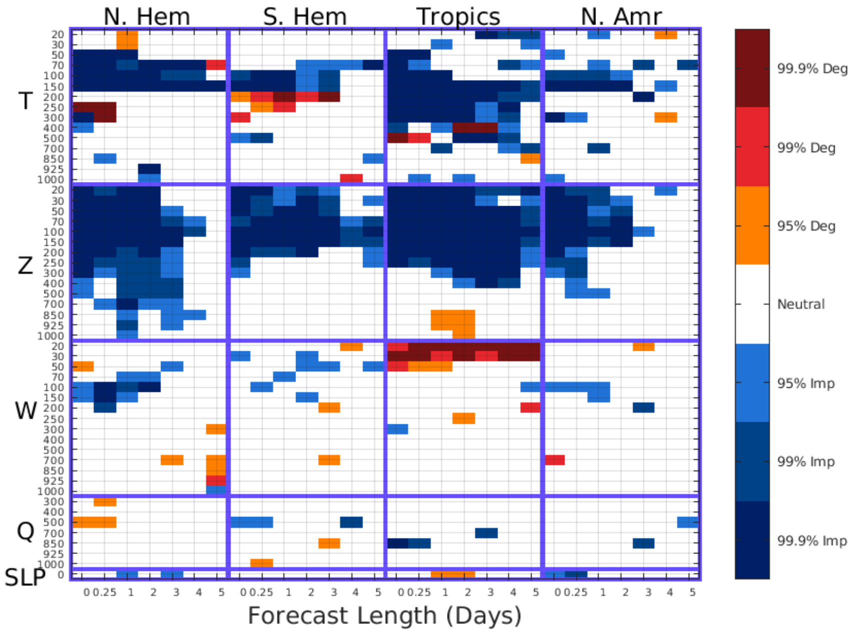
The two 1D operators perform comparably (current NOAA operator is 1D operator)

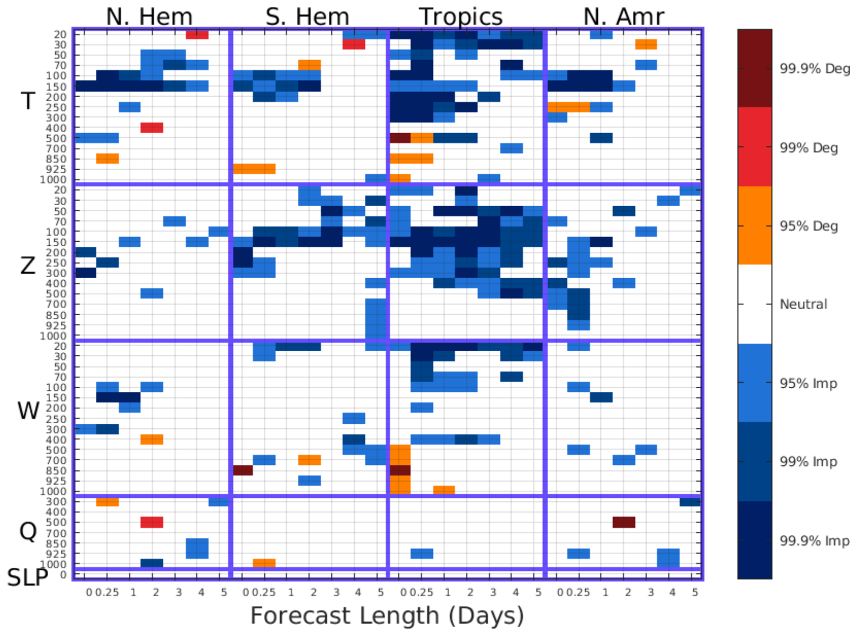
COSMIC-2 Impacts (2020 Implementation)

Fit to radiosonde

Blue indicates COSMIC-2 reduced forecast errors
Red indicates COSMIC-2 degraded forecast errors

Bias





RMSE

COSMIC-2 DA results in

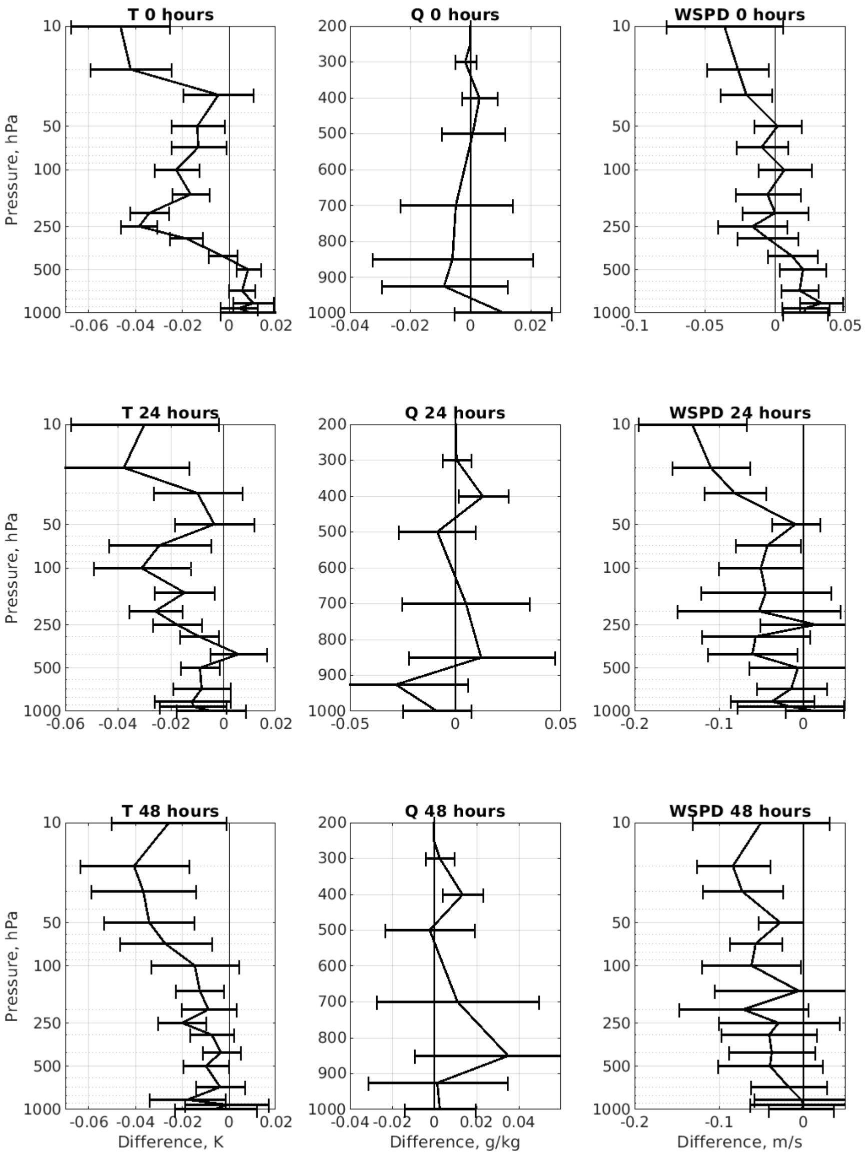
- Significant RMSE reduction in both analysis and forecasts for GH, T and wind for most vertical levels, especially for the tropical area
- Significant Bias reduction in both analysis and forecasts for GH and T globally
- While some improvements were shown in other areas, biases of wind in the tropical area was degraded for upper level (above 30hPa)

Using results up to May 18, 2020

(Plots from Hui Shao, Kristen Bathmann)

Fit to radiosonde (RMSE)

- Negative values indicate improvement due to COSMIC-2 data assimilation
- COSMIC-2 DA results in
  - Significant improvements in both analysis and forecasts for T and wind for most vertical levels
  - Some improvements for low level moisture analysis



Complementary Nature of assimilation of various observation types (1/2)

- **PRO Observations**: PRO provides high vertical resolution profiles of the atmosphere, particularly effective in detecting and characterizing precipitation and cloud structures through changes in the polarization state of GNSS signals.
- **Passive Microwave**: Passive microwave sensors measure upwelling natural microwave emissions from the Earth's surface and atmosphere, offering valuable data on atmospheric temperature and humidity profiles, as well as liquid and ice water content in clouds.
- **Space-Based Radar**: Space-based radar systems, such as those operating in the CloudSat mission, provide detailed information o

Complementary Nature of assimilation of various observation types (2/2)

- **Enhanced Atmospheric Profiling**: Combining PRO with passive microwave data offers a more comprehensive understanding of atmospheric thermodynamics. While PRO excels in precise altitude-based measurements, passive microwave sensors contribute broader spatial coverage and detailed information on water content.
- **Improved Precipitation Analysis**: Integrating PRO with space-based radar data leads to improved characterization of precipitation systems. PRO's sensitivity to hydrometeor orientation complements radar's strength in determining precipitation intensity and vertical structure.
- **Cross-Validation and Error Reduction**: Utilizing multiple observational sources allows for cross-validation of data, enhancing the overall reliability and reducing errors in atmospheric models.

Requirements for PRO Forward Operator Implementation in JCSDA applications

- **Polarimetric Phase Delay Modeling**: A key requirement is the development of an advanced forward operator capable of simulating the polarimetric phase delay in GNSS signals as they pass through various atmospheric constituents, particularly non-spherical hydrometeors.
- **Hydrometeor Representation**: Accurate representation of hydrometeor shapes, sizes, orientations, and dielectric properties is crucial. This involves integrating more complex scattering models and potentially updating the atmospheric model state representations.
- **Integration with Existing Frameworks**: The PRO forward operator must seamlessly integrate with the existing JEDI/UFO architecture, requiring compatibility with its data structures, assimilation algorithms, and processing workflows.

What Does Not Yet Exist

- **Specific Polarimetric Modeling Tools**: Currently, tools or modules specifically designed for polarimetric data processing within the JEDI/UFO frameworks are limited or non-existent. This includes lack of explicit handling of the polarization state changes of GNSS signals due to atmospheric interactions
  - both CRTM and OBS forward operator need to be updated / tested