Processing multiple GNSS RO data at NOAA/STAR using FSI and ROPP: initial results from the ROMEX

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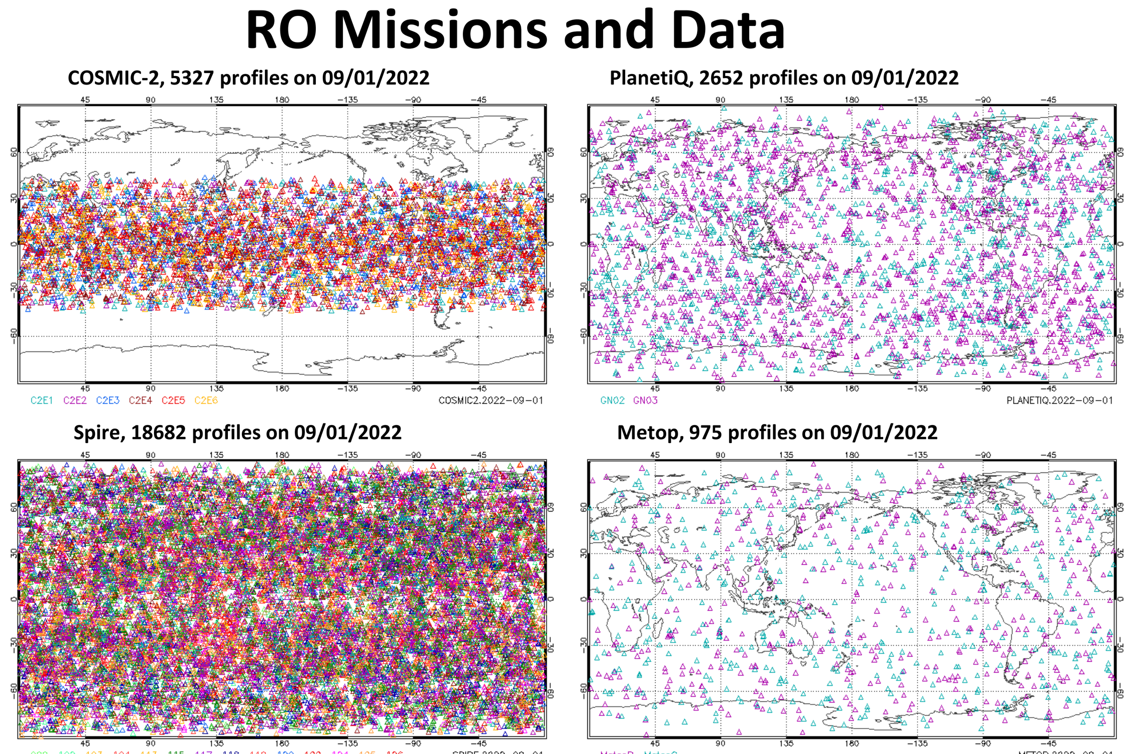
Abstract

- The importance of Global Navigation Satellite System (GNSS) Radio Occultation (RO) data continues to grow due to its vital contributions to weather forecasting and climate analysis. The Radio Occultation Modeling Experiment (ROMEX) initiative, endorsed by IROWG, has brought together RO data providers, including commercial entities, who have submitted their data to EUMETSAT for processing. ROMEX received an average of 35,000 to 40,000 profiles daily. The processed data, including excess phase, bending angle, refractivity, temperature, and water vapor, have been distributed to ROMEX participants through the ROM SAF.
- This paper outlines the development of an independent algorithm at NOAA/STAR for processing RO bending angle and refractivity data from multi-GNSS RO missions. The main objective is to understand the uncertainties introduced during processing, from excess phase data to bending angle and refractivity profiles. There are three main algorithms for converting RO excess phases to bending angles: full spectrum inversion (FSI), canonical transform (CT), and phase matching (PM). The STAR-developed FSI algorithm has been fully integrated into the ROPP version 10.0, providing users with a configurable alternative for bending angle retrieval.
- ROMEX serves an ideal platform for evaluating our RO data processing methods for multi-GNSS RO missions. This paper provides a comprehensive comparison of bending angle and refractivity produced by STAR FSI, ROPP, and EUMETSAT. The analysis highlights overall consistency, while investigating remaining discrepancies, with an emphasis on the uncertainties inherent in bending angle and refractivity processing. These insights into algorithm performance are crucial for interpreting the results of ROMEX forecast impact studies conducted by various numerical weather prediction centers.

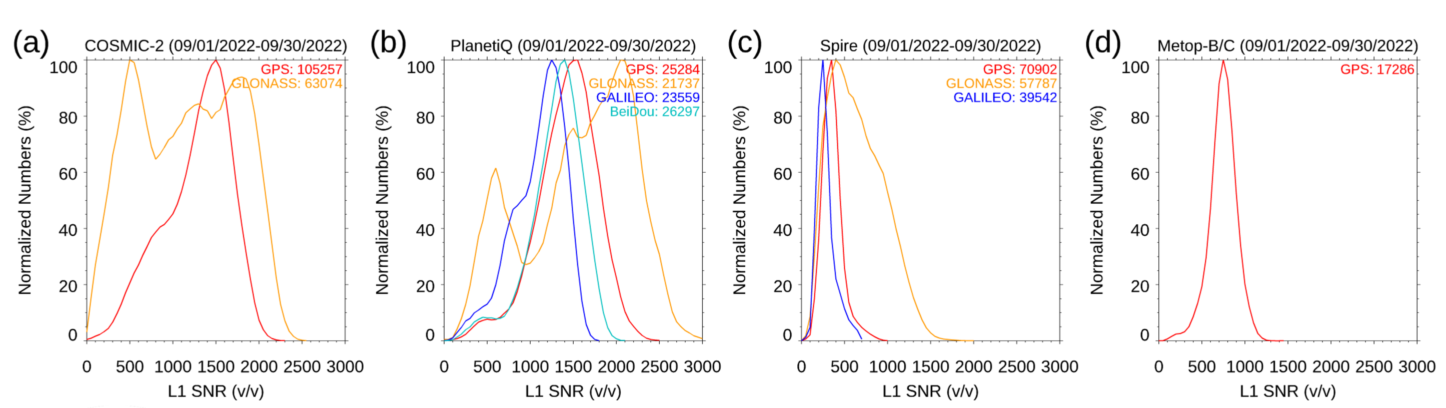
RO Missions and Data



Different RO missions have different receivers and LEO orbits, with different characteristics

	COSMIC-2 (6)	SPIRE (>20)	Metop-B/C	PlanetIQ
Receiver	TRIG	STRATOS	GRAS	PYXIS
RO Ant	2/G,R,E*, (100Hz)	2/G,R,E(50Hz)	2/G (50Hz)	2/G,R,E,C (GRC:100Hz; E:125Hz)
POD Ant	2/G,R, 1Hz only	1/G, 1Hz/50Hz	1/G, 1Hz	2/G,R, 1Hz

G:GPS; R: GLONASS; E: GALILEO; C:BEIDOU; E*: not available yet



Different RO missions have different satellite orbits, different global coverage and daily profiles numbers, and different Signal-to-noise ratio (SNR)

Different Approaches from Excess phase to Bending Angle

- RO signals in the low troposphere encounter multipath effects due to atmospheric irregularities
- Under the assumption of spherical symmetry of the refractivity (radioholographic methods, RH), the transform of the RO signal from time/coordinate to the impact parameter can be performed
- This assumption reduces the dimension of the inverse RO problem and is inherent to all RH and geometric optical (GO) inversion methods
- The RH methods include the Canonical Transform (CT2) (Gorbunov and Lauritsen, 2004), Full Spectrum Inversion (FSI) (Jensen et al., 2003, Adhikari et al., 2021), and Phase Matching (PM) (Jensen et al., 2004, Sokolovskiy et al., 2010)
- The length of the RO signal used for the inversion is a tunable parameter

Doppler frequency:

$$\omega = \frac{d\psi}{dt} = k\left(\dot{r}_L\sqrt{1-\frac{a^2}{r_L^2}} + \dot{r}_G\sqrt{1-\frac{a^2}{r_G^2}} + a\dot{\theta}\right)$$

Phase matching function:

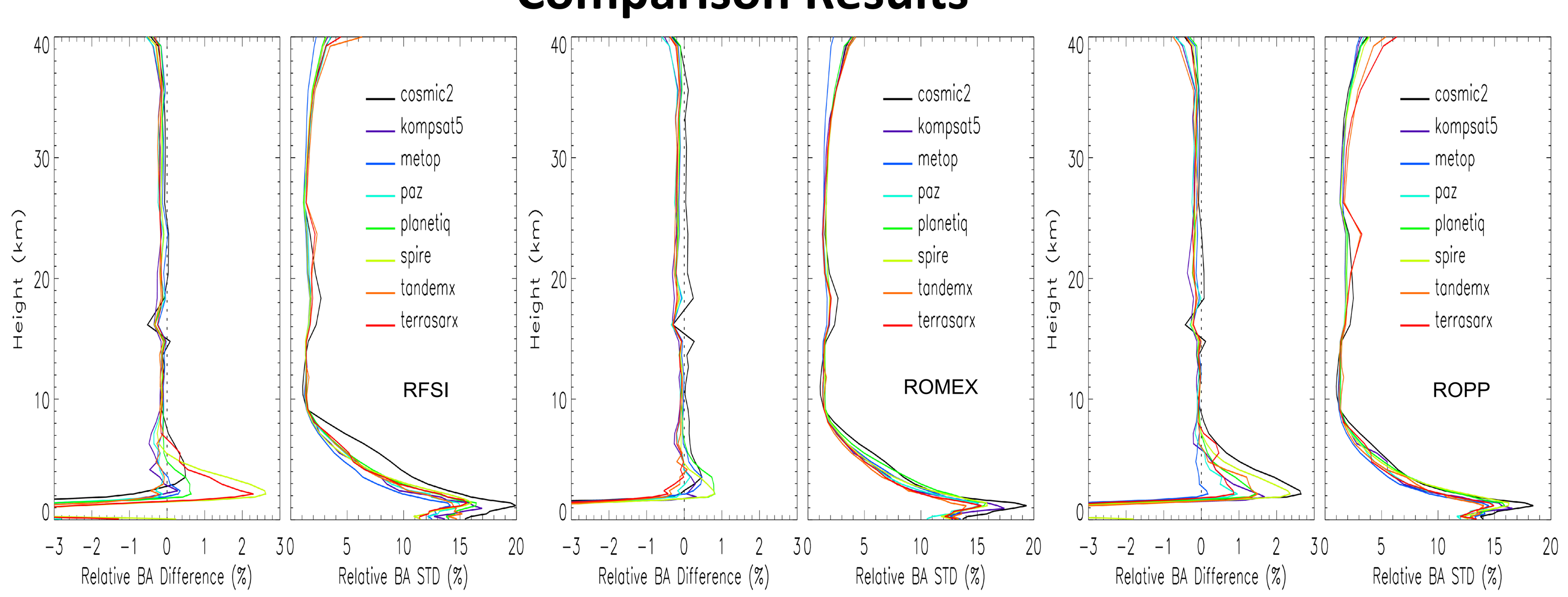
$$S(a,\theta) = a\theta + \sqrt{r_1^2(\theta)-a^2} + \sqrt{r_2^2(\theta)-a^2} - a[\arccos(a/r_1(\theta)) + \arccos(a/r_2(\theta))]$$

CT2	Uses a canonical transformation to map the phase path data onto a canonical surface; simplifies the signal processing and allows for efficient retrieval; is less sensitive to noise and other signal disturbances
FSI	Utilizes the full spectrum of the received signal; analyzes the Doppler shift and its spectral component; is highly sensitive to small-scale atmospheric features and to SNR cut-off height
PM	Matches the phase of the observed signal with a theoretical model; is effective in resolving phase ambiguities that can arise from multipath propagation and other distortions

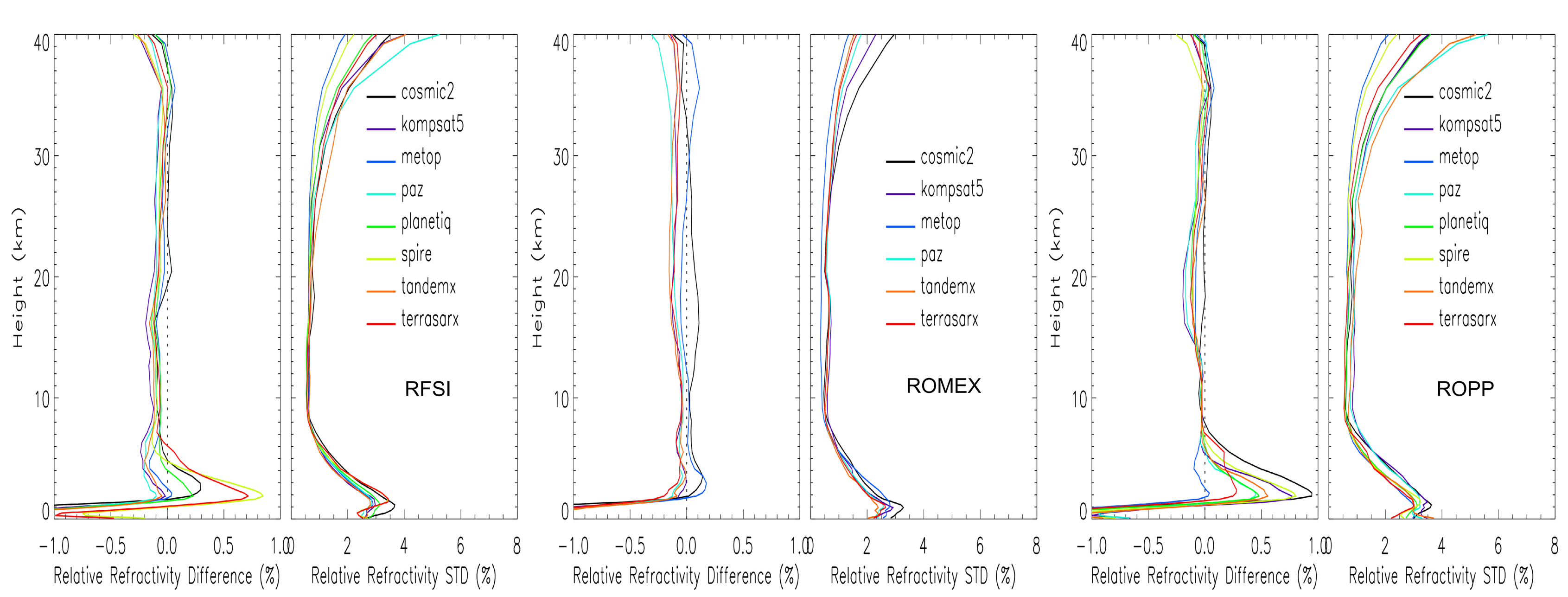
Excess Phase to Bending Angle Inversion

- STAR full spectrum inversion (FSI) algorithm (Adhikari et al., 2021) was developed to convert excess phases to bending angles
- This algorithm is fully integrated into the ROPP version 10.0 and can be used as an alternative method for wave optics (canonical transform type 2, CT2) and geometric optics (GO) through the user configuration in this revised package
- Modifying ROPP to include GPS/GLONASS/GALIEO/BeiDou signals
- Modifying ROPP for different missions: COSMIC-2, Spire, PlanetIQ, Metop-B/C and etc.
- Modifying configuration for different bending angle methods and different RO missions
- Using simulation from ERA-5 forecasts for Quality Control: 1) Improved forward operator 2) Post-preprocess to determining good/bad profiles

Comparison Results

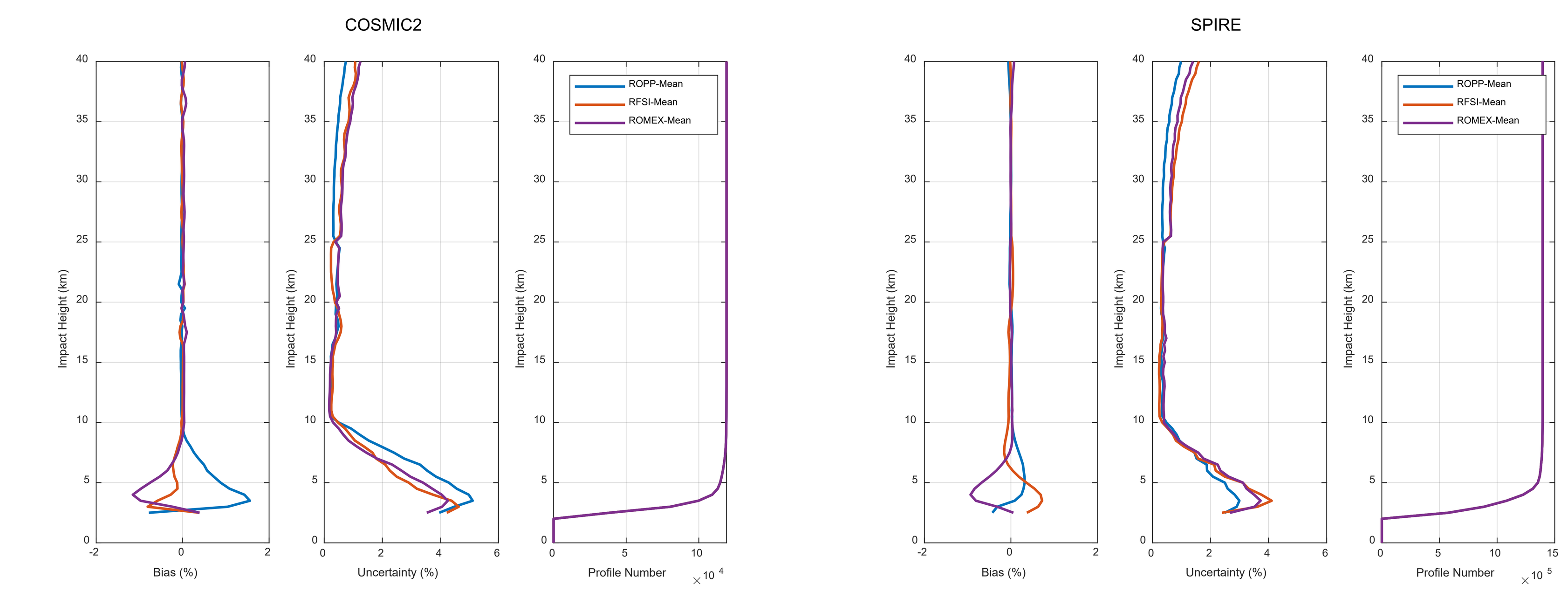


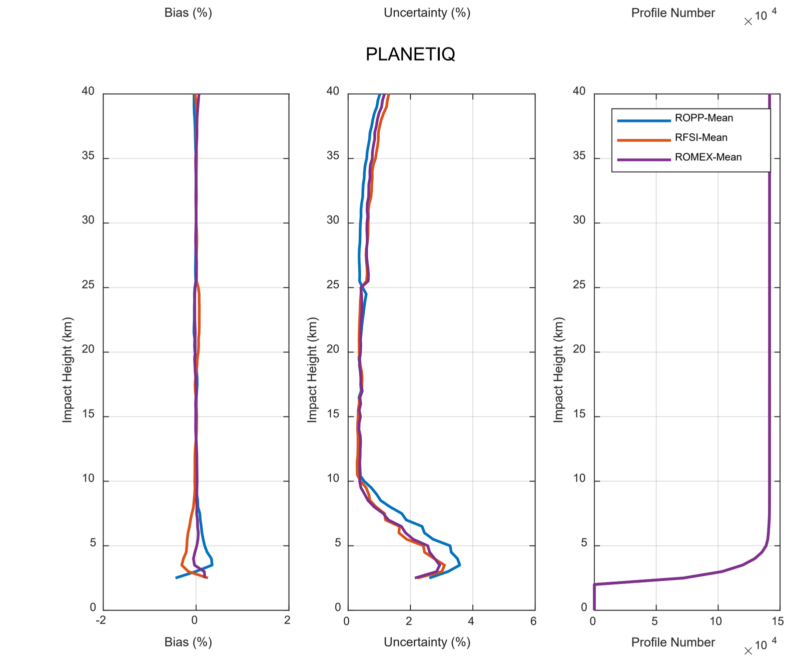
Bending angle comparison with ERA5 simulation over November 2022 for RFSI, ROPP and ROMEX



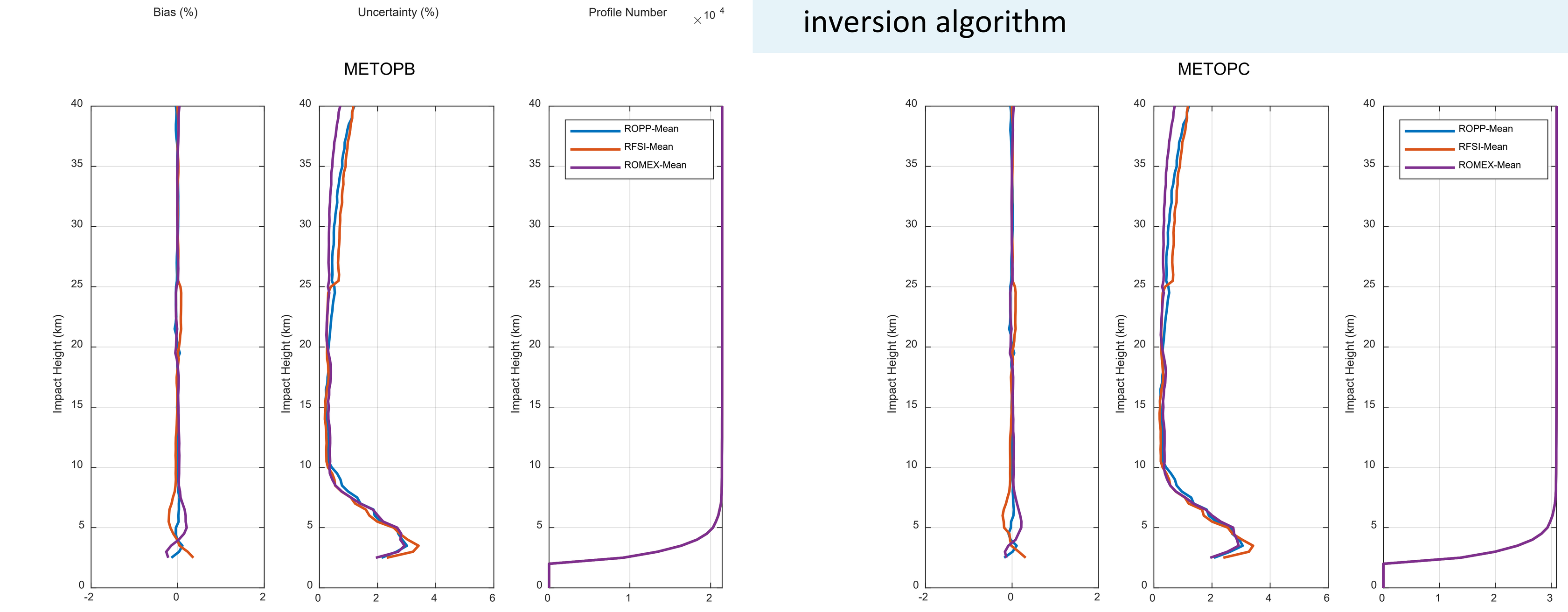
Refractivity comparison with ERA5 simulation over November 2022 for RFSI, ROPP and ROMEX

Structural Uncertainty among Different Processing Methods





- Three datasets mean as the reference for each mission
- The BA differences among these three processing methods are very consistent above 8 km
- Below 8 km, the BA differences exceed 1-2% for COSMIC-2 and Spire, while they remain less significant for PlanetIQ and Metop-B/C, staying below 0.5%
- Uncertainty above 25 km increases due to the use of different ionospheric correction methods
- The filtering method to connect above 25 km and below 25 km (maximum height for WO processing) also impact the BA results
- Uncertainty below 10 km increases due to the dependency on the RO signal cut-off height used in the inversion algorithm



Summary

- This study investigates different algorithms for converting RO excess phases to bending angles
- The STAR-developed FSI algorithm has been seamlessly integrated into ROPP version 10.0, providing a significant advancement by offering a customizable alternative to wave optics (CT2) and geometric optics
- We present an in-depth comparative analysis of bending angles and refractivity data generated by the FSI, CT2, and EUMETSAT for RO missions within ROMEX
- We emphasis RO data from COSMIC-2, Spire, PlanetIQ, and Metop-B/C, providing a deep understanding of algorithmic performance under varying conditions
- This analysis highlights the discrepancies and uncertainties inherent in processing bending angles and refractivity, providing valuable insights into the intricacies of each algorithm and offering a critical perspective on their performance

ROMEX RO data generated from NOAA/STAR RFSI algorithm are available to download from EUMETSAT for evaluation

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