Characterizing the Uncertainty of GNSS RO Bending Angles in the Lower Troposphere with the Local Spectral Width Analysis

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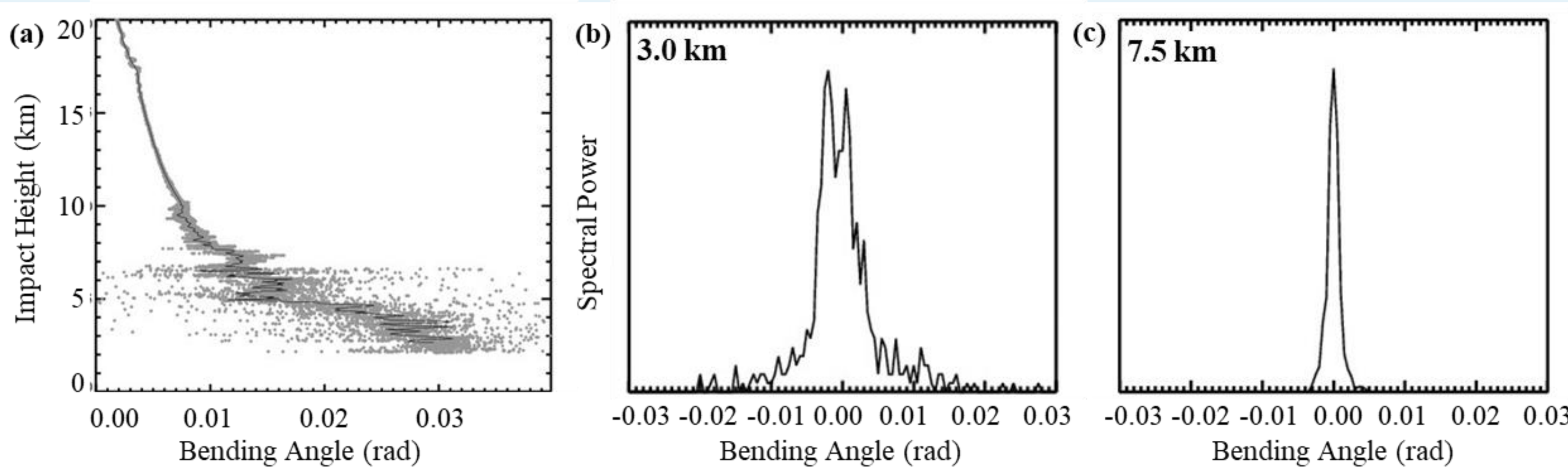
Introduction

- Global Navigation Satellite System (GNSS) Radio Occultation (RO) provides sounding measurements of the atmosphere with high vertical resolution and accuracy, making it particularly useful for understanding climate changes, monitoring environmental conditions, and enhancing weather forecasting capabilities. However, one of the challenges for optimally using RO data for numerical weather prediction through data assimilation is to accurately estimate RO observation errors, especially in the lower troposphere. It is well known that the lower tropospheric water vapor irregularities introduce large uncertainties in retrieved bending angle profiles. In addition, the moisture variation in the lower troposphere and strong vertical density gradient on the sharp top of the atmospheric boundary layer can result in a considerable bending angle uncertainty owing to multiple paths. When multipath occurs, the wave-optics converted RO bending angle spectrum contains multiple spectral components, increasing the overall width of the spectrum or the local spectral width (LSW).
- This study characterized the uncertainty of GNSS RO BA profiles from COSMIC-2, Spire, and PlanetiQ in the lower troposphere using the Center for Satellite Applications and Research (STAR) -derived local spectral width (LSW).
- The National Oceanic and Atmospheric Administration (NOAA) STAR Full Spectrum Inversion (FSI) package is used to derive and calculate the relative dynamic bending angle observation error (DBAOE) for each mission.
- The overall DBAOE results over land and ocean between three missions are reported and their trends also are evaluated.
- The spatial distribution of the DBAOE is calculated over 5° longitude × 5° latitude grids at selected altitudes to identify the regions of maximum and minimum DBAE globally and trace them to the regional climatological mean states.
- The DBAOEs according to different signal noise ratios (SNR) are compared to examine the impacts of SNR on DBAOE.
- The DBAOEs according to different latitude regions are compared to examine the impacts of spatial distribution on DBAOE.
- The DBAOEs according to bending angle bias are evaluated to examine the impacts of DBAOE on BA bias in terms of background.
- Reason for the smaller DBAOE of Spire are also evaluated.

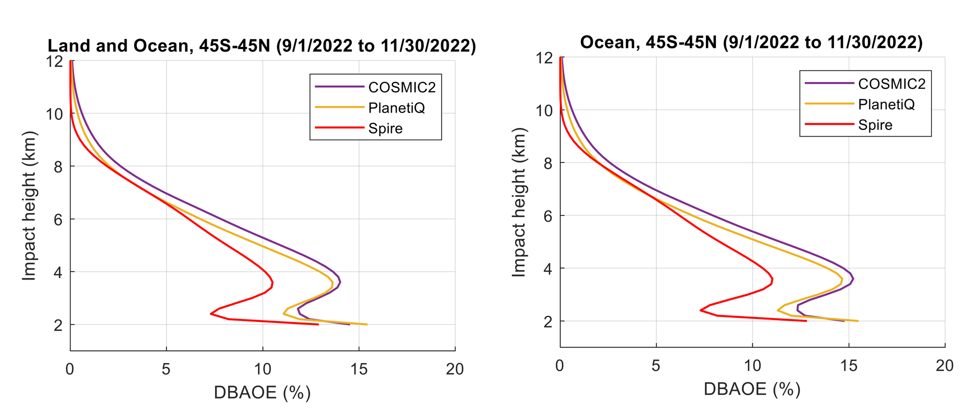
STAR Local Spectral Width (LSW) Method

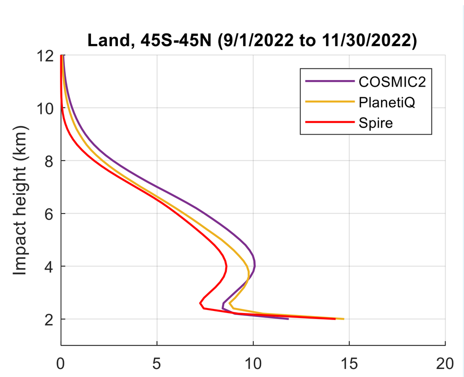
The raw bending angle profile is derived at high vertical resolution using the Full Spectrum Inversion (FSI) method:

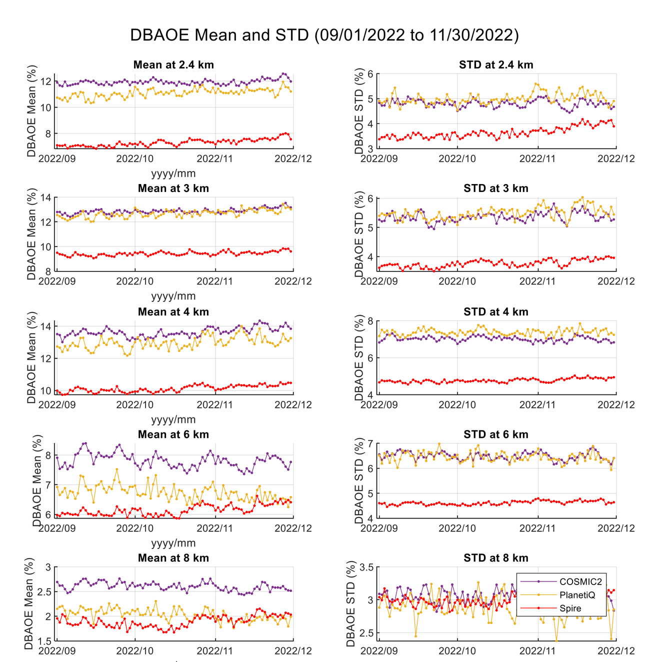


(a) Spectrogram of the RO signal, spectral power of the sliding spectrogram at (b) 3 km and (c) 7.5 km impact height

DBAOE comparison and its trending



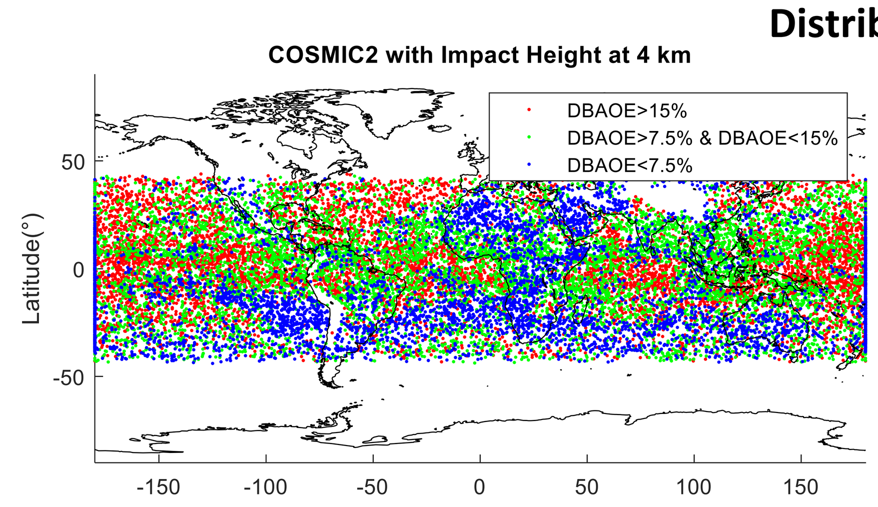


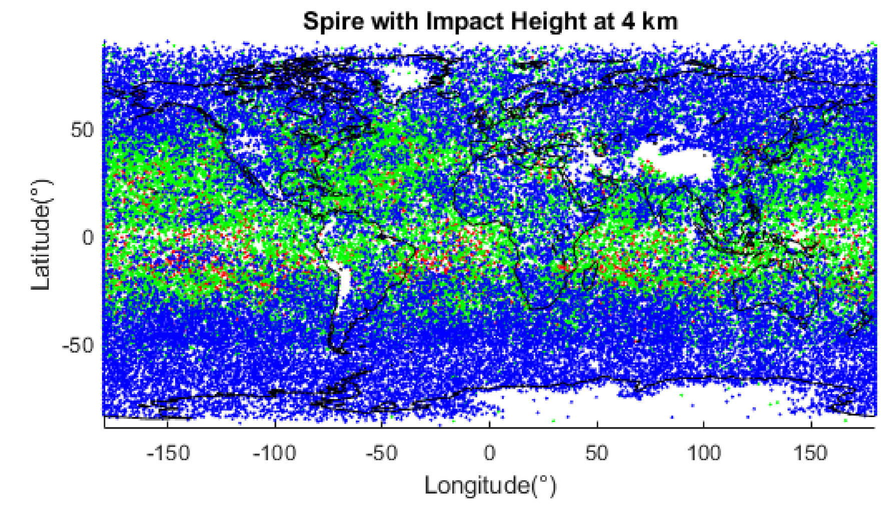


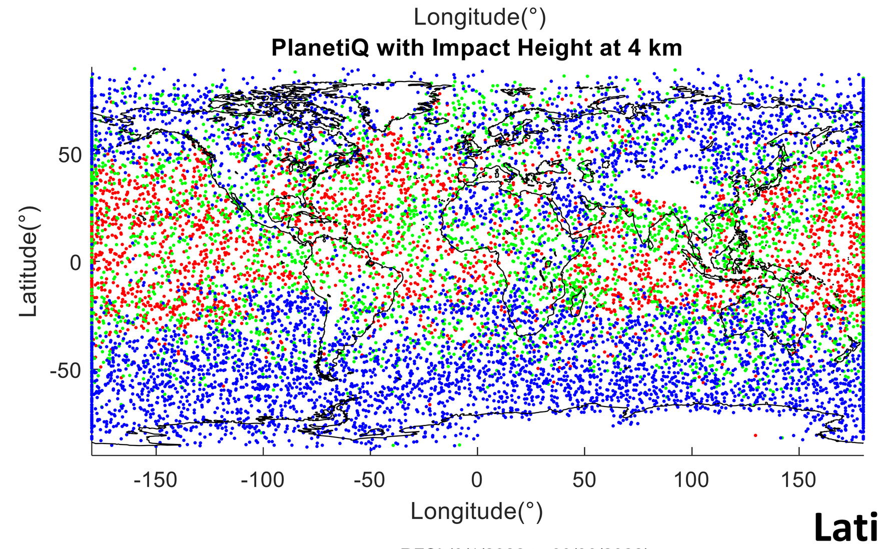
- For DBAOE trends comparison:
  - COSMIC-2 and PlanetiQ show upward trends in lower altitudes (2.4km, 3km, and 4km impact height), while being relatively flat at higher altitudes.

- For DBAOE overall comparison:
  - Spire shows consistent lower DBAOE profiles in the 45S-45N region for ocean and land, and ocean.
  - In the land region, on the other hand, Spire shows consistent DBAOE relative to COSMIC-2 and PlanetiQ.
  - On the other hand, relative to land, ocean areas have greater DBAOE due to their greater moisture content.

Distribution of RO DBAOE

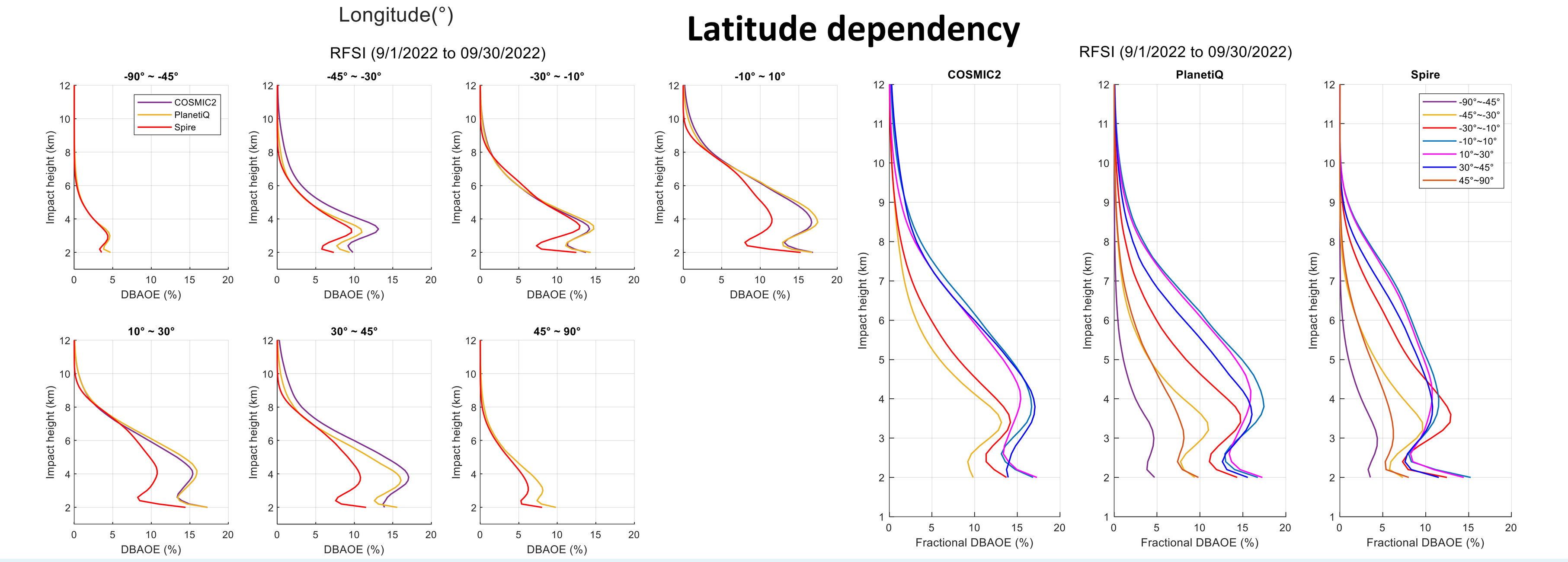






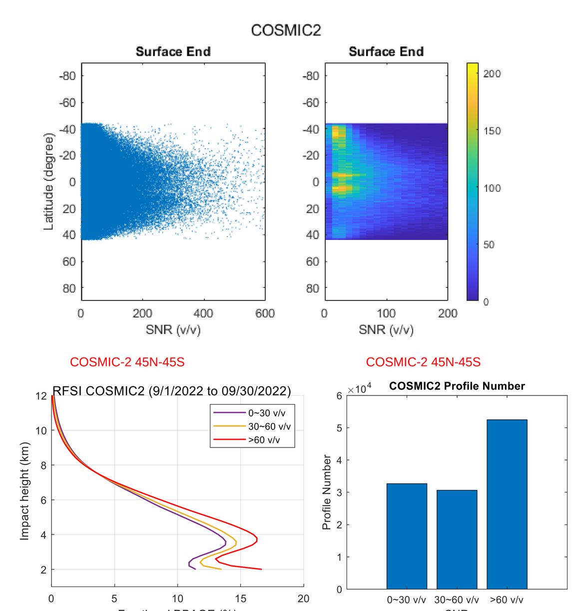
- The distribution of DBAOE for three missions are similar:
  - Most of the high DBAOE (>15%) occurred over the tropical and north subtropic oceans, indicating that RO in those regions had high uncertainties.
  - A majority of the low DBAOEs occurred over the continents and south subtropic oceans, where moisture was relatively low, suggesting that RO in those regions had low uncertainties.
- For Spire and PlanetiQ, 45S to 90S and 45N to 90N regions are almost completely covered in low DBAOE (<7.5%).

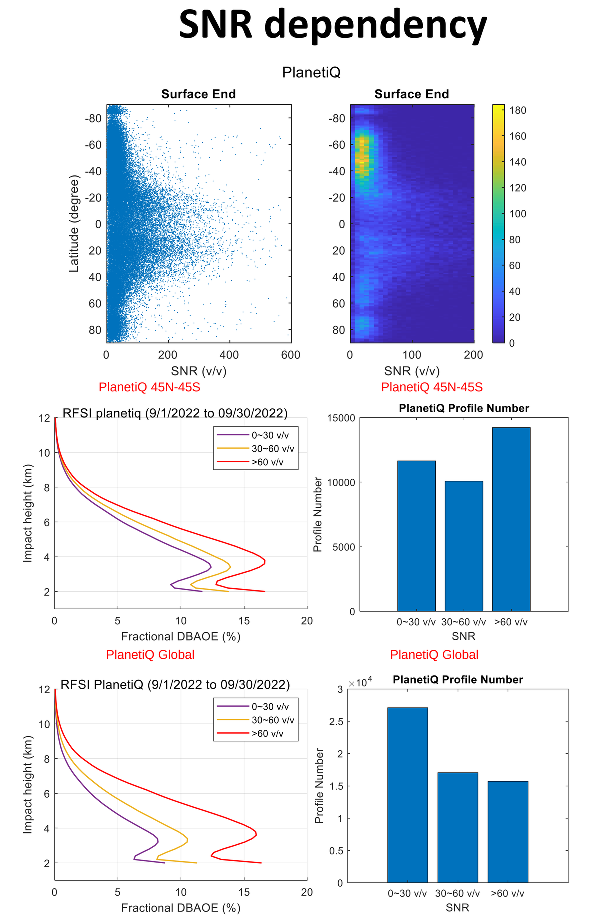
Latitude dependency

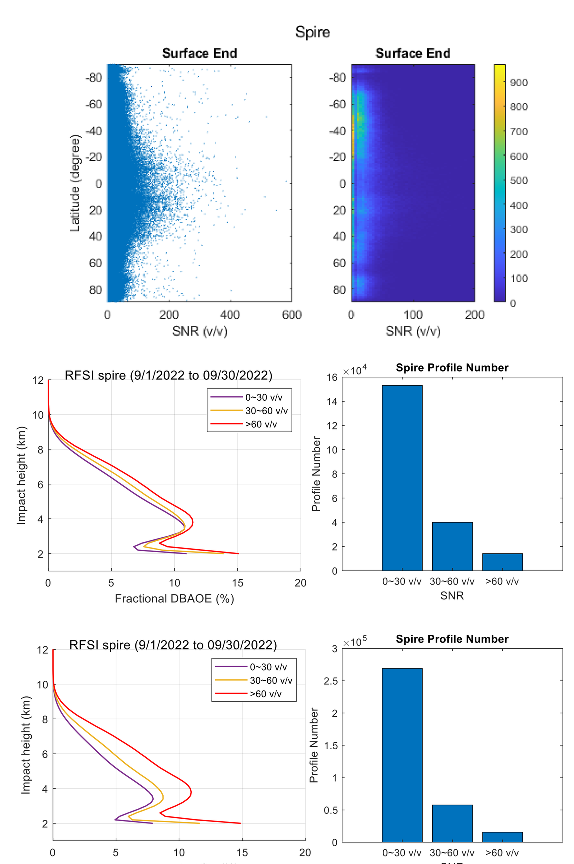


- All three missions show greater DBAOE in the tropical and northern subtropical ocean regions with higher humidity.
- In contrast, in the sub-boreal and boreal regions, Spire and PlanetiQ show very low uncertainties.

SNR dependency



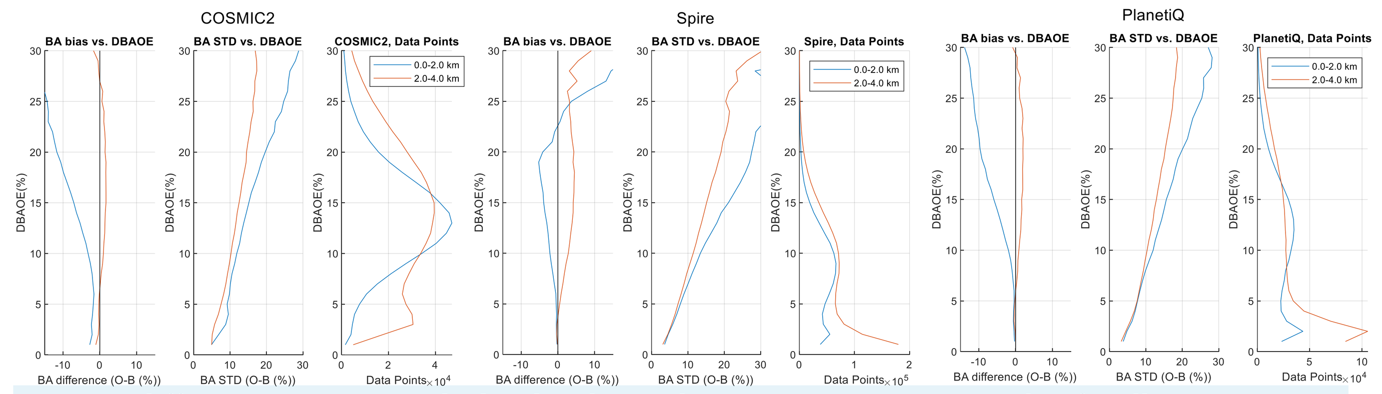




- **SNR definition in this work**: NOAA STAR FSI processes excess phase data by truncating it using the SNR of the time series to optimize the excess phase data. In this study, the DBAOE at different SNR was analyzed by using the **truncated surface SNR** instead of the conventional SNR at 80km altitude.

- The three mission SNRs have similar pattern, and the higher SNR concentrated in tropical region.
- The phenomenon of higher SNR has lower DBAOE occurs for all three mission with or without latitude limitation. One possible reason for this feature is that below 5 km, the effect of non-spherically symmetric irregularities dramatically increases due to the larger water vapor horizontal gradient in the atmosphere, and then the larger SNR could more easily detect these irregularities.

Mean BA bias as a function of LSW within 0-2km, 2-4 km



- Mean differences in BA are calculated within each consecutive 1% DBAOE bin for all RO-background collocated data within the specified altitude ranges.
- For all three missions, BA differences are negative for all ranges of DBAOE and their magnitudes increase rapidly with increasing DBAOE in 0-2 km height layer.
- When DBAOE is less than 10%, the differences are relatively small
- In the 0-2 km layer:
  - For COSMIC-2 and PlanetiQ, when DBAOE is greater than 10%, the differences increase quickly.
  - But for Spire, BA bias decreases when DBAOE greater than 25%.
- In the 2-4 km layer:
  - For COSMIC-2 and PlanetiQ, BA bias is independent of DEAOE
  - For Spire, BA bias increases slightly with DBAOE.
- BA STD is positively correlated with DBAOE

Discussion: the sampling rate impact on DBAOE

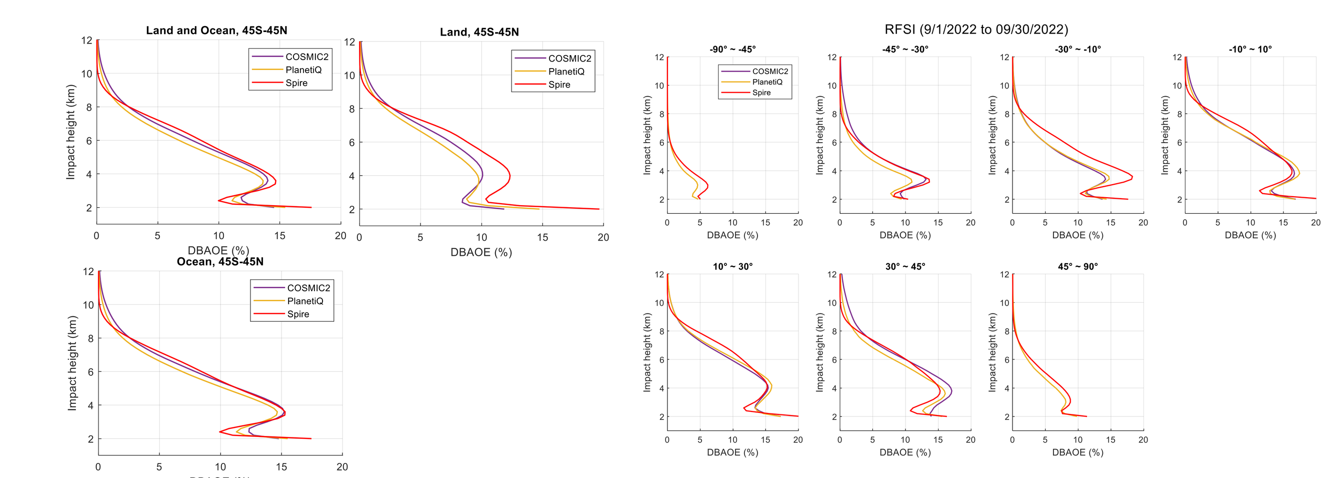
- One possible reason for the DBAOE difference between RO missions is the different sampling rates.
- To compare the observation noise from these two instruments consistently, here the integration time is accounted for, as longer integration times result in less noise. The noise reduction follows the square root rule: doubling the integration time reduces noise by a factor of sqrt(2).
- Sampling rate normalization:

Mission	Sampling rate	Normalizing factor (f_{sr})
COSMIC-2	100 Hz	1
PlanetiQ	100 Hz	1
Spire	50 Hz	Sqrt(2)

- The LSW as the mean of the spectral power (p_i) weighted by the shifted frequency (α) is calculated:

$$LSW = \frac{\sum_{i=1}^{n} P_i |\alpha| \delta\alpha}{\sum_{i=1}^{n} P_i \delta\alpha} \times f_{sr}$$

DBAOE comparison after the sampling rate factor applied



- After the factor been applied:
  - The three RO missions show consistent DBAOE profiles in the 45S-45N region as well as in their oceanic regions.
  - All three RO missions show consistent DBAOE profiles in different latitude regions, except that Spire shows relatively large DBAOE in south subtropic region.

Summary

- High DBAOE occurs in tropical and northern subtropical marine areas where humidity is higher.
- The distribution of DBAOE in the 45S to 45N regions is approximate for the COSMIC-2 and PlanetiQ. Spire shows lower DBAOE. All three missions exhibit a greater DBAOE in the ocean relative to the land.
- All three missions show greater DBAOE in the tropical and northern subtropical ocean regions with higher humidity.
- The three mission SNRs have similar pattern, and the higher SNR concentrated in tropical region; The phenomenon of higher SNR has lower DBAOE occurs for all three mission with or without latitude limitation.
- For all three missions, BA differences are negative for all ranges of DBAOE and their magnitudes increase rapidly with increasing DBAOE in 0-2 km height layer.
- One possible reason for the lower DBAOE of Spire is the lower sampling rate of Spire.

Acknowledgments

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect those of NOAA or the Department of Commerce.