Processing GeoOptics Radio Occultation Data at NOAA/STAR using the Full Spectrum Inversion method

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April 08, 2021

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Motivation

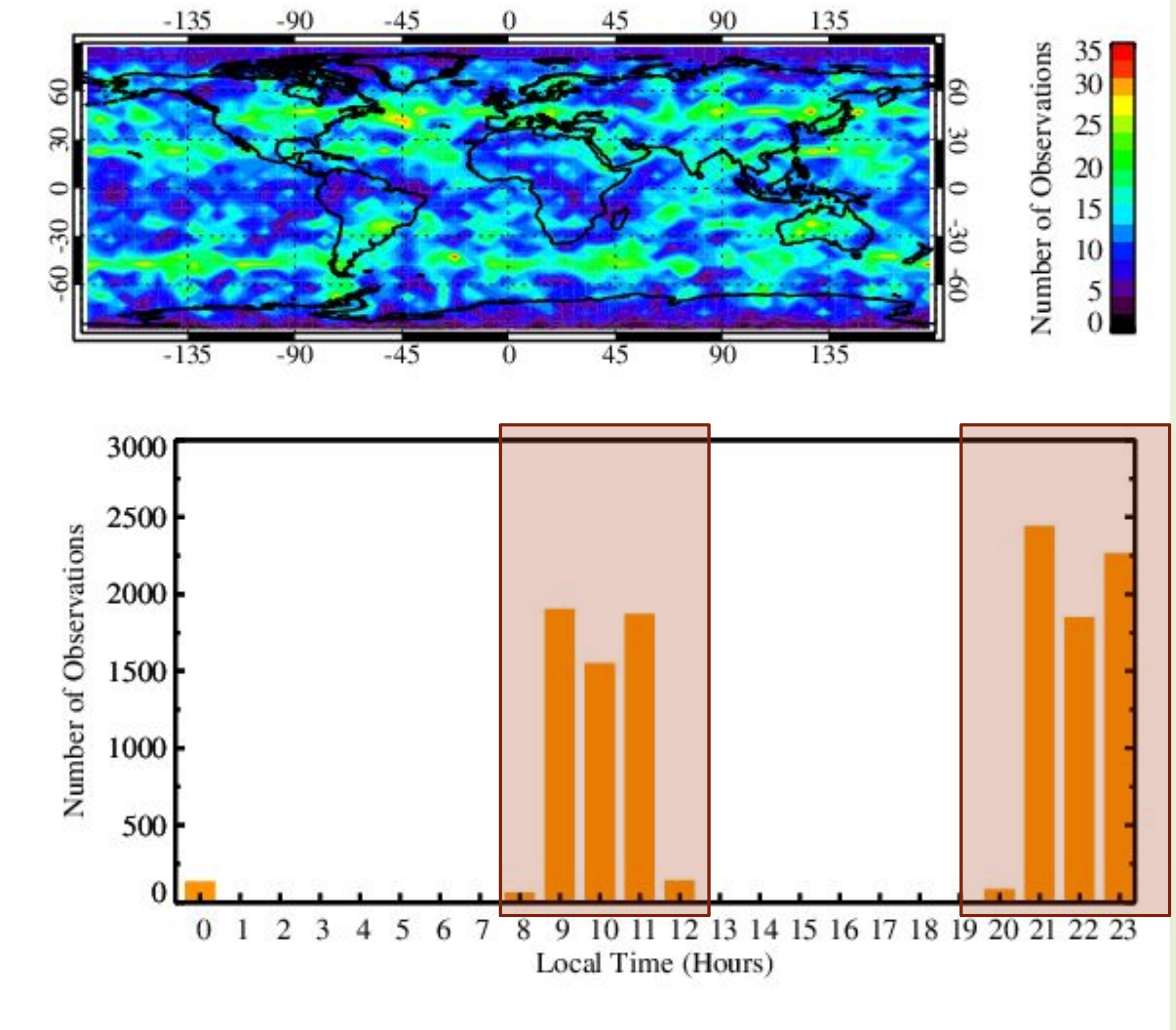
- GNSS RO observations are important part of NOAA's operational weather forecasting
- Due to multiple GNSS RO missions, NOAA/STAR needs to develop capabilities for quality control of data
- NOAA STAR's quality control can be best performed by developing capabilities to process RO data from different sources
- NOAA STAR processed data provides additional RO data source for public use

Salient Features of NOAA STAR Processing

- FSI method uses FFT of the complete profile, making processing computationally efficient
- Single inversion method at all vertical levels makes the vertical resolution independent of height

Data

Data count for 5 lon x 5 lat box for 1 month

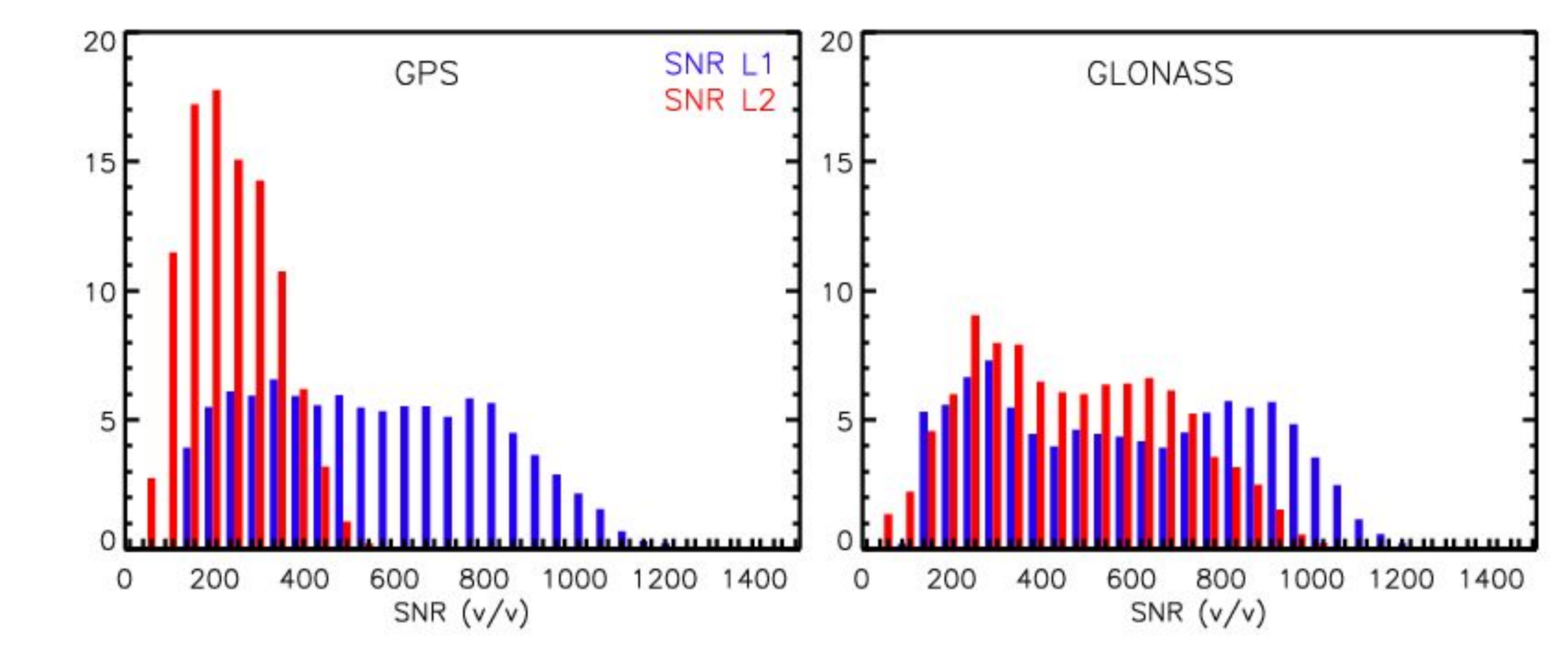


- UCAR processed GeoOptics Level 1b and Level 2 data for Dec 15, 2020 – Jan 14, 2021
- ERA-5 temperature, pressure and specific humidity profiles for Dec 15, 2020 – Jan 14, 2021

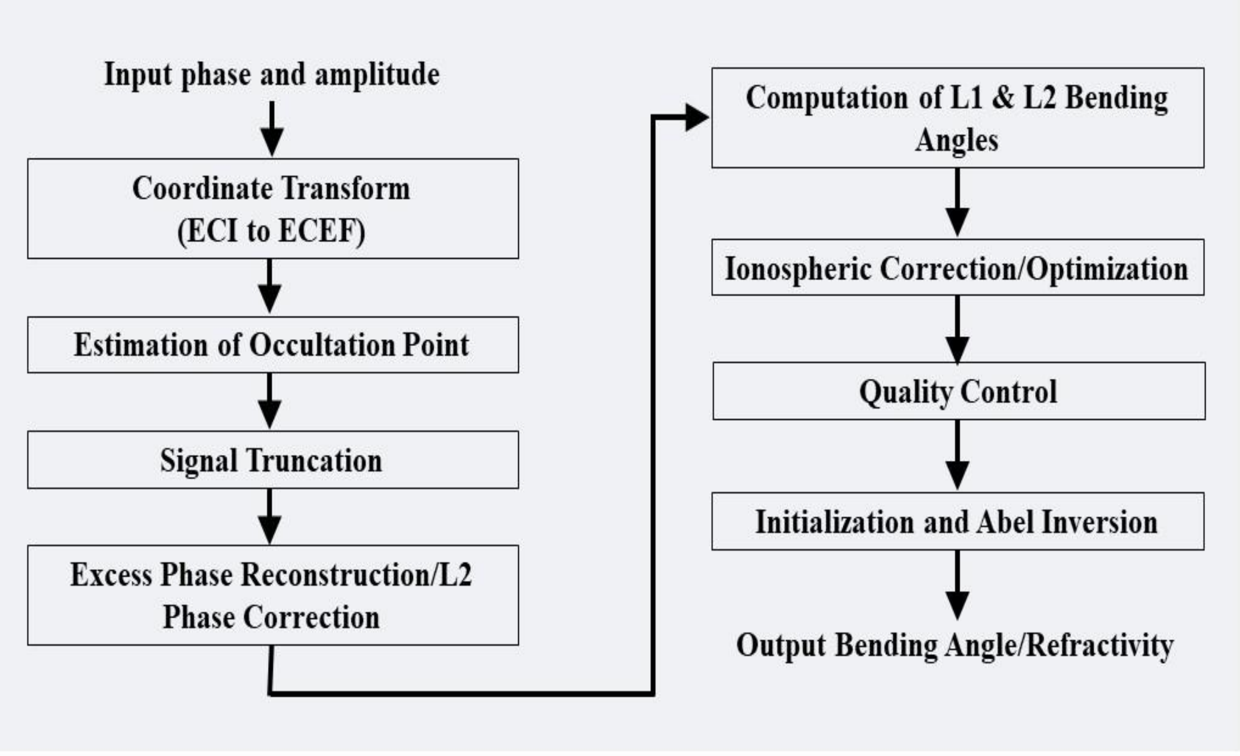
- Larger data density in mid-latitudes
- Measurements at 9 – 11 AM and PM local solar times

Local solar times calculated based on reference tangent Longitude

Signal-to-Noise Ratio (SNR)



NOAA STAR Processing System: Phase Data to Refractivity

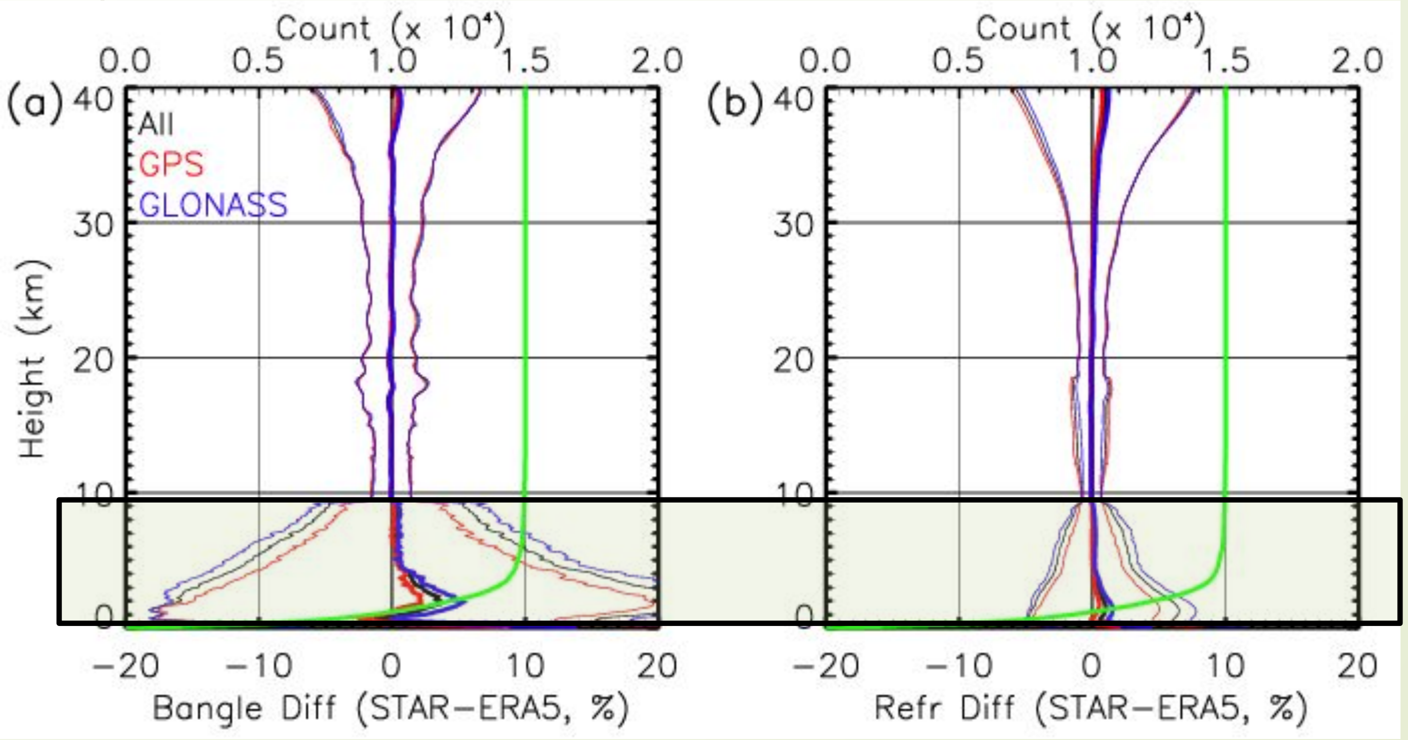


Processing Step	Implementation Approaches
Input data	Input UCAR orbit in Cartesian ECI coordinates, L1 and L2 excess phase and SNR data
Coordinate Transform	Transforming ECI coordinates to ECEF Coordinate
Signal Truncation	Based on L1 SNR, truncating signals using threshold on calculated base SNR
Excess Phase Reconstruction	Computation of excess phase after Fourier filtering of Doppler using 0.5-second window
Bending Angle Computation	Full Spectrum Inversion
Ionospheric Correction	Linear combination and statistical optimization of L1 and L2 bending angles
Quality Control	Mean L1 – L2 difference at 25 – 50 km < 100 μrad, mean fractional bending angle difference (GEO-CIRAQ) at 25 – 40 km < 0.5
Initialization	Exponential fit above 55 km
Refractivity Calculation	Abel inversion of the ionospheric corrected bending angle with the exponential fit

Overview of the implementation of the NOAA STAR processing system

Validation: Comparison with ERA-5

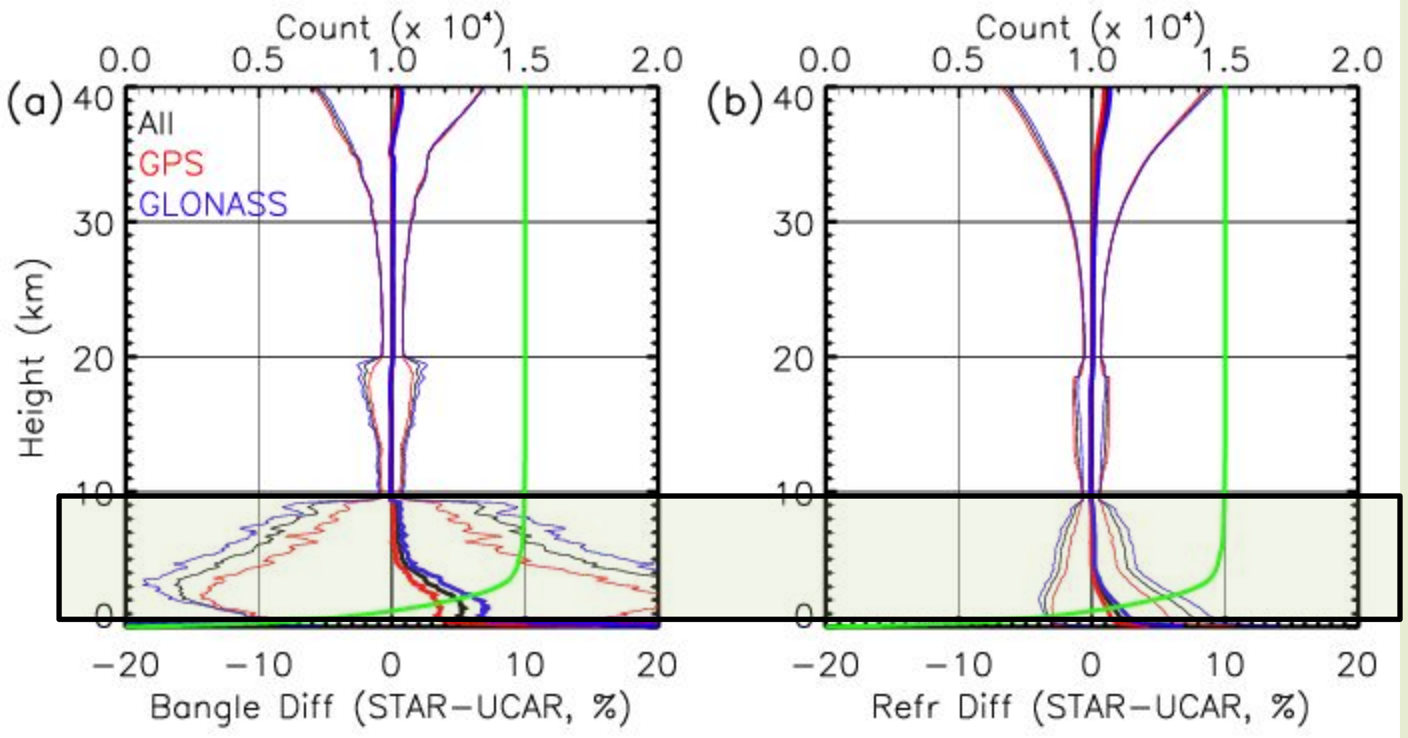
- Interpolate ERA-5 temperature, pressure, and specific humidity to COSMIC-2 reference tangent point location and time
- Calculate Refractivity (N) as $N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2}$
- Use Abel integration with the COSMIC-2 reference radius of curvature to calculate ERA-5 bending angle profiles corresponding to each COSMIC-2 profile



- **Positive bias at 2 – 5 km**
- **Standard deviation rapidly increases below 10 km**
- **GLONASS has larger bias and standard deviation than GPS**
- **Discontinuity at ~9 km due to using unfiltered data to invert bending angle below 10 km impact height**

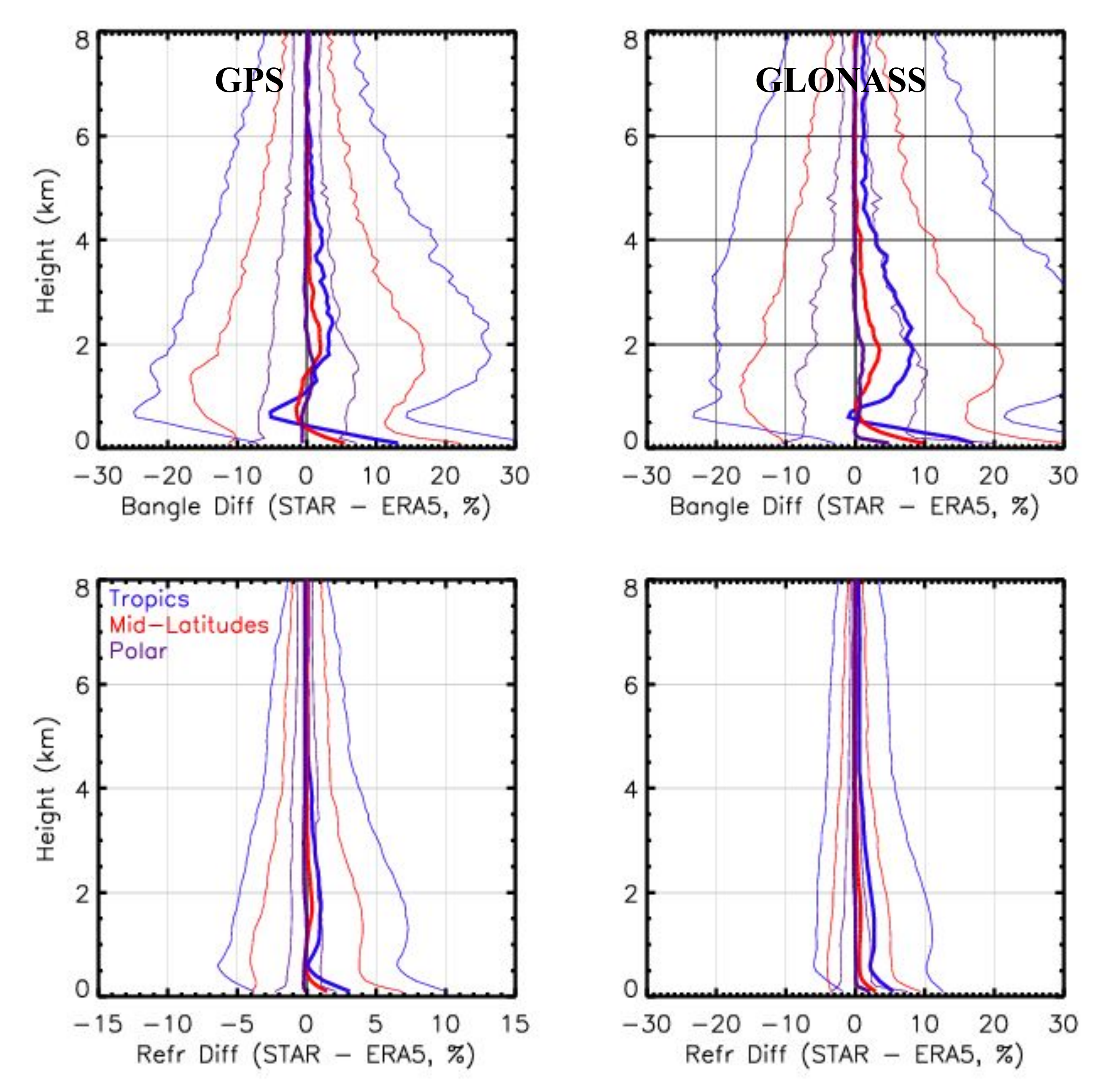
Validation: Comparison with UCAR

- Profile-to-profile comparison between UCAR and STAR for profiles that pass both UCAR and STAR QC criteria



- **Positive bias at below 6 km and above 36 km**
- **Standard deviation increases rapidly from 10 km downwards**
- **Discontinuity at ~10 km due to using raw data to invert bending angle below 10 km**

Comparison with ERA-5 at Different Latitude Bands

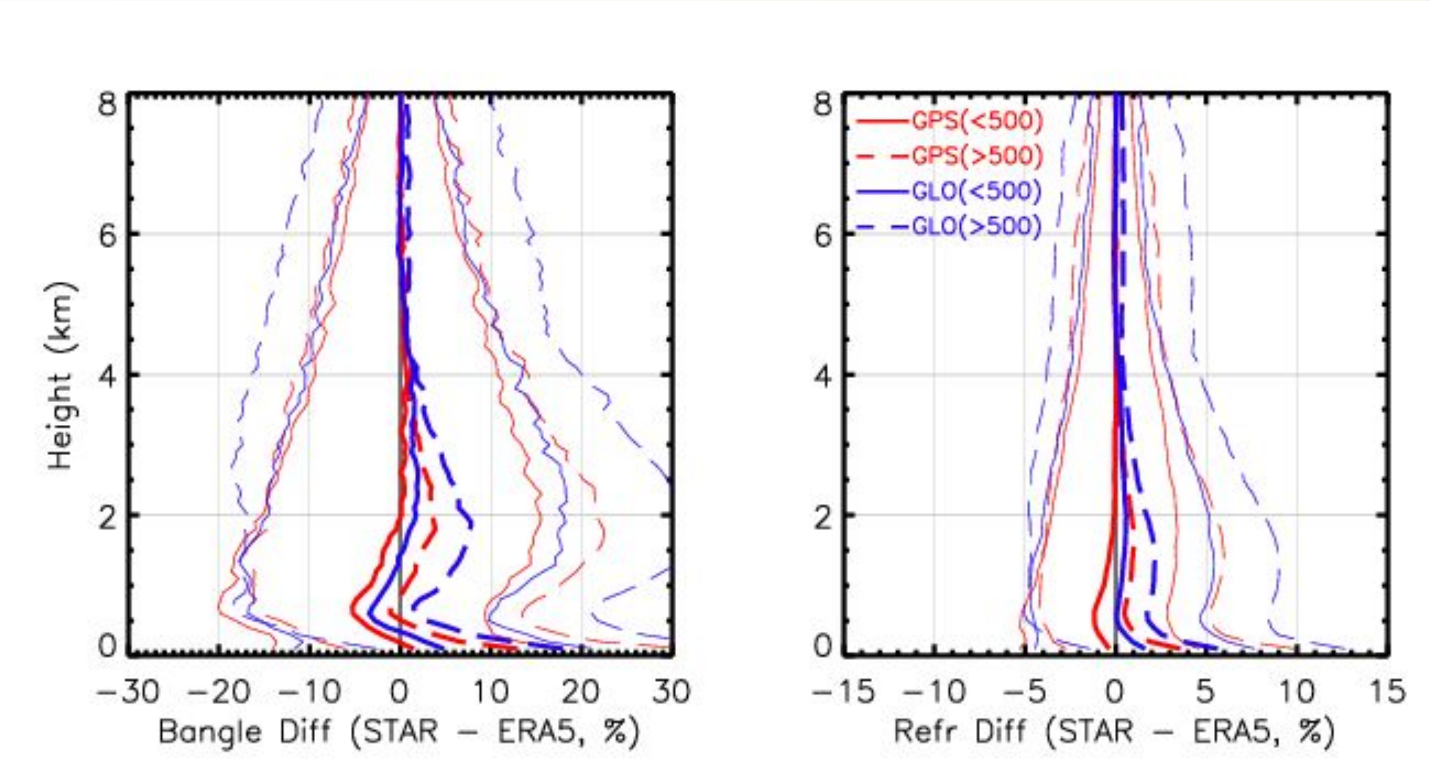


- Tropics (30N – 30S)
- Mid Latitudes (30N/S – 60N/S)
- Polar (60N/S – 90N/S)

		GPS	GLONASS
Tropics 30N – 30S	Bending Angle	1.27 (15.30)	3.66 (20.04)
	Refractivity	0.42 (3.94)	1.34 (5.55)
Mid-Lat (30 – 60)	Bending Angle	0.36 (8.98)	0.99 (10.61)
	Refractivity	0.07 (2.27)	0.25 (2.66)
Polar (60 – 90)	Bending Angle	-0.04 (3.74)	0.15 (4.49)
	Refractivity	-0.14 (0.84)	-0.09 (1.13)

Larger positive bias and standard deviation of GLONASS than GPS at all latitude bands

Comparison with ERA-5 at Different SNR Bands



- Solid lines: Low SNR
- Dashed lines: High SNR
- GPS
- GLONASS

	SNR < 500 v/v		SNR > 500 v/v	
	Bending Angle	Refractivity	Bending Angle	Refractivity
GPS	-0.36 (10.17)	-0.17 (2.35)	0.48 (11.14)	0.21 (3.00)
GLONASS	1.30 (12.11)	0.37 (3.20)	3.07 (17.51)	0.99 (4.76)

- GLONASS is consistently positively biased than GPS
- Larger standard deviation for high SNR cases compared to low SNR

Local Spectral Width (LSW)

1. Spectral Analysis
   - Calculate the spectra of local frequencies (bending angle) at high vertical resolution
   - Calculate spectra at a 500-m window
   - Downshift the local bending angle by the central bending angle of the window
   - Calculate frequency (power) of the spectra at 0.0005 radians at 100-m intervals
2. Calculation of the Width of the spectrum ($\Delta\alpha$)

$$\Delta\alpha = \frac{\sum_{i=1}^{n} P_i |\alpha_i| \delta\alpha}{\sum_{i=1}^{n} P_i \delta\alpha}$$

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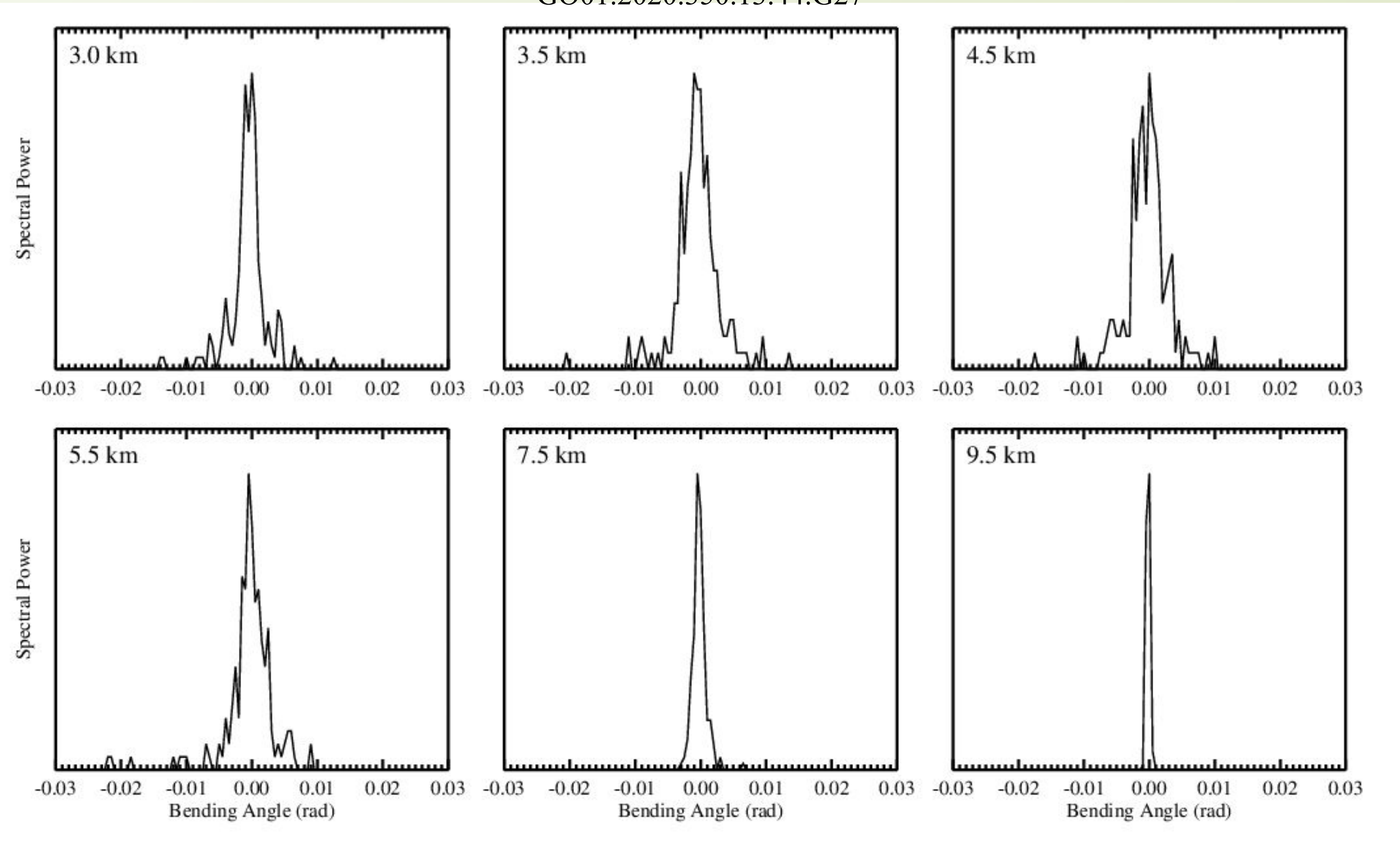
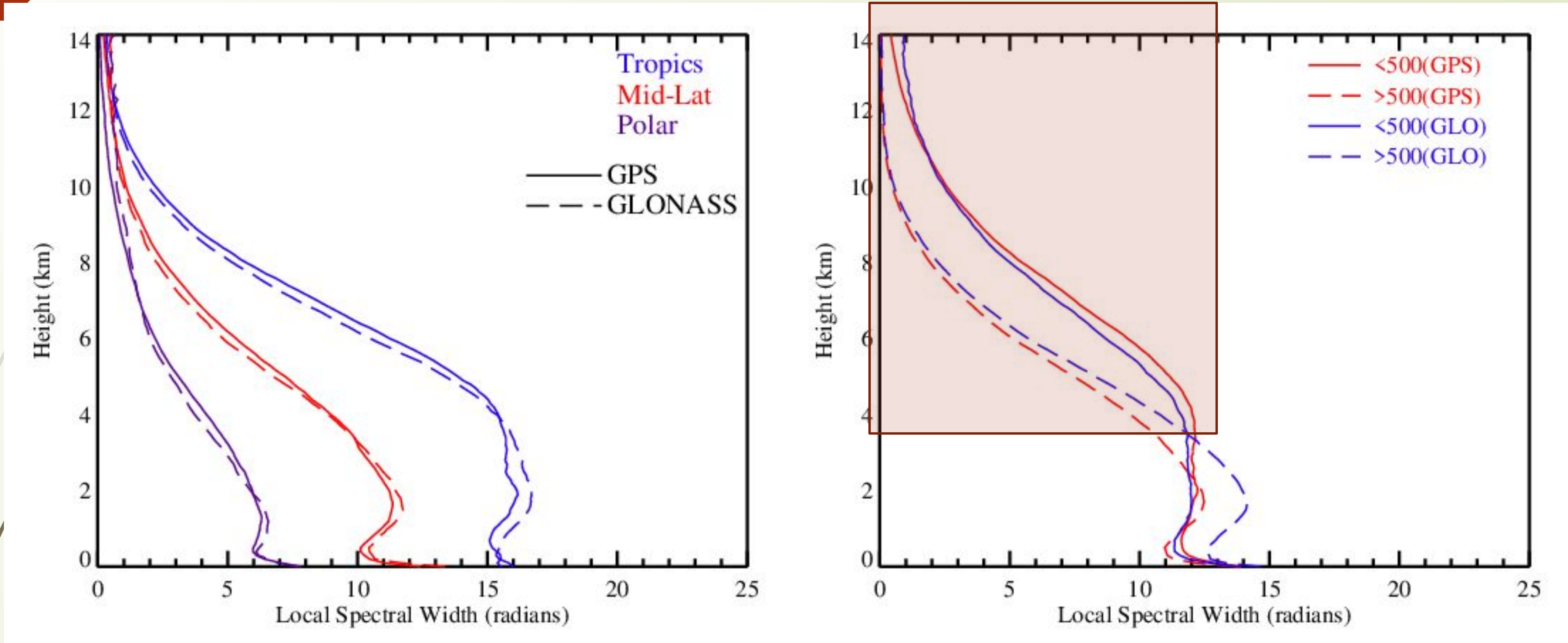


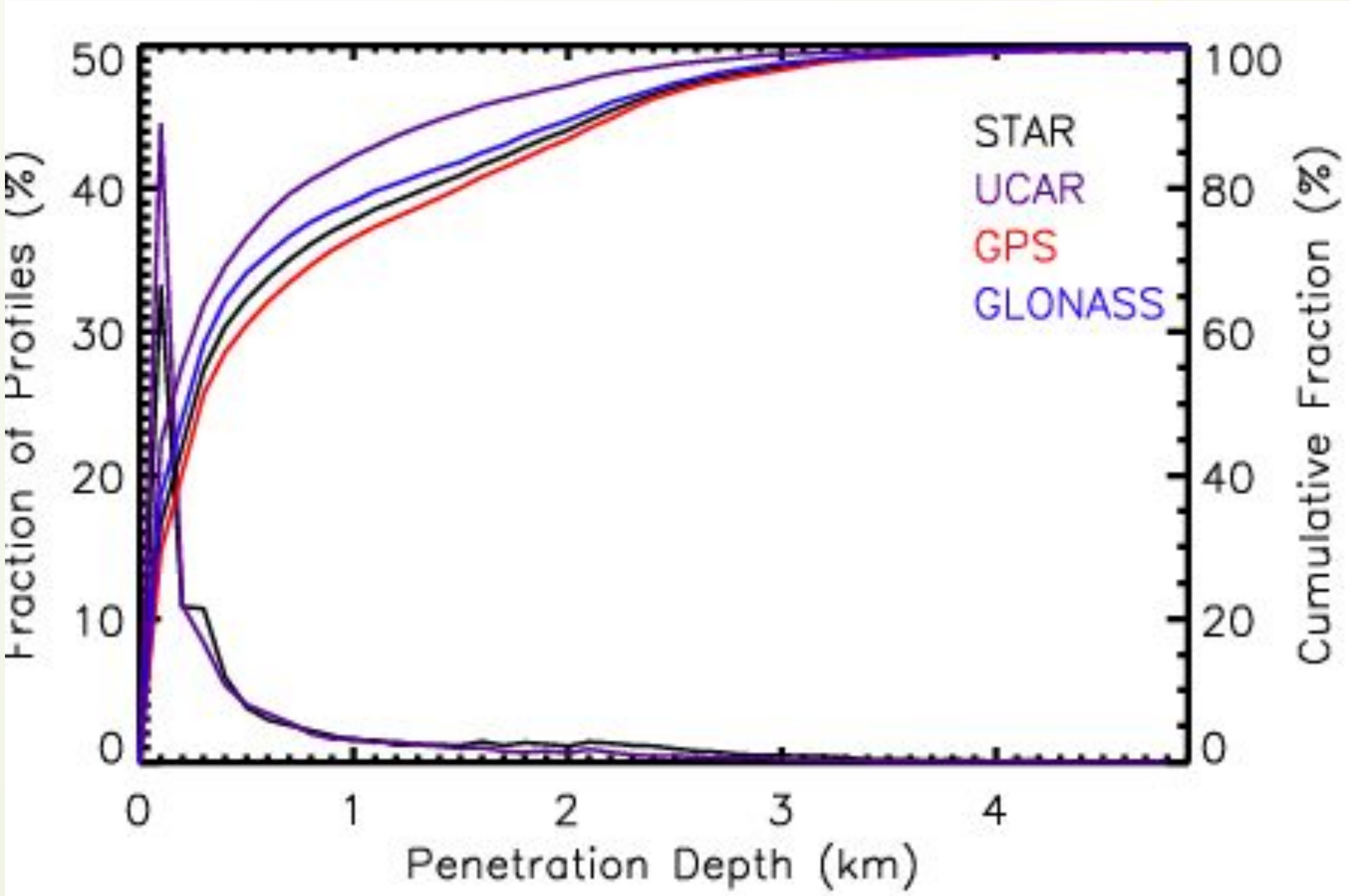
Power Spectrum at different Impact heights

Local Spectral Width (LSW)



- LSW larger for SNR > 500 below 3 km.
- Above 3 km, LSW decreases rapidly for SNF > 500 and $LSW_{SNR < 500} > LSW_{SNR > 500}$

Penetration Depth



Summary and Conclusion

- NOAA STAR Inversion method of time series of the geometry and phase data to profiles of bending angle and refractivity using FSI method for the complete profile
- NOAA STAR processed bending angle and refractivity are validated with (1) ERA-5 interpolated to GeoOptics tangent point position and time, and (2) profile-to-profile comparison with UCAR profiles for Dec 15, 2020 – Jan 14, 2021 data
- STAR RO products from GLONASS have a larger positive bias and standard deviation compared to those from GPS
- The NOAA STAR processed data provide independent source of RO data