



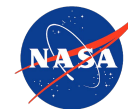
IGARSS 2024

Observing GNSS-RO grazing reflection and its applications to characterize planetary boundary layer

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July 9, 2024

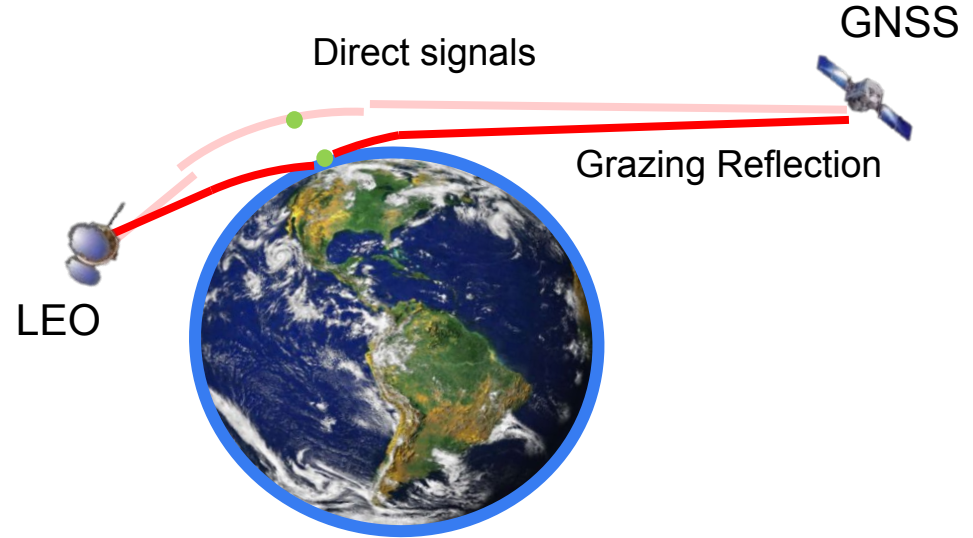


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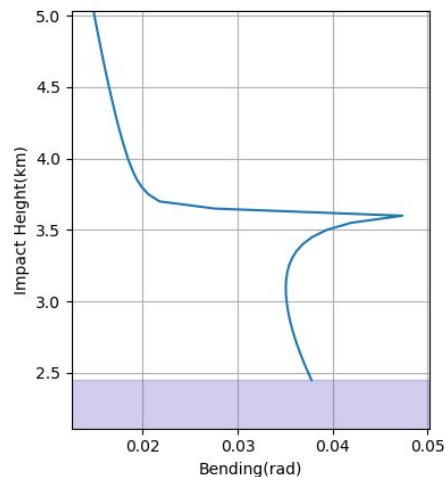
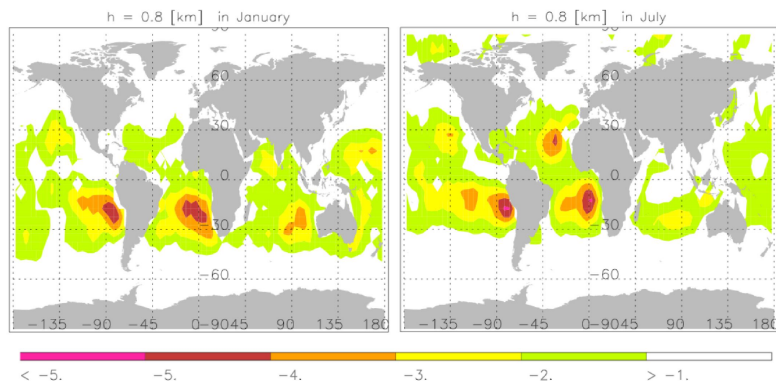
Outline

- **Motivation**
- **Ducting & Grazing reflection**
- **Grazing RO processing**
- **COSMIC-2 grazing RO**
- **OL tracking for grazing RO**
- **Conclusion**

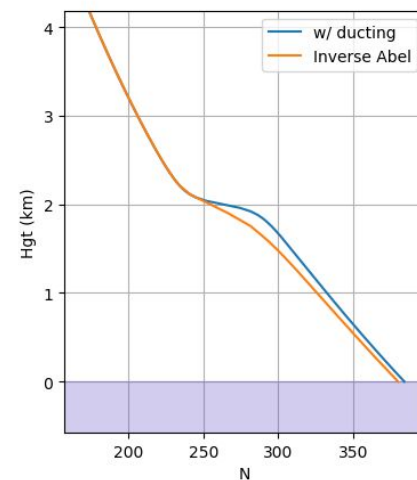


Motivation

- **Abel inversion** assumes 1-to-1 relation between each bending angle and refractivity pair. However, this is not always the case.
- **Ducting** condition breaks the 1-to-1 relationship and causes negative bias in refractivity retrieval (*N*-bias)



Bending Angle Profile



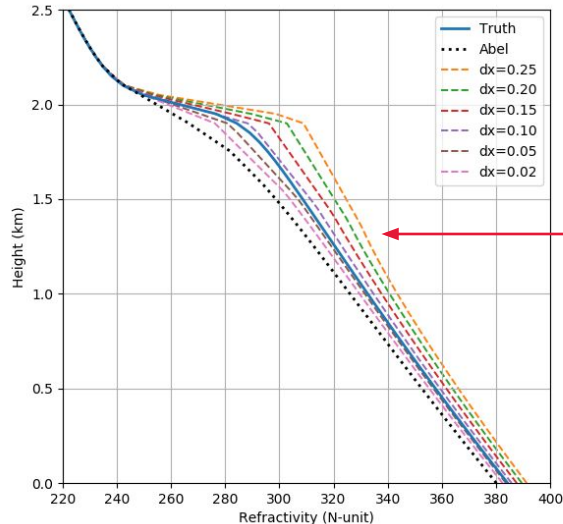
N Profile

Abel Inversion

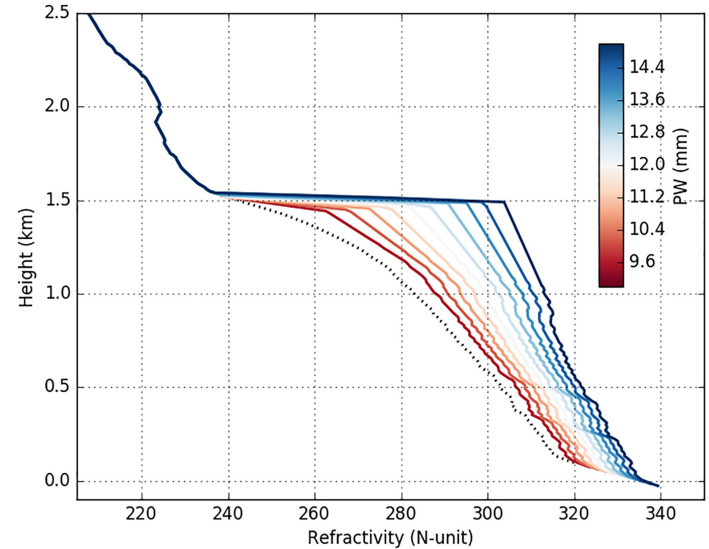
[Xie et al, GRL, Vol. 37, 2010]

N-bias reduction

- **[Xie et al., 2006]** derived analytical refractivity solution family using Abel-inversed RO refractivity retrieval. However, an extra constraint is needed to identify the unbiased profile.



Refractivity profiles corresponding to the same **direct bending angle profile** under ducting condition



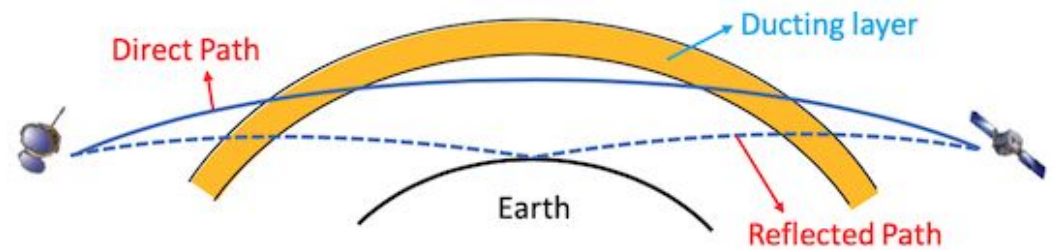
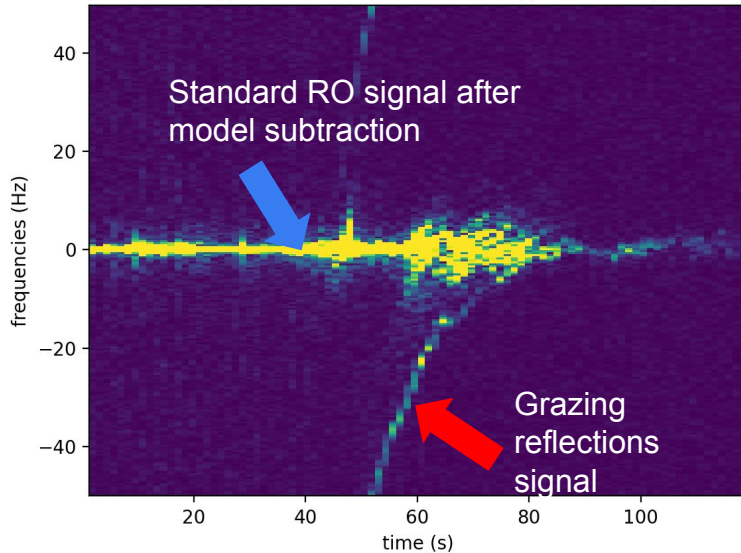
[Wang et al., 2017] proposed using PW from the collocated MWR measurements to identify the profile

Grazing reflection

- The grazing reflection signals can be observed in the existing RO spectrum

Grazing reflections signal from COSMIC-2

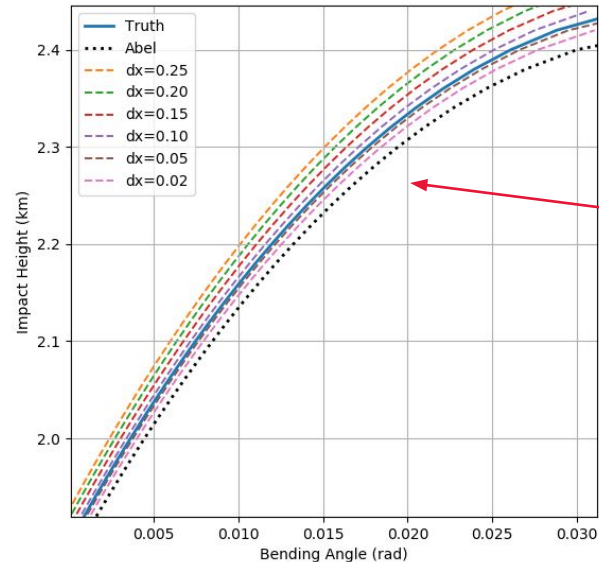
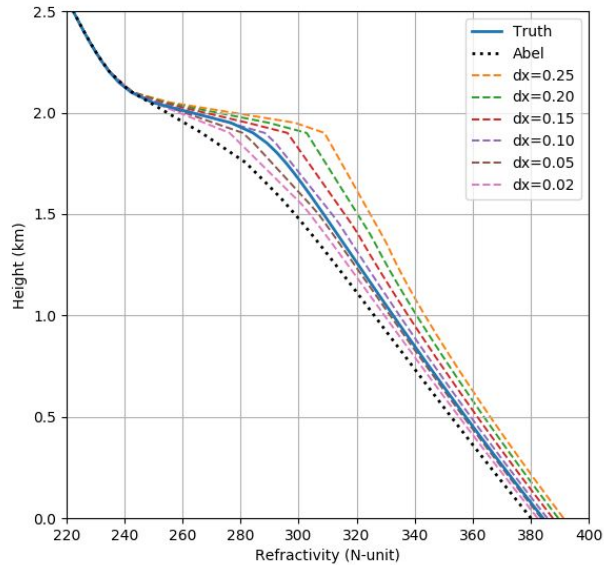
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- Grazing reflection signals also contain atmospheric information which can be used as a constraint to select the unbiased profile.

Grazing reflection

- The bending of grazing reflection is sensitive to the refractivity within PBL, even when ducting occurs [Aparicio et al., 2018].

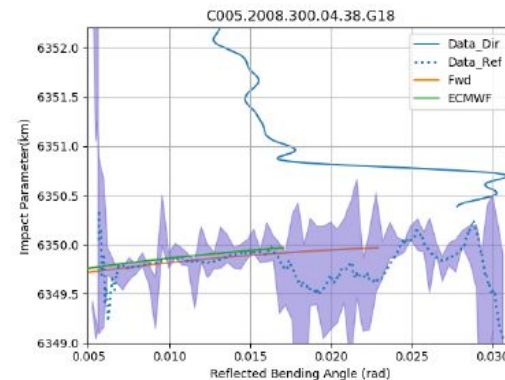
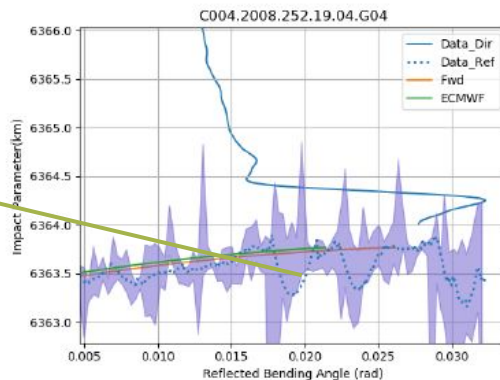
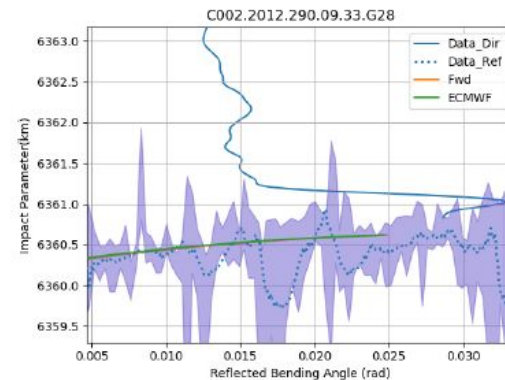
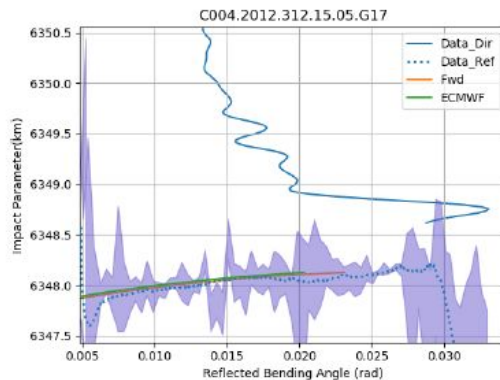


Each possible refractivity profile has its own **distinct reflected bending angle**

Grazing RO retrieval

bending angle calculation

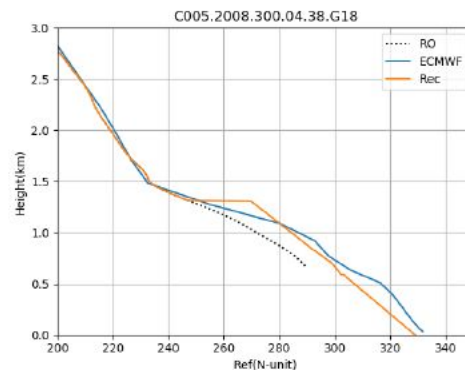
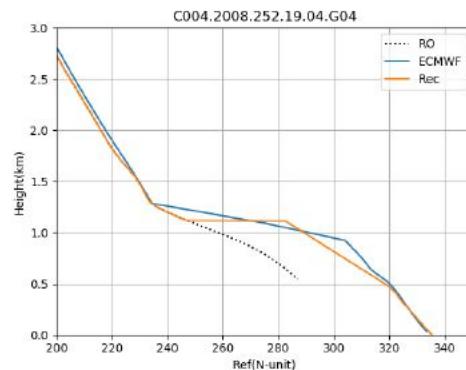
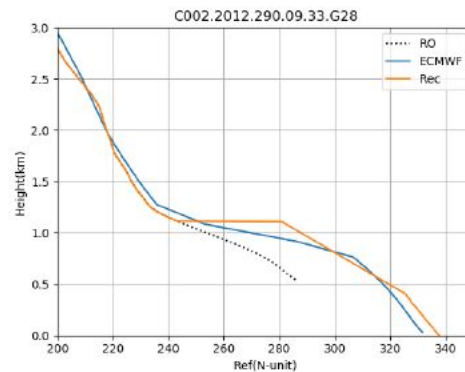
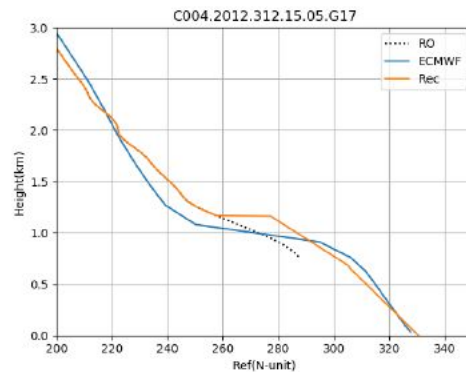
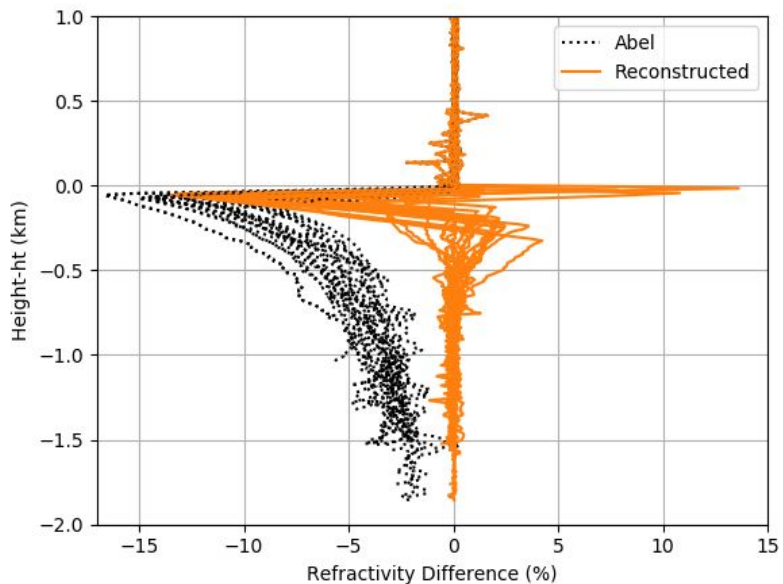
- Geometric optics
- Optimal estimation – search for the profile in the family that can best fit the observed bending angle



Large fluctuations
due to low SNR

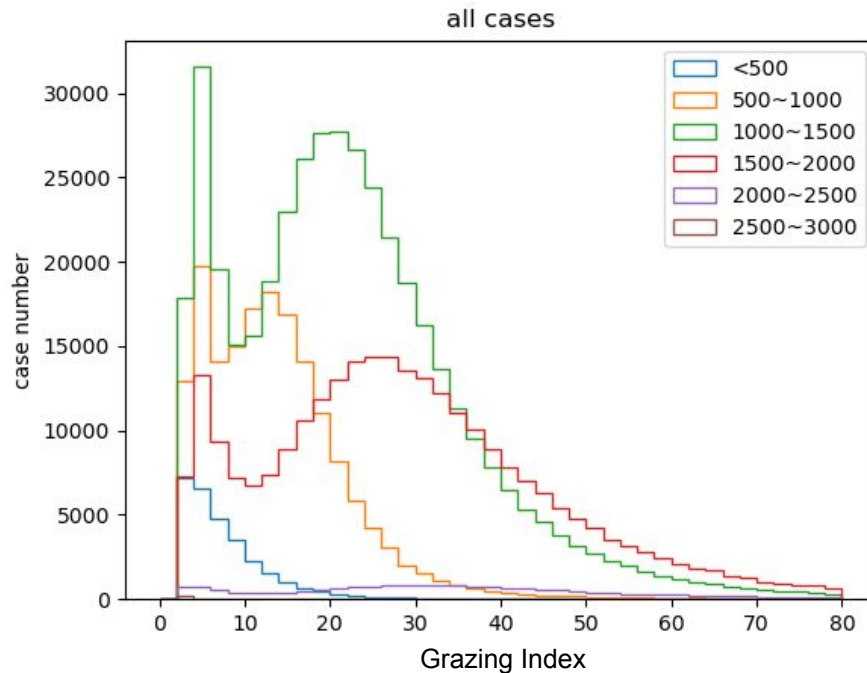
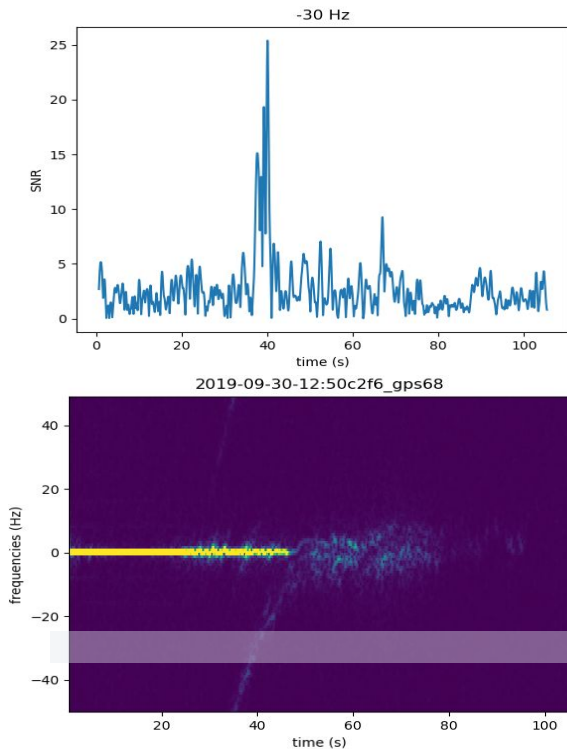
Grazing RO retrieval

Ducting N -bias correction results [Wang et al., 2020]



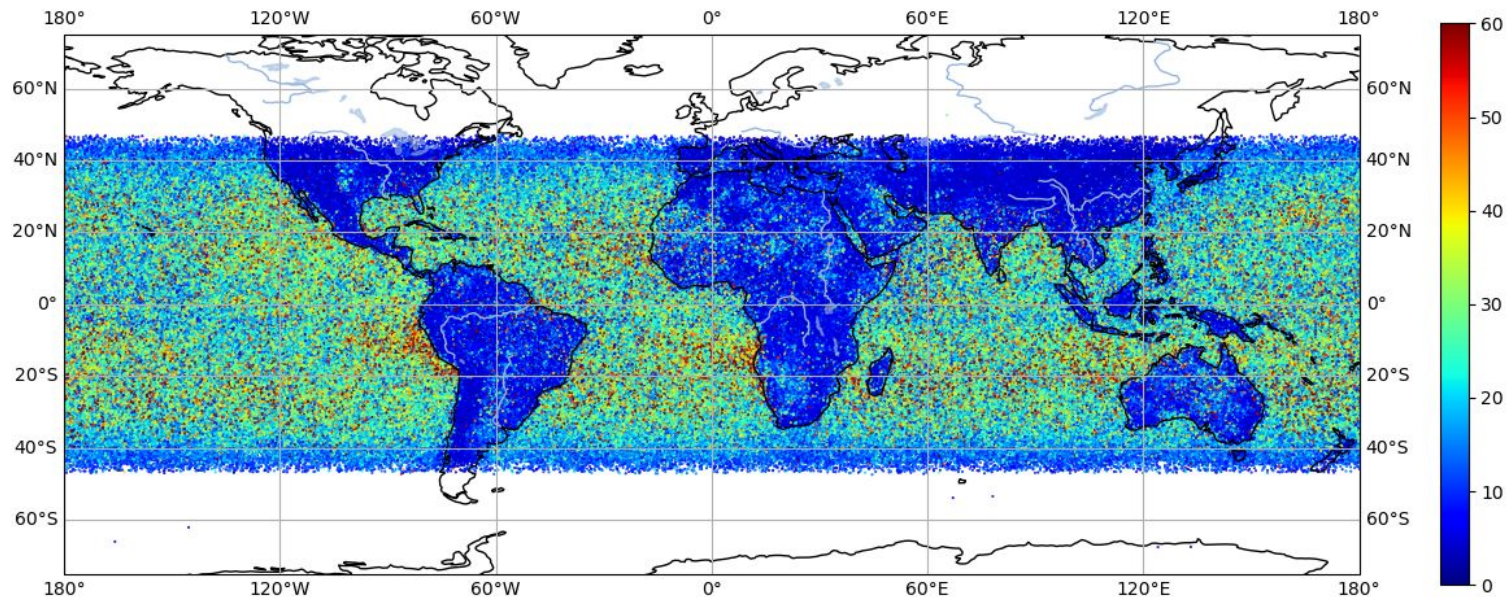
COSMIC-2 grazing statistics

- Grazing signal detection grazing index $(\overline{SNR}_{p,25\sim35})/SNR_N$



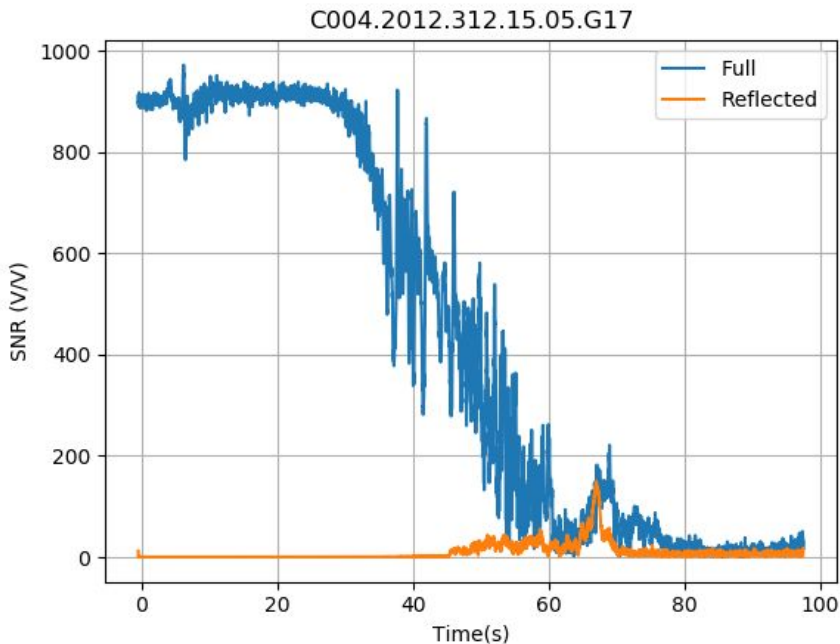
COSMIC-2 grazing statistics

- Grazing signal strength using COSMIC-2
- Signal strength => Ocean: SST/atmospheric stability
Land: Reflectivity/surface roughness



Grazing reflection open-loop (OL) tracking

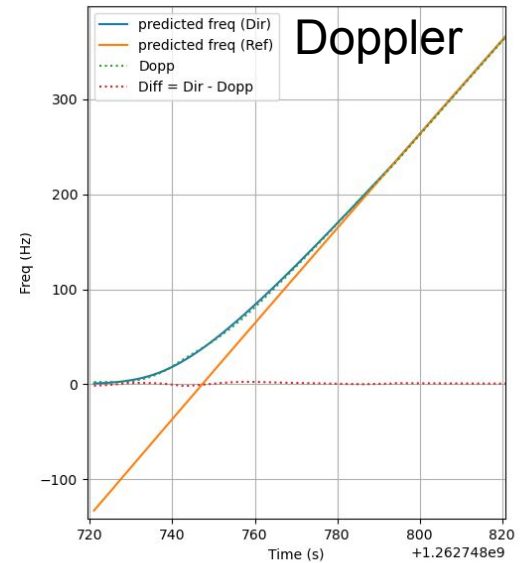
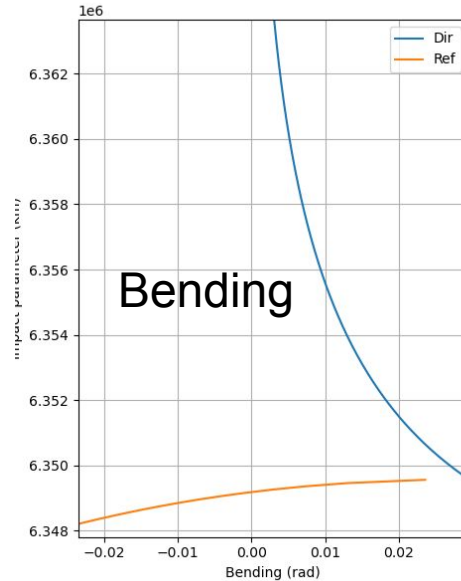
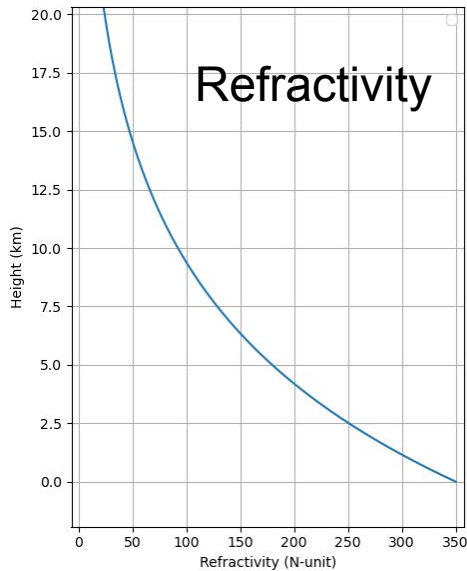
- Current grazing RO retrieval difficulties:
 - SNR is low (< 100 V/V)
 - Suffer from multipath
 - Elevation angle range is low ($< 2^\circ$)
- Can we do OL tracking on reflected signals?
 - HW: no change
 - SW: OL model needs to be calculated



Grazing reflection open-loop (OL) tracking

Grazing OL model

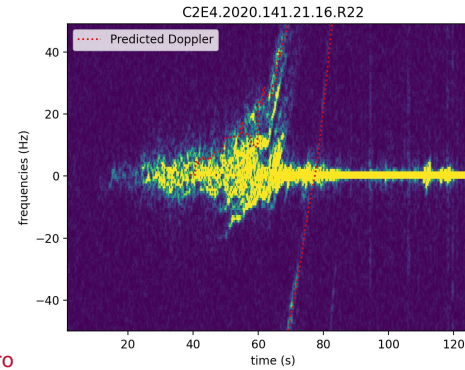
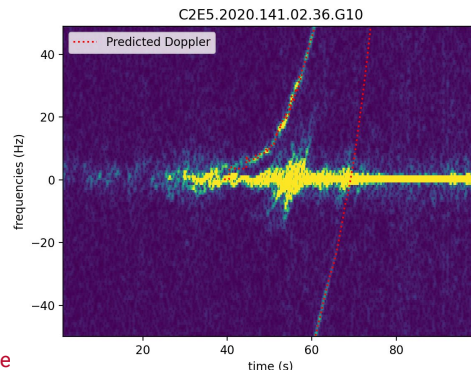
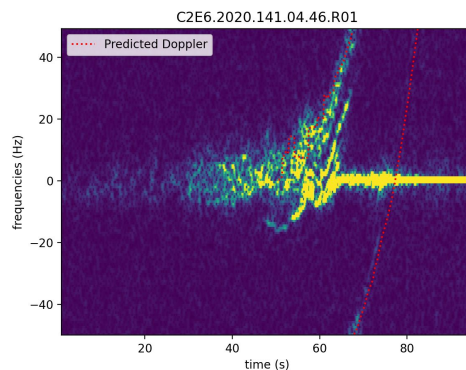
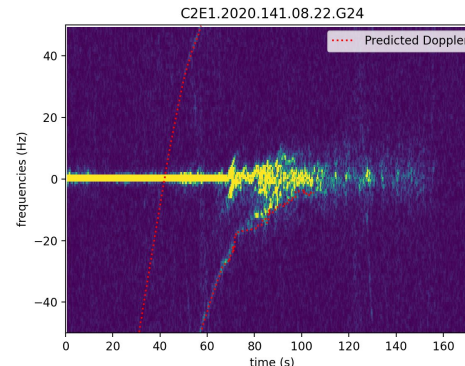
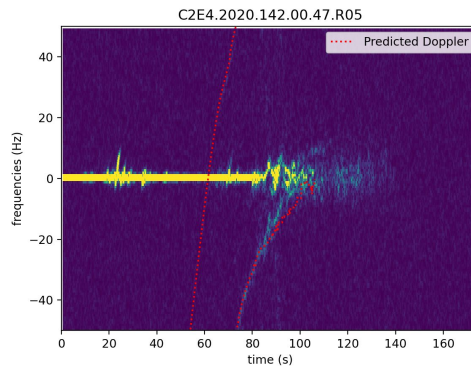
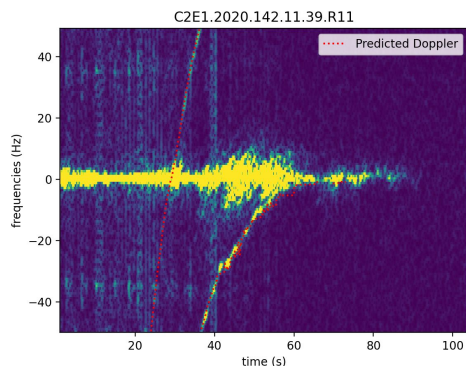
- Doppler/Range model based on the known profile



Grazing reflection open-loop (OL) tracking

Grazing OL model

- Validation



Conclusion

GNSS-RO grazing reflection

- In this research **the grazing reflection** is explored to constrain GNSS-RO observations within PBL under ducting condition
- The results show that the grazing reflection observations contain the atmospheric information needed for PBL characterization when SNR is sufficient.
- OL tracking for grazing reflection observations is developed for better quality signals, and hopefully will be tested in the near future



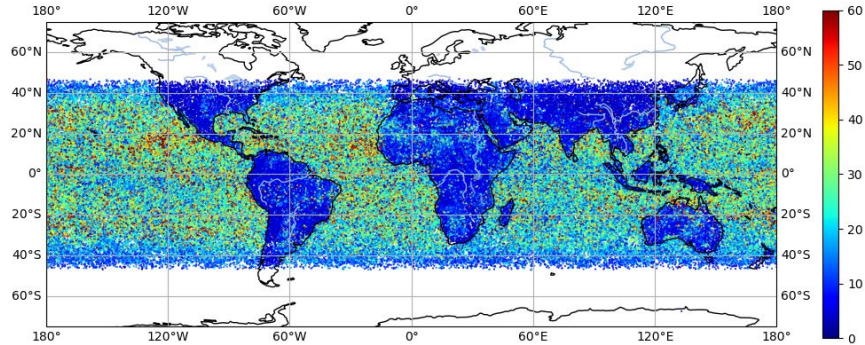
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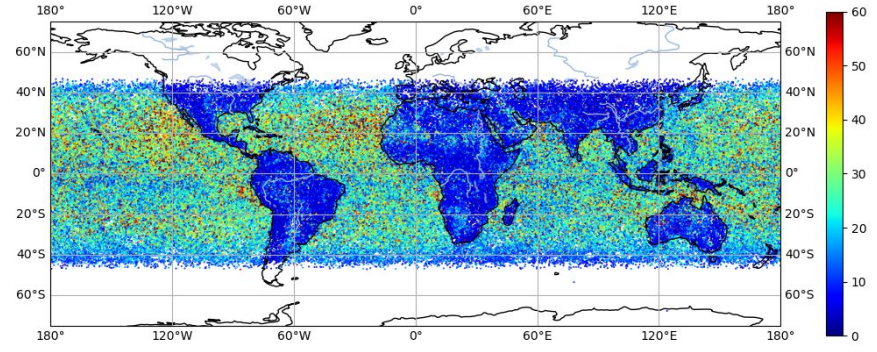
Backup

Statistics (seasons)

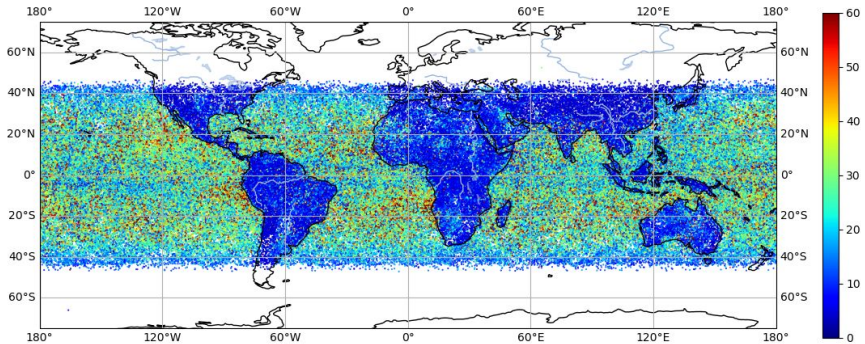
MAM



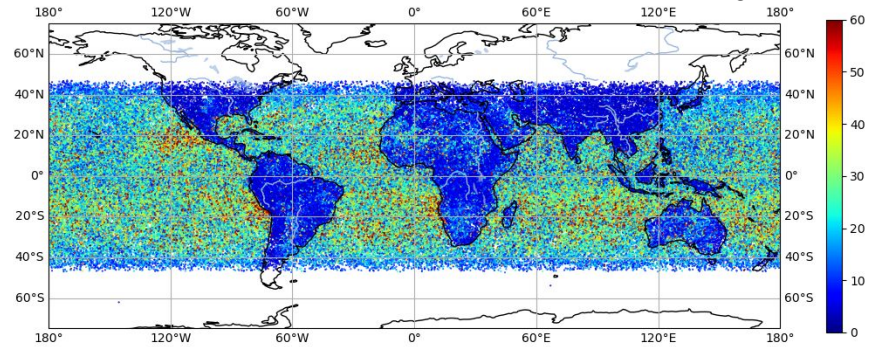
JJA



SON

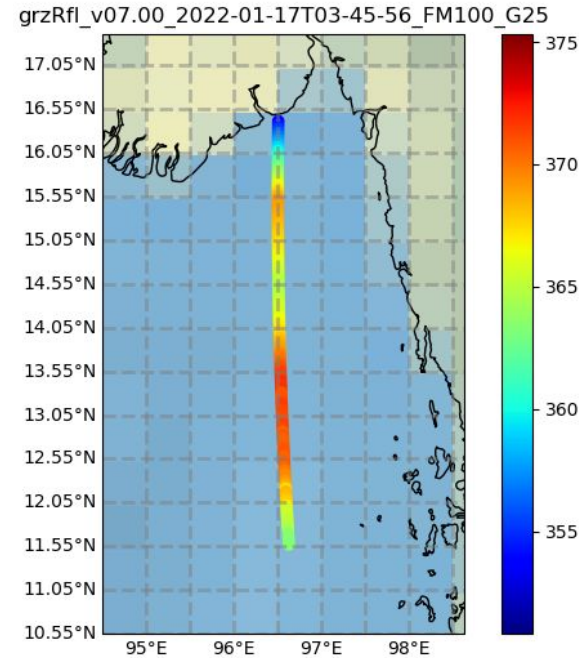
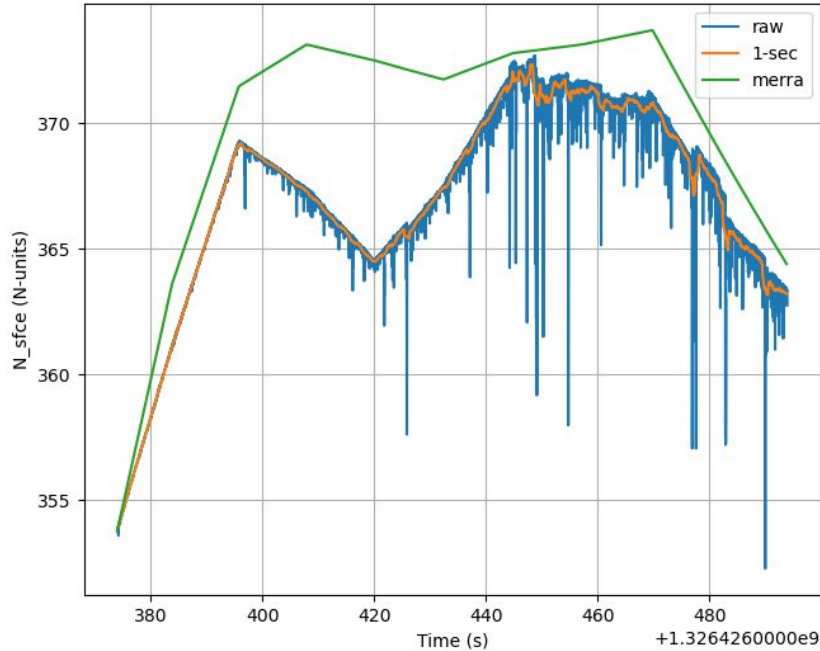


DJF



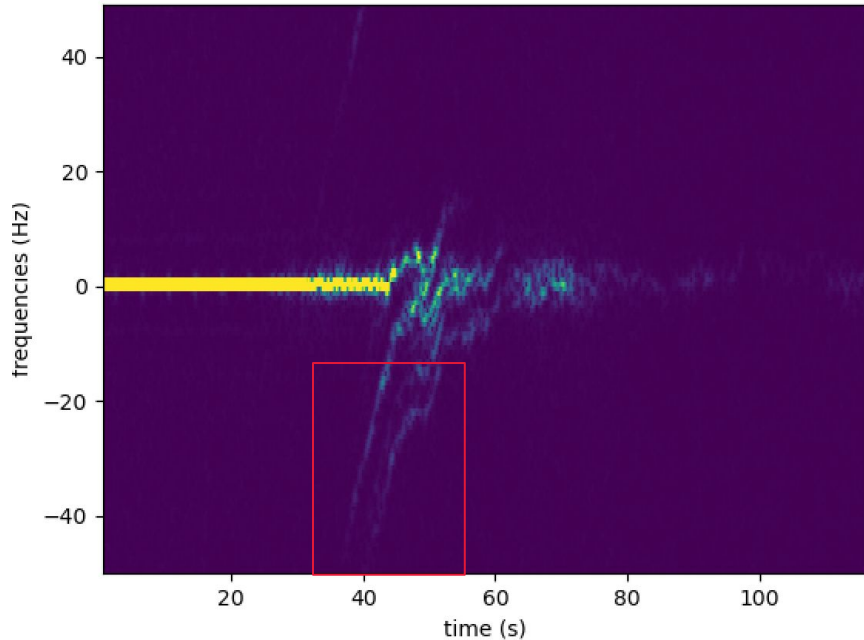
Backup

CSDA – near-surface refractivity retrieved from Spire data



Backup

Multipath

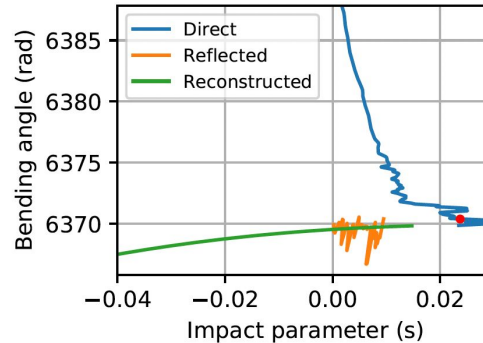
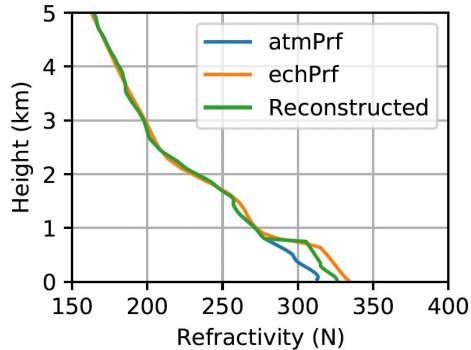
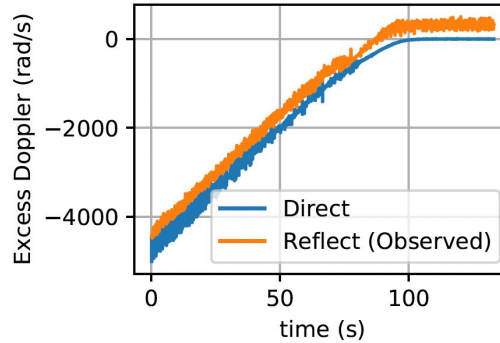
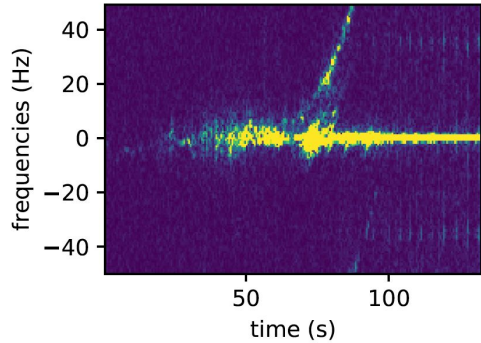


- Multipath from different reflection altitudes
 - Signal are received at the same time
 - Violates the RH assumption: each impact parameter shows only once during RO period.

Backup

COSMIC-2 single case reconstruction

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Backup

How does it connect to the atmosphere?

- Abel transform (Forward)
 - Direct signal (RO)

$$\alpha_D(a) = -2a \int_a^\infty \frac{1}{n(x)} \frac{dn(x)}{dx} \frac{dx}{\sqrt{x^2 - a^2}}$$

- Reflected signal (Grazing reflection) [*Aparicio et al, 2018*]

$$\alpha_R(a) = -2a \int_{a_s}^\infty \frac{1}{n(x)} \frac{dn(x)}{dx} \frac{dx}{\sqrt{x^2 - a^2}} - 2 \cos^{-1} \left(\frac{a}{n_s r_s} \right)$$

Refraction

Reflection

Near surface refractivity

Backup

GNSS-RO grazing reflections

- Why do we care about grazing reflections?
 - Scientifically – Sensitive to the surface properties, near surface atm., and PBL
 - Technically – No HW change is needed from RO!

	Deep Grazing	Grazing	GNSS-R
Elevation	$< 2^\circ$ (RHCP)	$5^\circ \sim 20^\circ$ (RHCP)	$> 40^\circ$ (LHCP)
Obs.	Coherent phase	Coherent phase	DDM
Sen. - rough	Low	Medium	High
Sen. - Atmos.	High	Medium	Low
Applications	PBL/low Tropos.	Ice altimetry	Wind, Soil moisture
Mission	<i>COSMIC etc.</i>	<i>Spire</i>	<i>CYGNSS, HydroGNSS</i>

Backup

- **Ducting** condition breaks the 1-to-1 relationship and causes multiple refractivity solutions corresponding to the same measured bending angle profile

