Estimation of the heights of superrefraction layers from radio occultation signals

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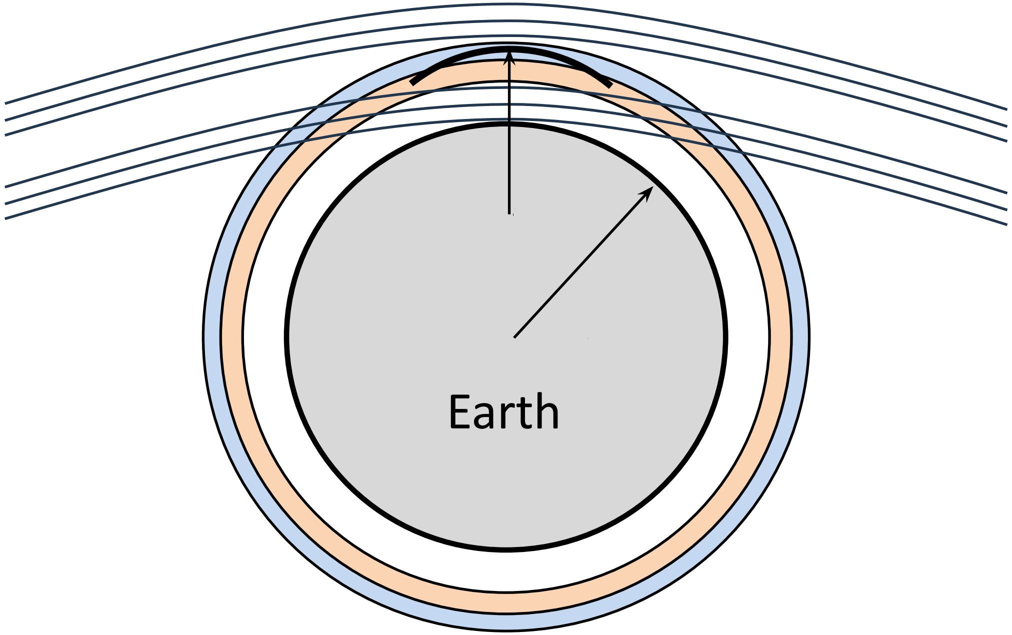
What is the super-refraction (SR) in radio occultation (RO)?

SR in RO is a phenomenon similar to superior mirage in optics; both are caused by anomalous curvature of rays

Definition of SR in this study: ray curvature radius at tangent point < Earth's radius; dN/dz < -157 km^{-1}



Credit: The Guardian; Photograph: Triangle News/Ryan Rushforth

SR layer

SR layer + layer below = **ducting layer**

NO external rays with tangent points inside the ducting layer

SR often occurs at the top of ABL over the subtropical ocean

Elevated and surface ducts

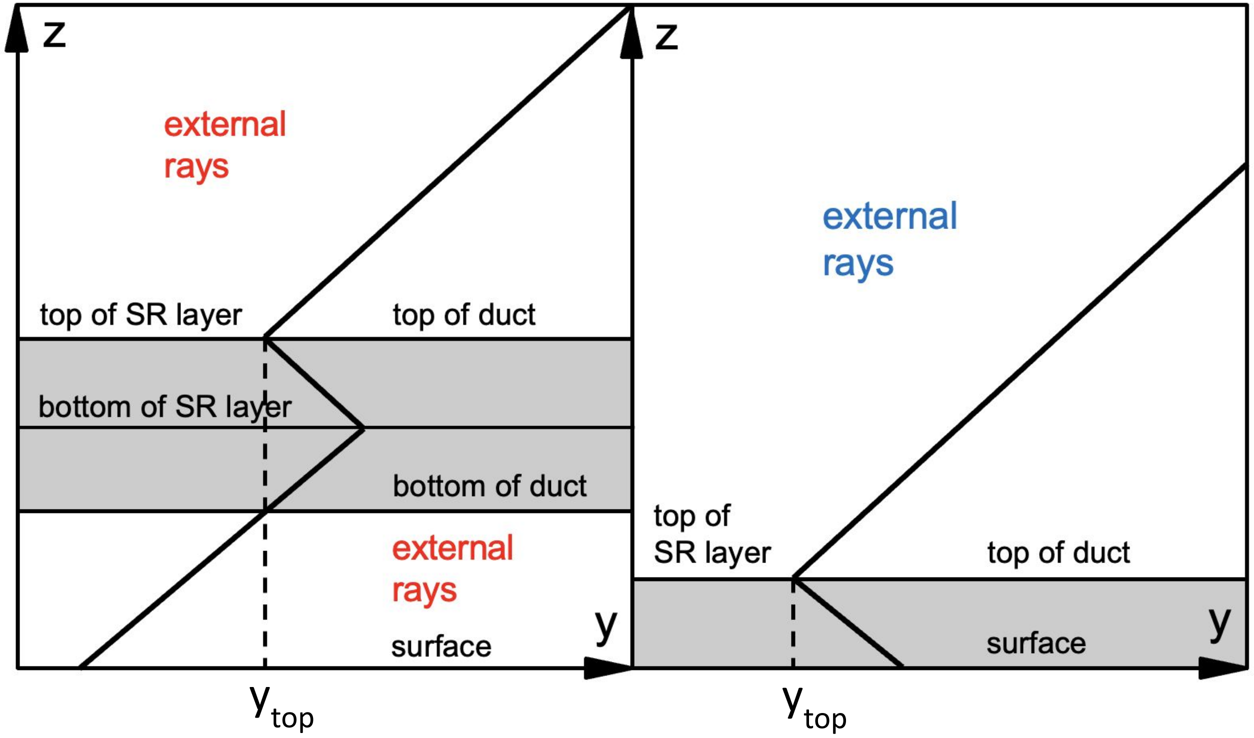
Commonly, they use modified refractive index: $m = n - 1 + z / r_e$ for specification of ducts

In RO DA, they use refractional radius: $x = r * n(r)$; refractional height: $y = x - r_e$

- SR layer: $dy / dz < 0$
- Ducting layer: $y > y_{top}$
- No external rays with TP inside ducting layer
- **Elevated ducts are detectable from deep RO signals:** Sokolovskiy et al., (2014, 2024)

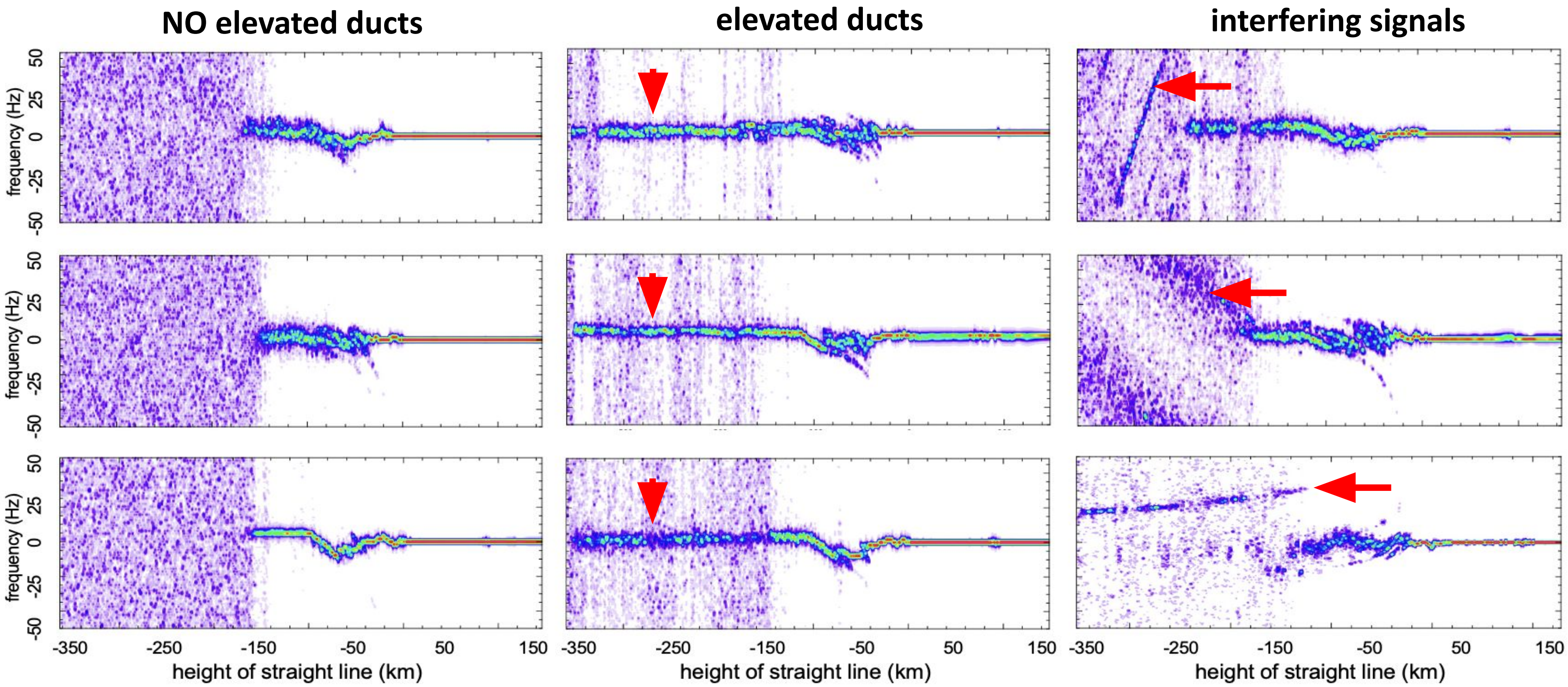
- **uncertainty in data assimilation**
- **negative N-bias in stand. inversion**
- **constrained inversions:** Xie et al. (2006, 2010); Wang et al. (2017, 2020)

Elevated ducts (detectable) **Surface ducts (not detectable)**



Examples of spectrograms of COSMIC-2 RO signals

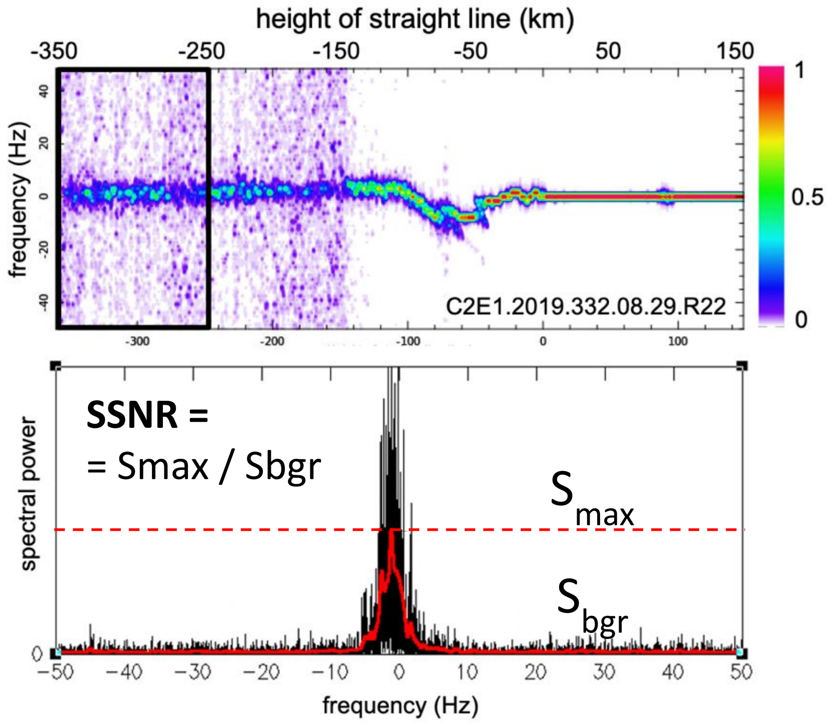
Elevated ducts induce weak diffracted RO signals ("deep signals") at HSL well below -150 km
Deep signals are detectable in the spectrograms (obtained with reference frequency model)



Detection of SR in previous study

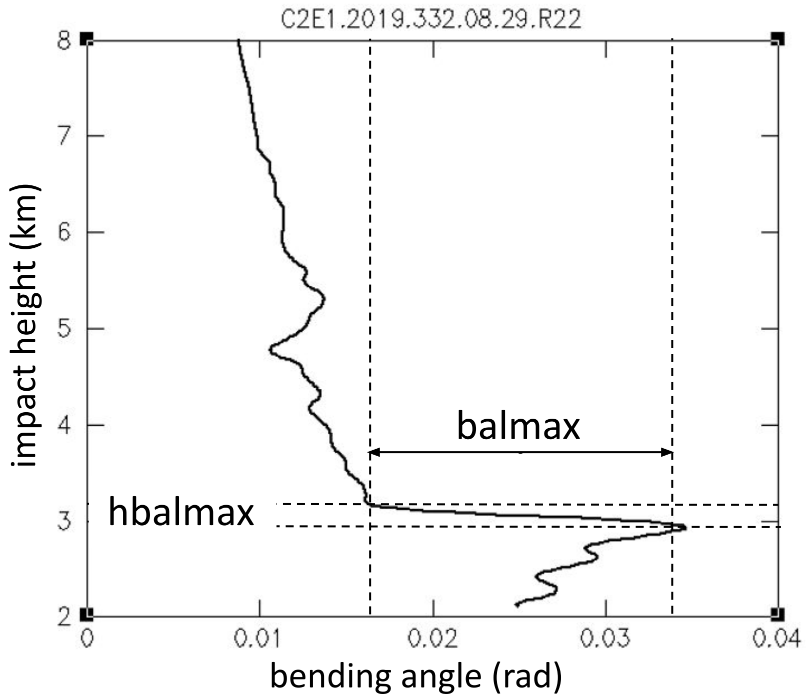
Metric 1: **Spectral analysis in a large HSL window between -350 and -250 km**

spectral SNR (SSNR) > 8



Metric 2: **Existence of strong inversion layer in BA profile (2007GL030458)**

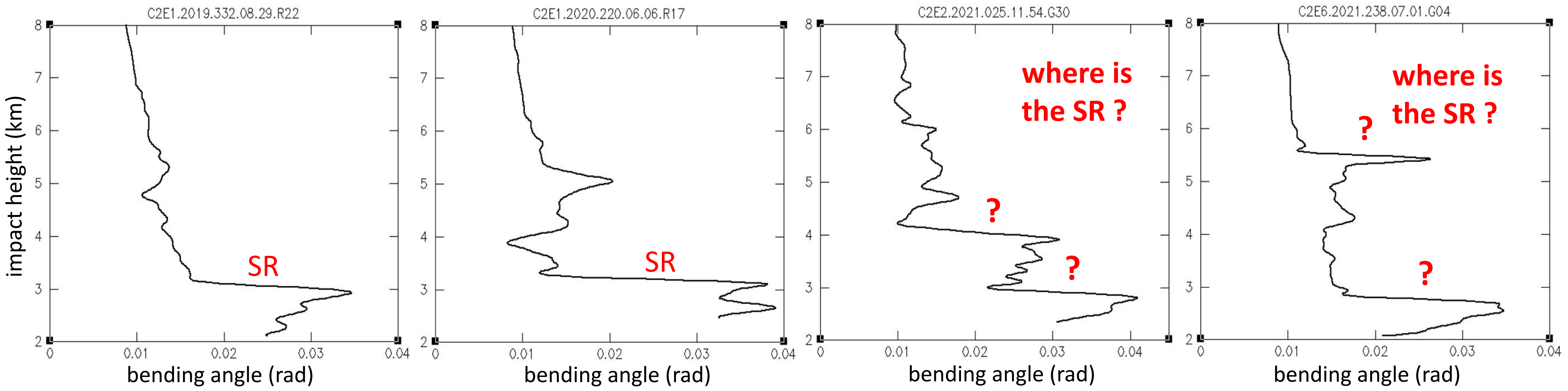
max. BA lapse (balmax) > 7E-3 rad



Examples of COSMIC-2 BA profiles

Metric 2 (large balmax) was used for discrimination of the interfering signals of a certain type.
In previous study, the height of balmax (hbalmax) was also used as the proxy for the duct height.
Analysis shows that this proxy works well for most (but not all) occultations.

Examples of BA profiles for the occultations with SR detected from spectrograms:

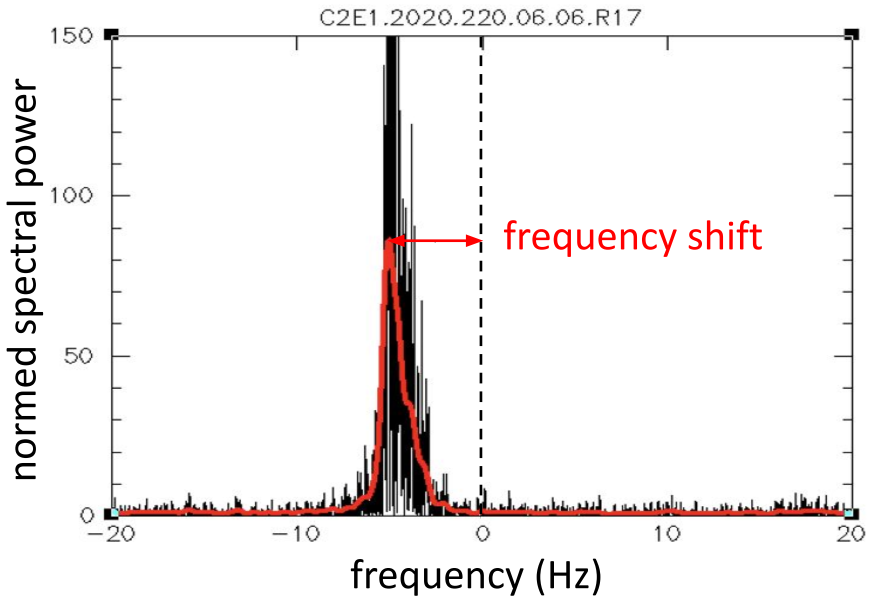


It is possible to independently determine duct height from RO signal by using GO or WO

Independent estimation of duct heights by GO and WO

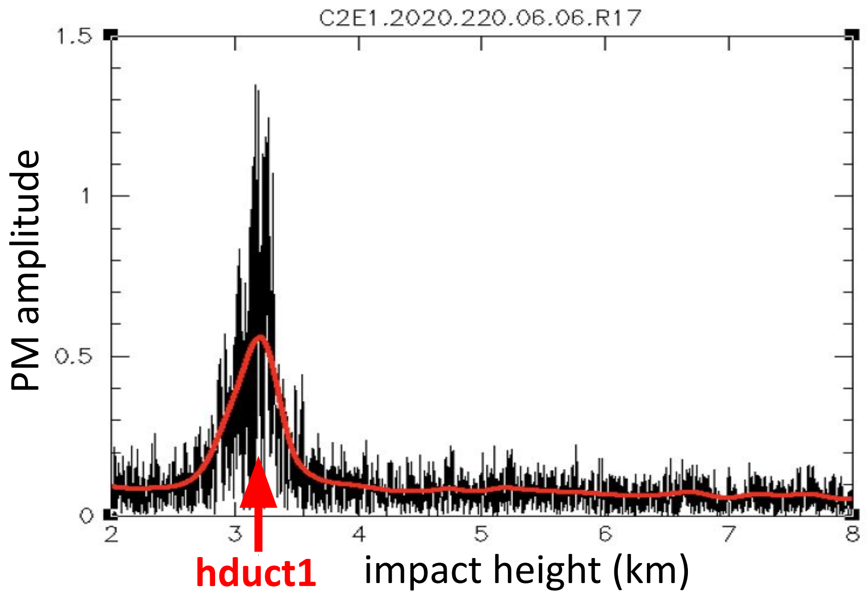
Geometric optics (GO) (hduct)

From standard GO inversion of the:
<u>frequency model + frequency shift</u>
measured from the spectrogram
at -350 km < HSL < -250 km

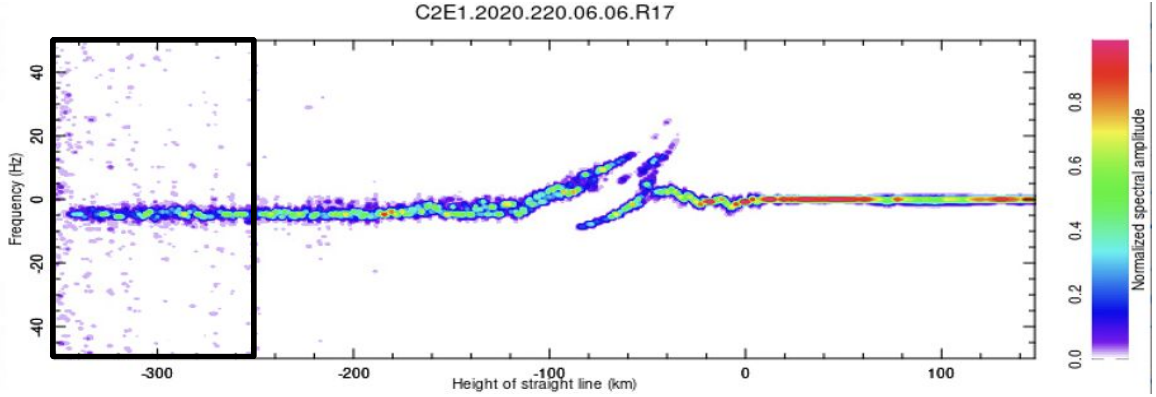


Wave optics (WO) (hduct1)

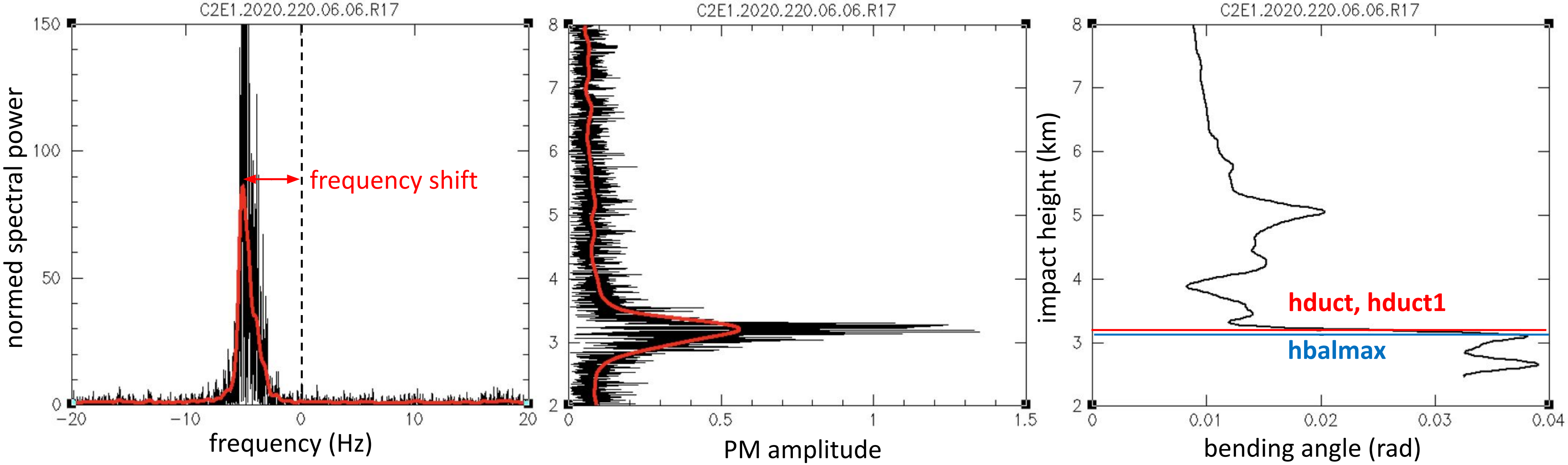
From the amplitude of RO signal
transformed to impact parameter
representation by phase matching
at -350 km < HSL < -250 km



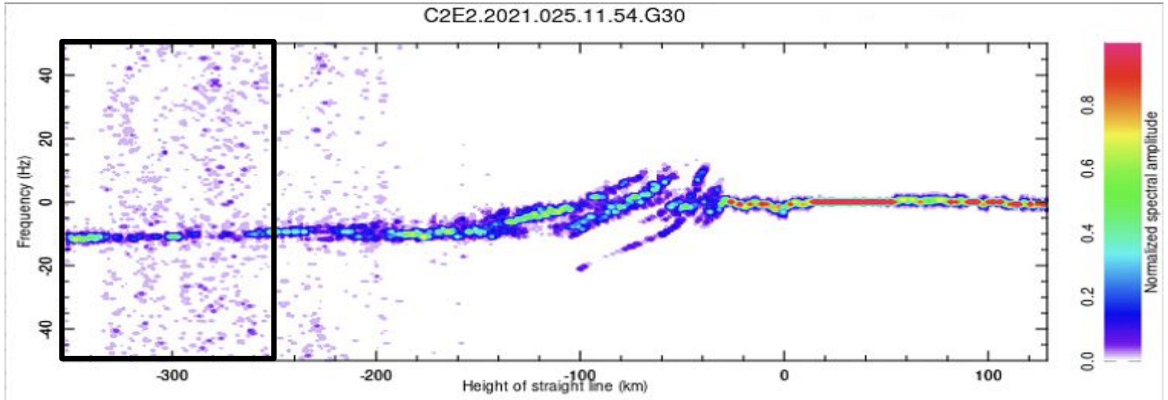
Estimation of duct height (example 1)



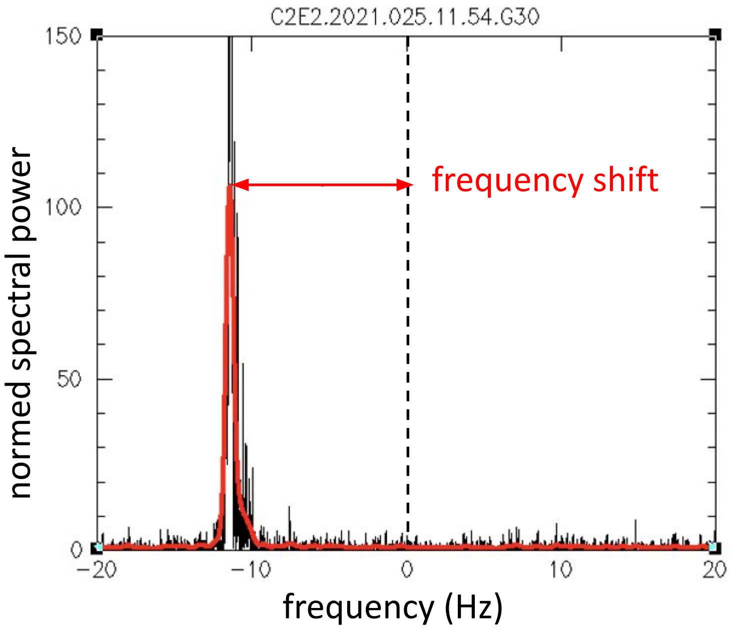
GO duct height:
hduct = 3.26 km
WO duct height:
hduct1 = 3.22 km
hbalmax = 3.19 km

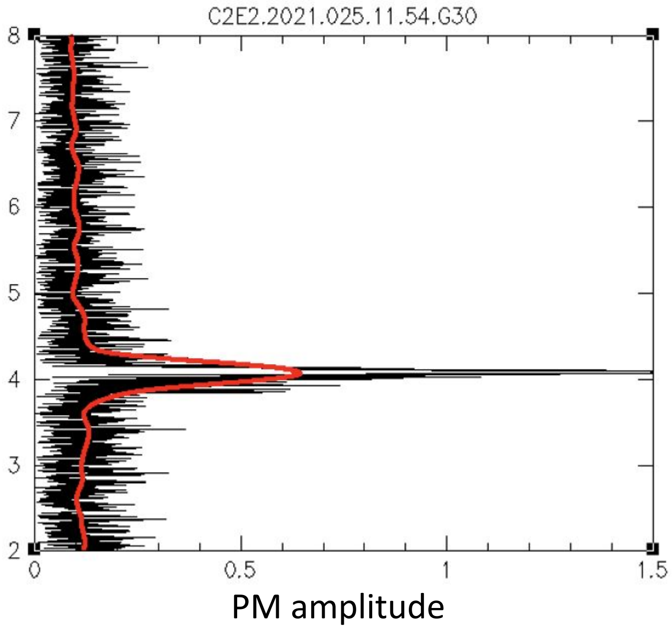


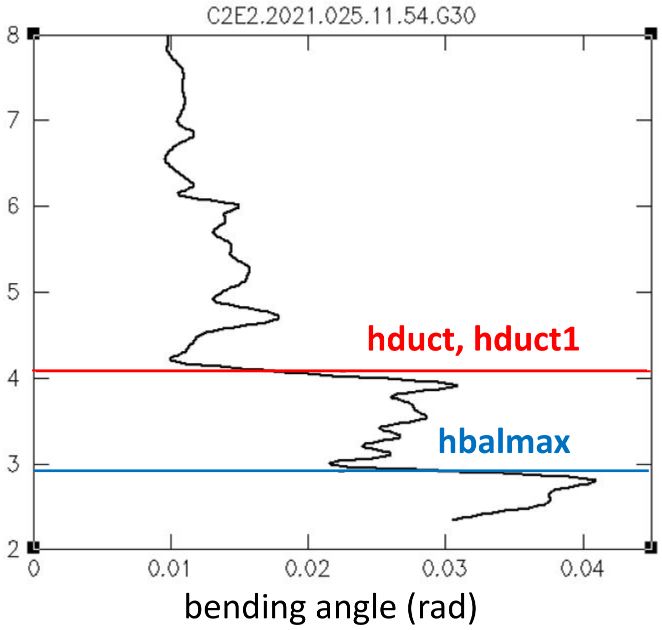
Estimation of duct height (example 2)



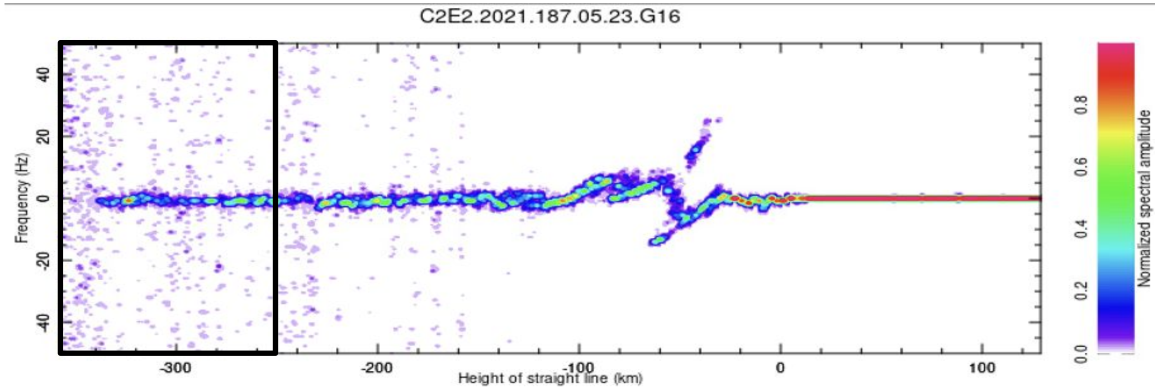
GO duct height:
hduct = 4.05 km
WO duct height:
hduct1 = 4.07 km
hbalmax = 2.9 km



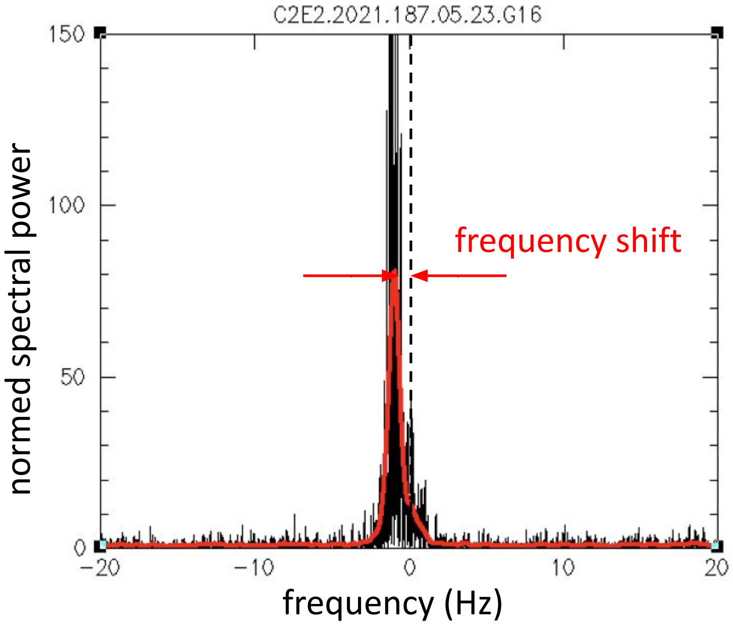


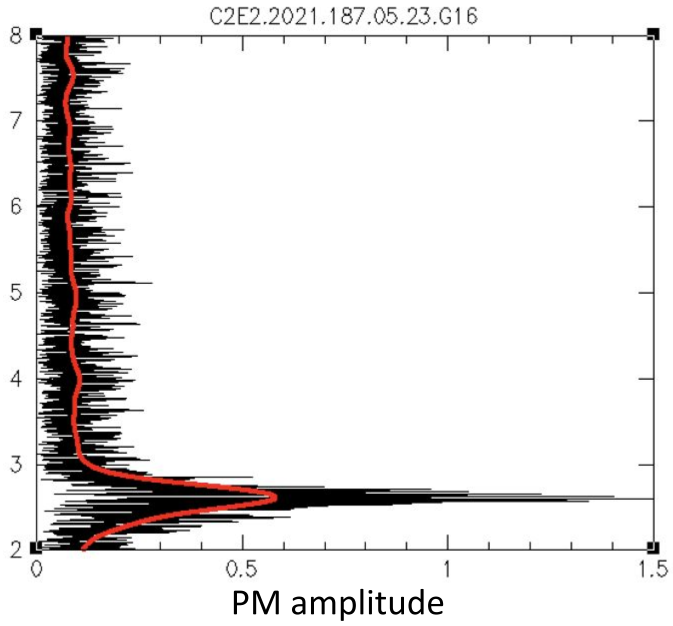


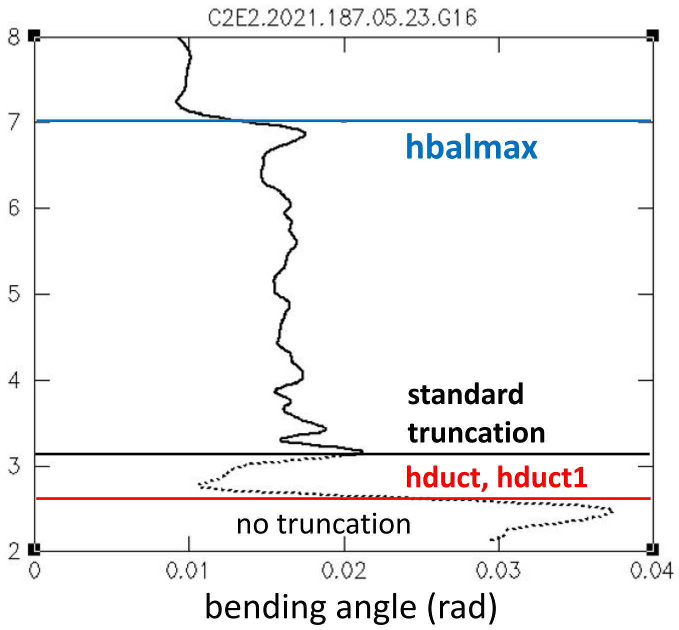
Estimation of duct height (example 3)



GO duct height:
hduct = 2.58 km
WO duct height:
hduct1 = 2.59 km
hbalmax = 7.03 km

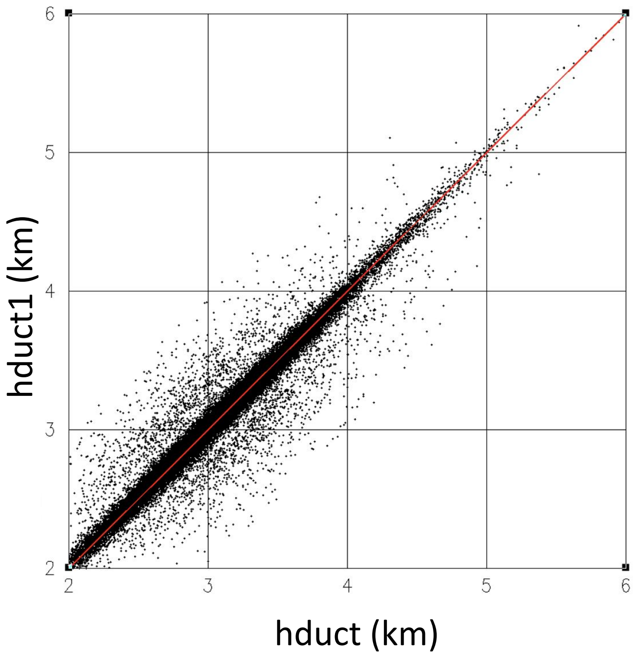




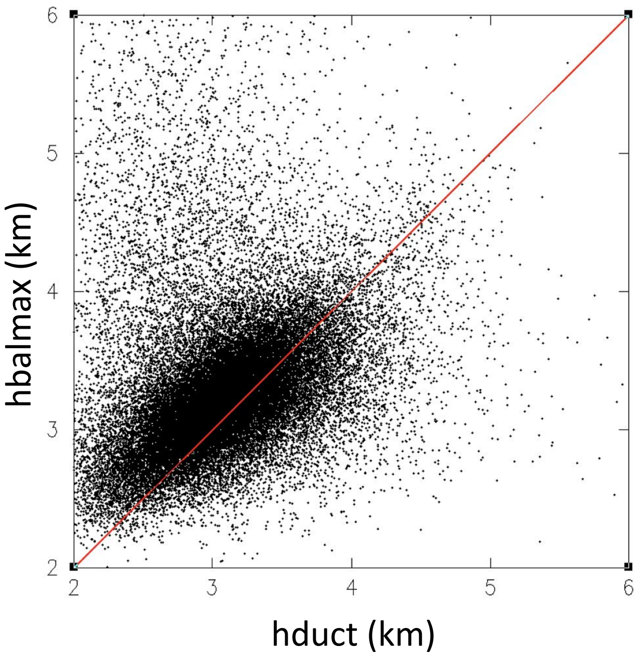


Comparison of GO and WO duct heights and proxies

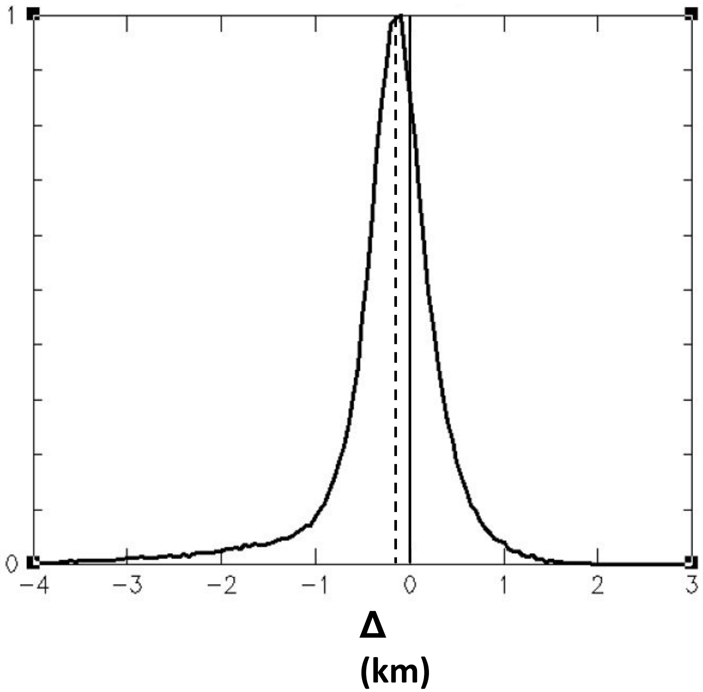
hduct compared to hduct1
mean difference = 0.08 km
stand. dev. = 0.12 km



hduct compared to hbalmax
mean difference = -0.23 km
stand. dev. σ = 0.67 km



distribution of Δ = hduct - hbalmax
small |Δ| – horizontal gradients
large |Δ| – multiple inversion layers

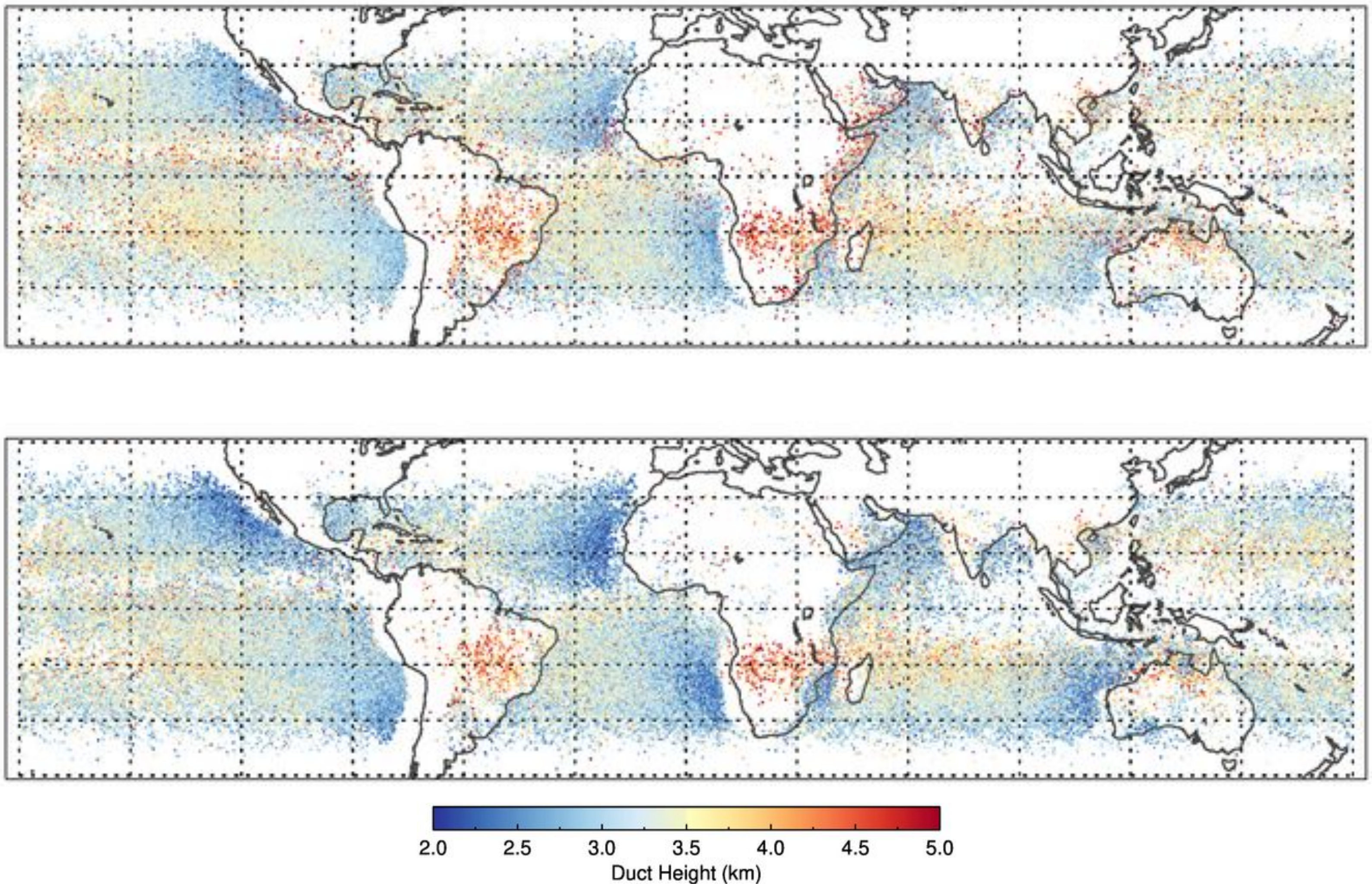


Current metric for duct detection: ssnr > 7.5; wsnr > 2.5; |hduct – hduct1| < 1 km
Current definition of duct height: hduct

Global maps of SR and heights for 4 years of COSMIC-2 RO

Old:
duct heights estimated from proxy: height of max. BA lapse

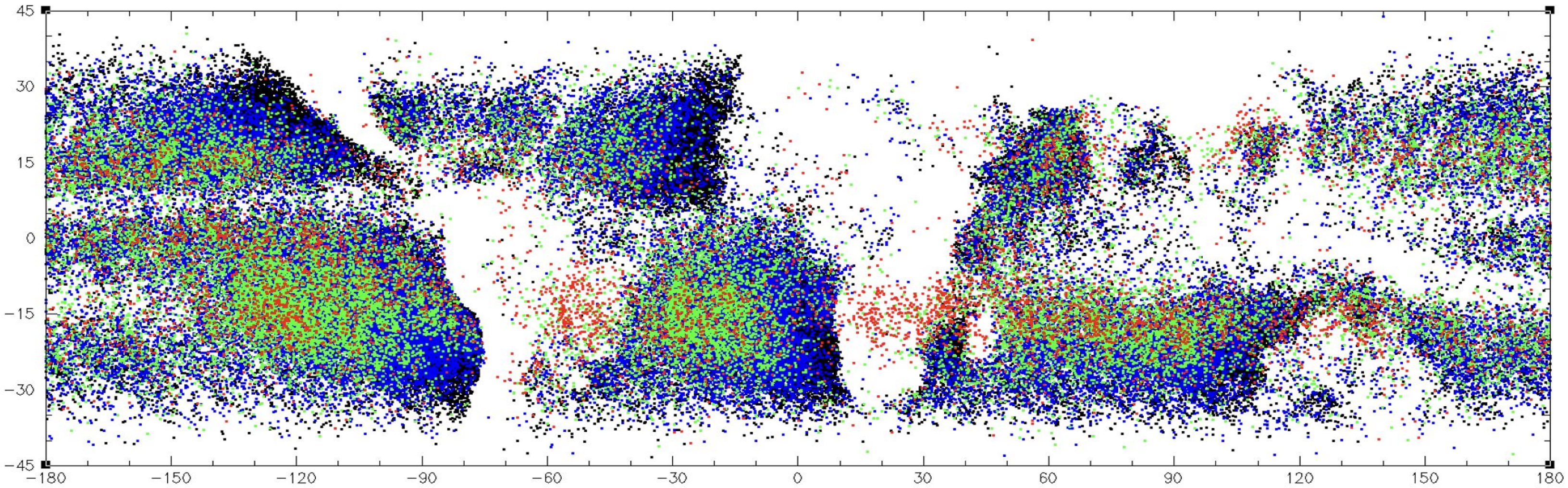
New:
duct heights estimated by GO (frequency shift of the spectrum between -250km and -350km)



Global maps of SR and heights for 4 years of COSMIC-2 RO

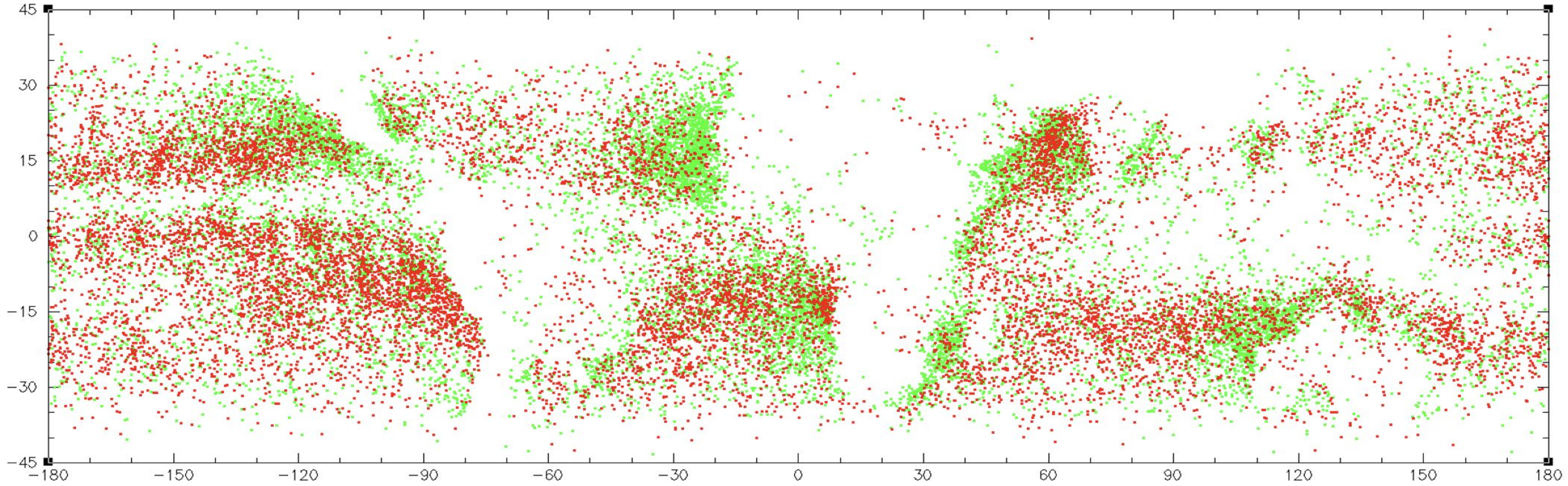
Map 1
Duct heights estimated from frequency shift

hduct < 3km
3km < hduct <3.5km
3.5km < hduct < 4km
hduct > 4km

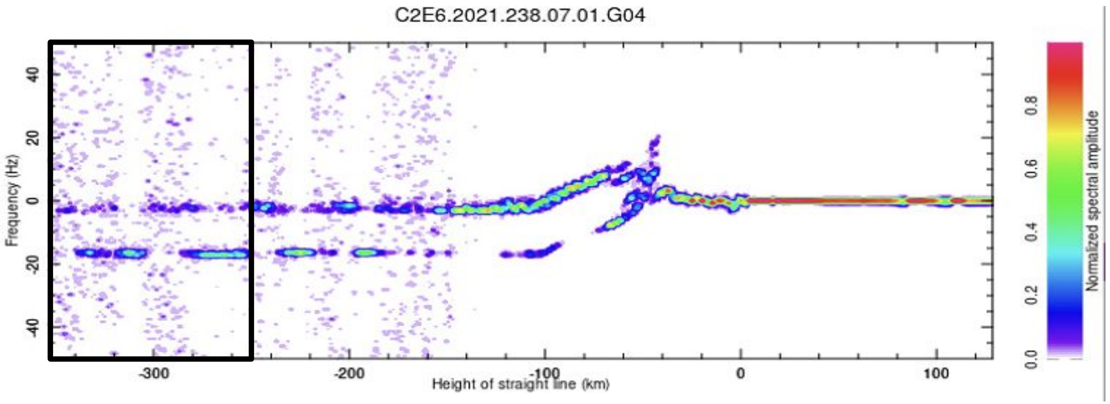


Map 2
Δ = hduct – hbalmax
mean(Δ) = -0.23km
stdev(Δ) = 0.67km

Δ < mean – stdev
Δ > mean + stdev

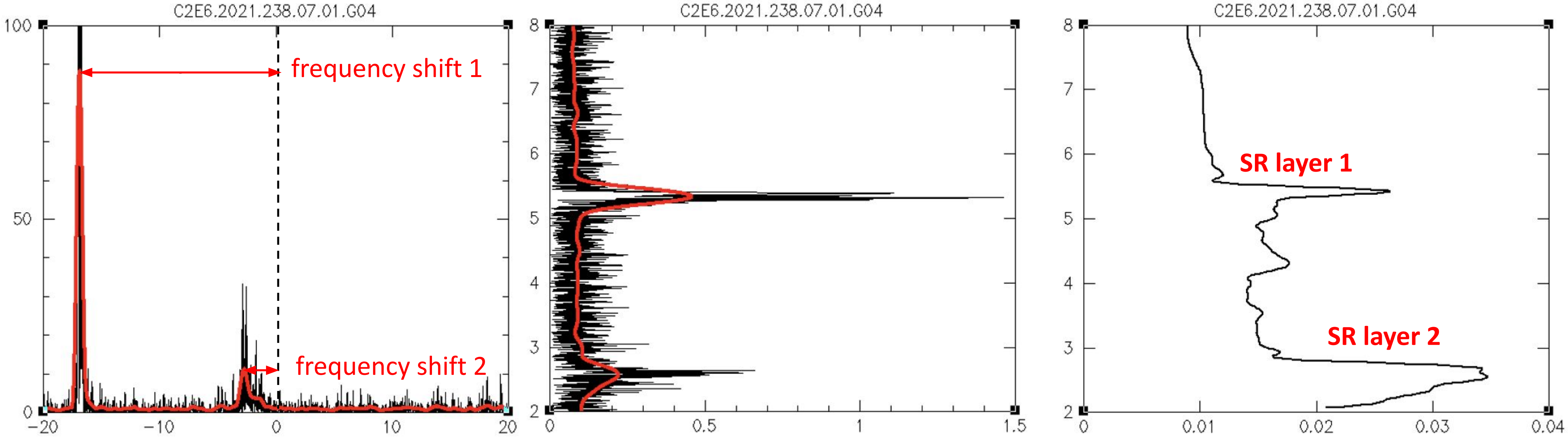


Multiple SR layers



Multiple SR layers

Identification of multiple SR layers will be included in the automated detection algorithm.



Summary

- Detection of SR from RO is an independent measurement complementary to prediction by models; should be useful for RO DA in the ABL.
- New development: independent estimation of SR heights using GO and WO: a physical measurement, not a proxy.
- Results from 4 years of COSMIC-2 RO: (i) are consistent with SR climatology; show differences between the measurement and the proxy.
- Cases of multiple (two) SR layers are detected.

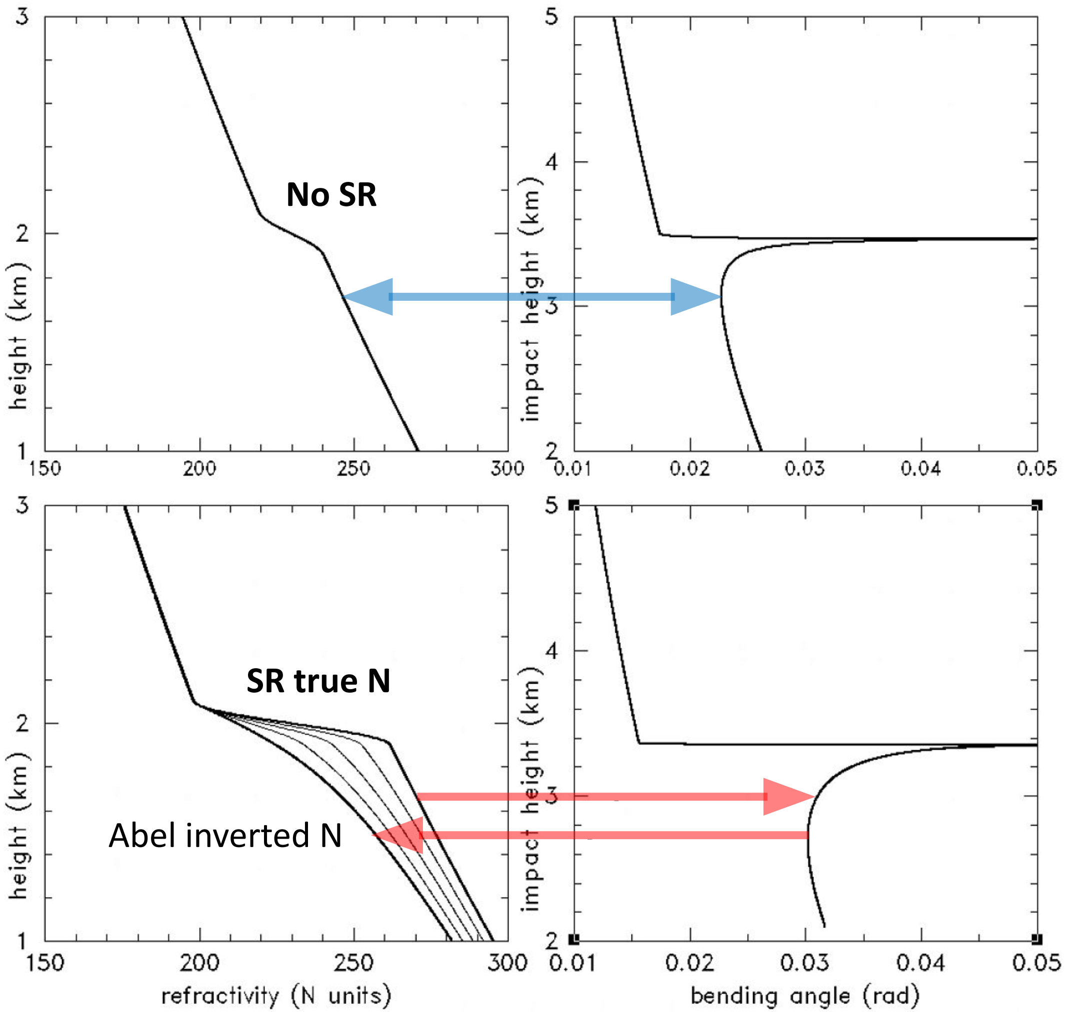
Comment: Our study uses conservative metrics, thus provides high confidence but underestimates the capability of the method. Estimation of the capability by relaxing metrics requires more extensive validation.

Reference: Sokolovskiy et al., 2014RS005436, JTECH-D-22-0100.1

Supplementary slides

How SR affects RO inversions and DA?

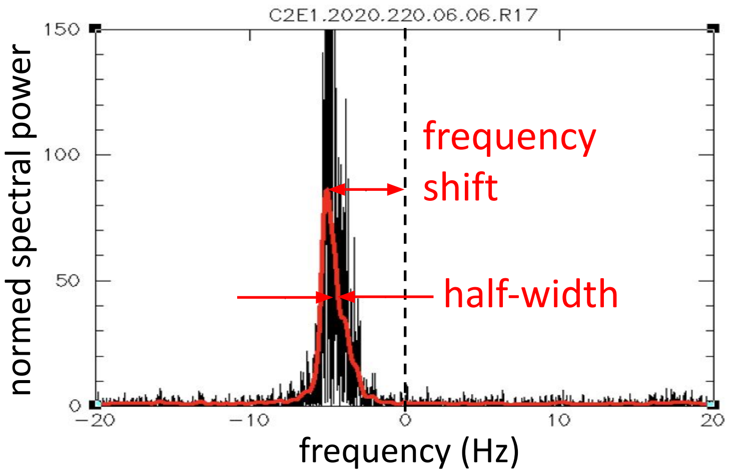
- **No SR**: unambiguous relation between N and BA profiles
- **SR**: multiple N profiles correspond to the same BA profile
- SR makes RO inversion and RO DA an ill-posed problem
- Constrained inversions (not implemented in DA): Xie et al. (2006, 2010); Wang et al. (2017, 2020)
- Occurrence of SR cannot be determined from BA profile
- Thus, an independent information about SR at the top of ABL should be useful for RO DA



Independent estimation of duct heights by GO and WO

Geometric optics (GO)

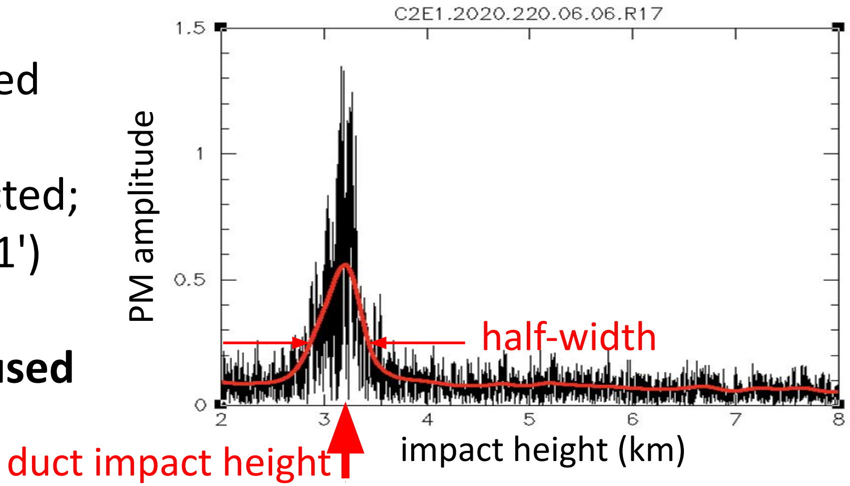
1) The spectrogram is obtained with the reference frequency model (based on orbits and N climatology).
2) The frequency shift of the spectral maximum is determined.
3) The frequency shift is added back to the model and subject to the standard GO inversion.
4) The impact height averaged **between -350 and -250km** HSL corresponds to the duct impact height ('hduct')



Wave optics (WO)

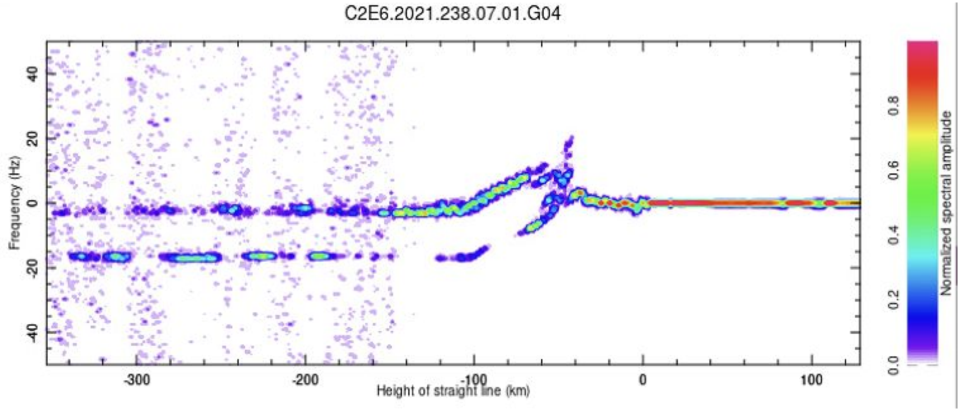
1) The RO signal **between -350 and -250km HSL** is transformed to the impact height representation by the Phase Matching.
2) The PM amplitude is smoothed and the maximum is detected; the maximum corresponds to the duct impact height ('hduct1')

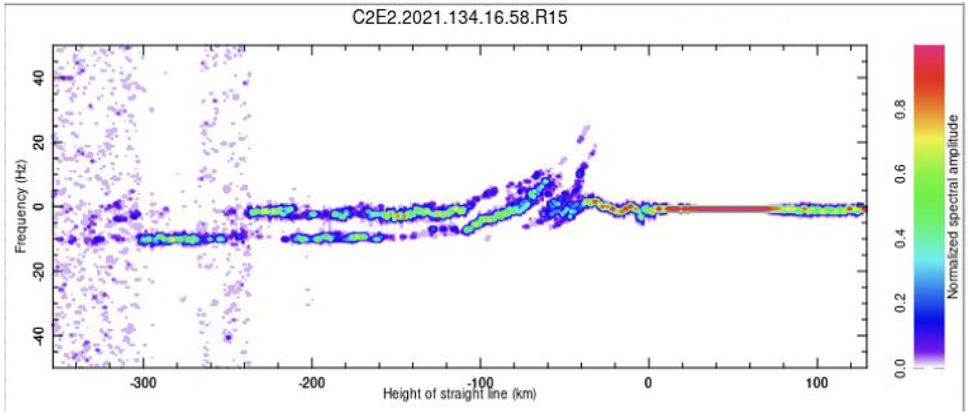
Half-widths of the PM amplitude and spectral maxima are used for characterization of the impact height uncertainties

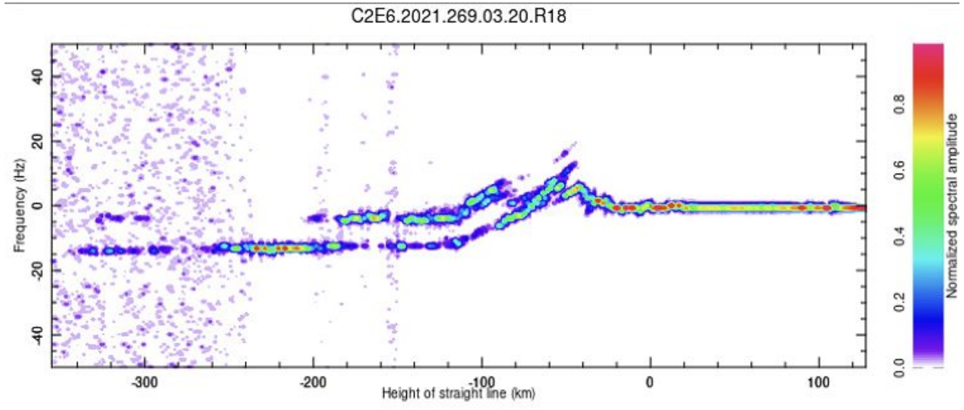


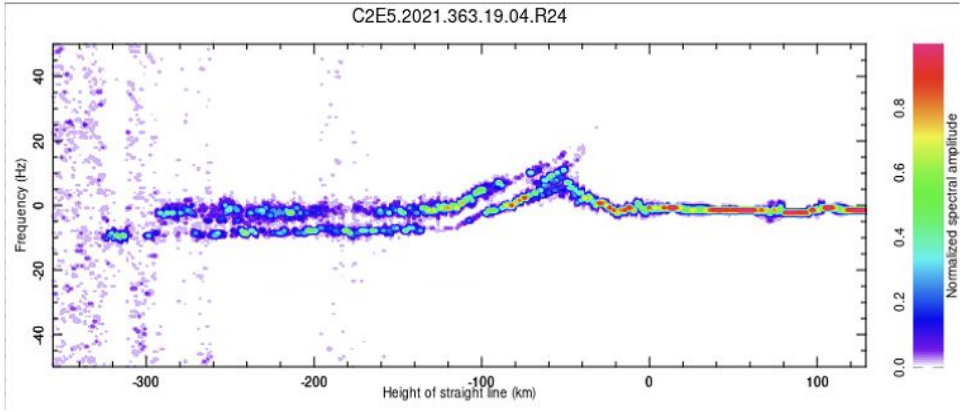
Multiple SR layers

Examples of COSMIC-2 occultations with multiple (two) SR layers









Dependence of SR detection rate on the SNR

SNR histogram for all COSMIC-2 setting occultations

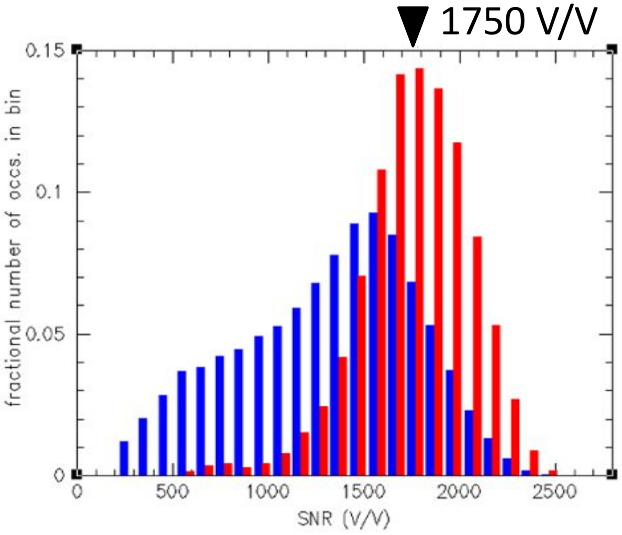
SNR histogram for all COSMIC-2 occultations with detected SR

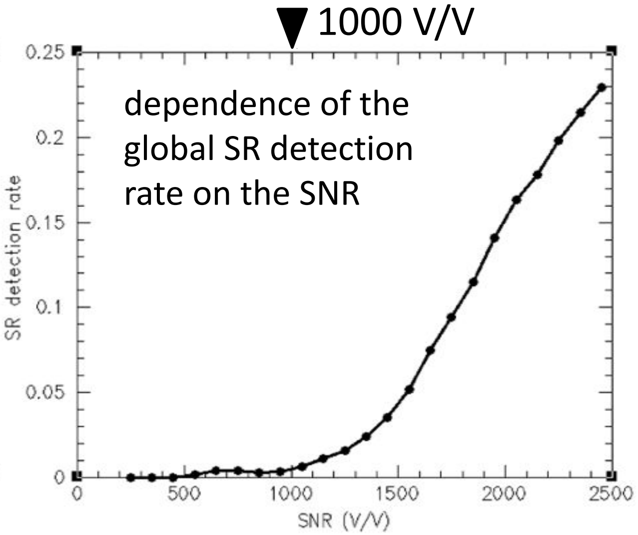
● SR detection increases for the SNR > 1000 V/V

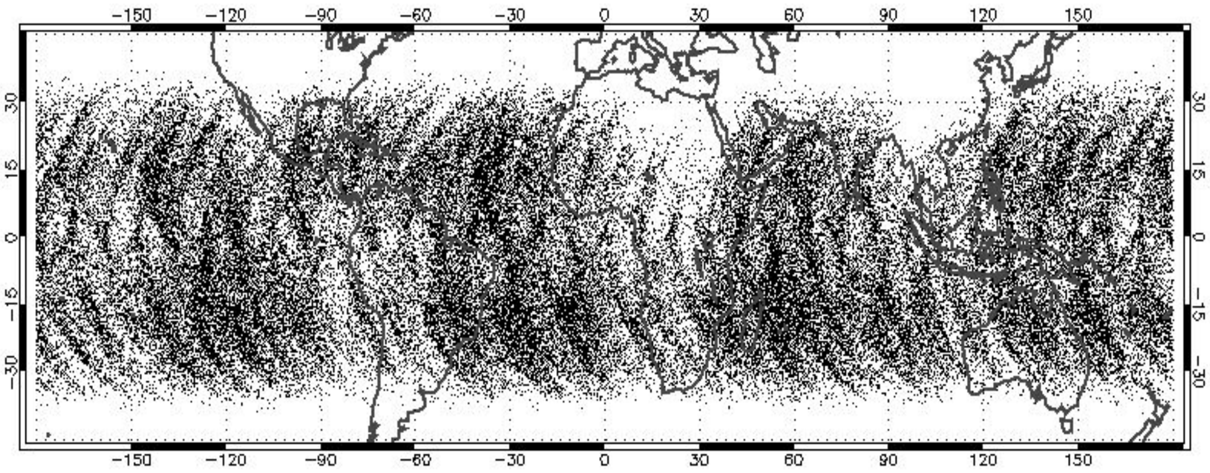
● 50% of SR cases were detected at SNR > 1750 V/V

● Global distribution of COSMIC-2 setting occs. with SNR > 1750 V/V

● Non-uniformity of the sampling with high SNR







How SR affects RO signals? Wave optics modeling

Inversion layers, No SR

Strong elevated ducts

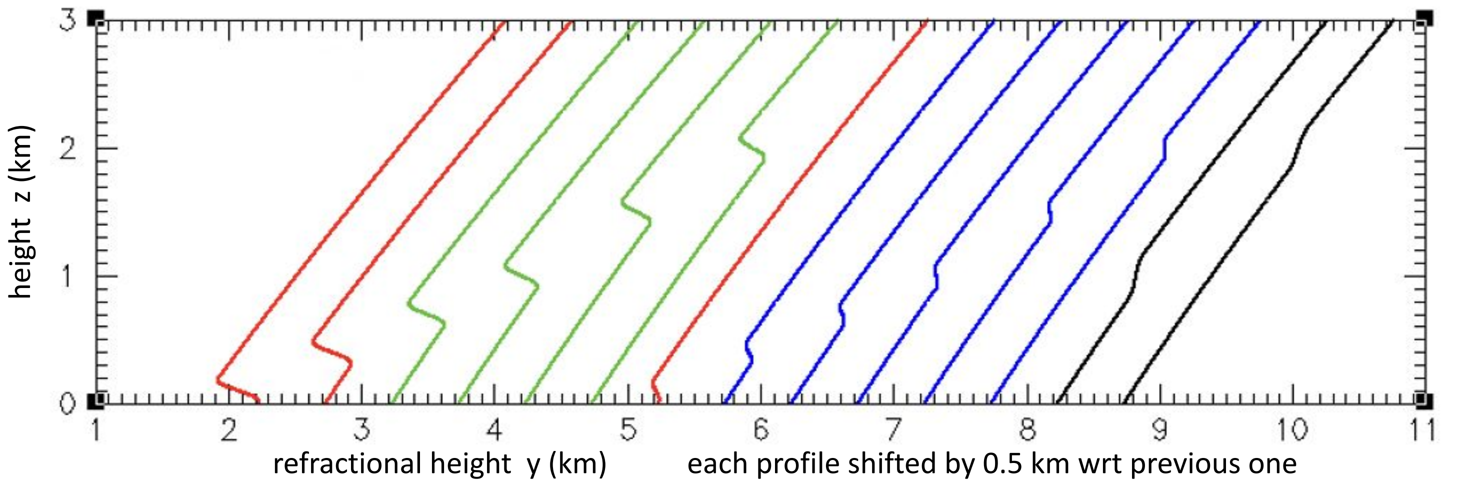
Weak elevated ducts

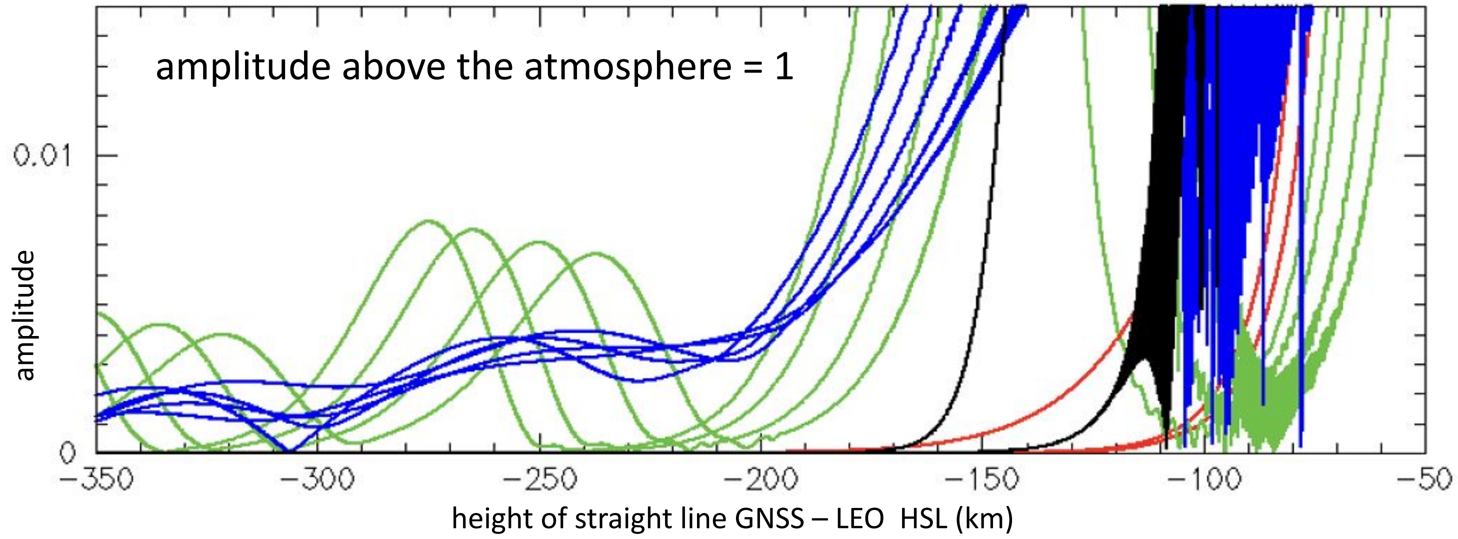
Surface ducts

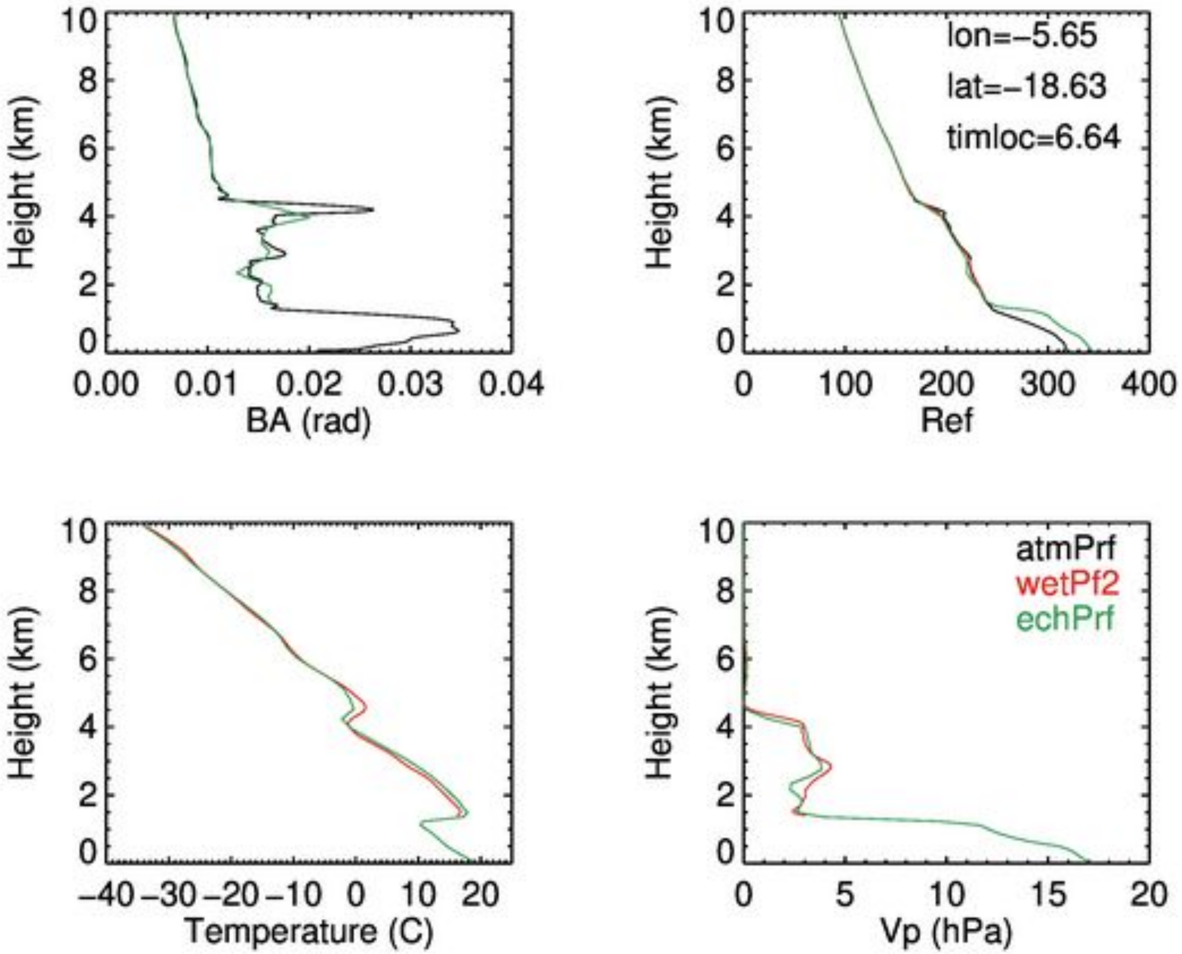
● Commonly, RO signals extend down to HSL about -150 km

● Elevated ducts result in deep diffracted signals down to HSL -350 km

● Surface ducts do not produce deep signals







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atmPrf: C2 RO atmPrf

wetPf2: C2 1DVar product

echPrf: EC short-term forecast