

# RO Analysis for CLARREO

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# CLARREO SDT Tasks

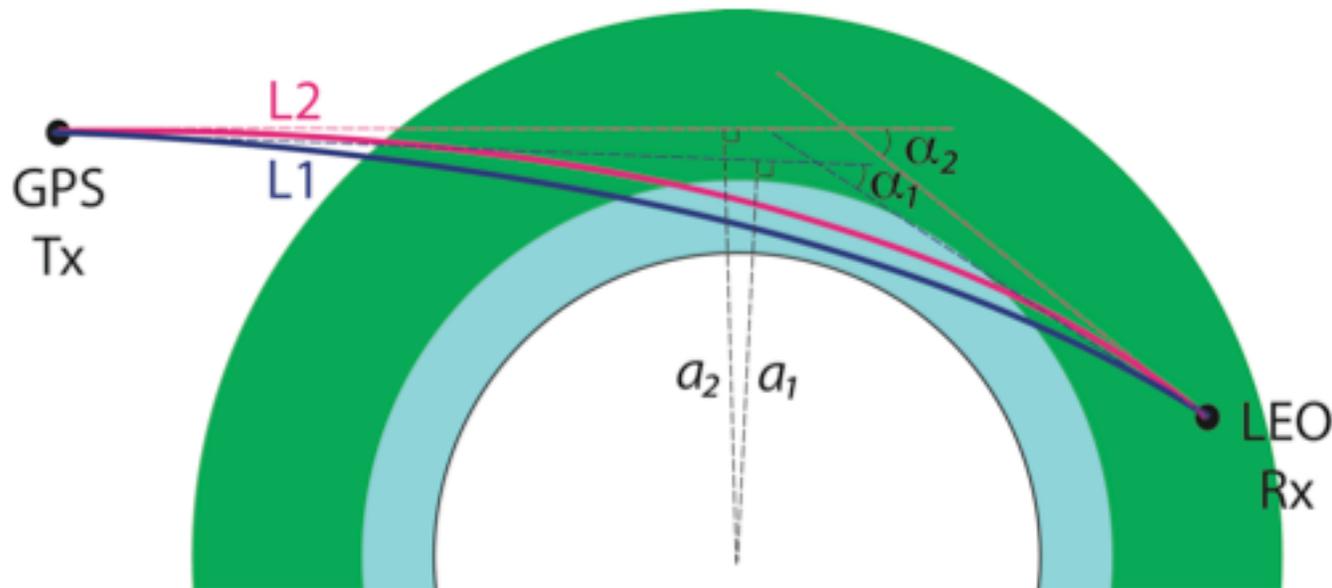
- Uncertainty analysis for  $> 20$  km (Stratosphere)
- Uncertainty analysis for  $< 5$  km (Lower Tropo)
  - Identify key sources of systematic error in refractivity
  - Evaluate via simulation & analysis of current RO data
  - Investigate mitigation approaches
- Climate data analysis using existing RO data (2001-): Collaboration with Stephen Leroy (Harvard)

# Stratosphere ( > 20 km)

- **Atmosphere is tenuous so measurements need to be more accurate.**
- Systematic error sources:
  - Ionosphere
  - local multipath
  - thermal noise (lead to bias through upper boundary condition)
  - GNSS & LEO clocks
  - orbits (incl. antenna phase center relative to s/c center of mass)

# Ionospheric Residual

- Ionospheric residual error arises from incomplete cancellation in the standard dual-frequency correction. It is arguably the worst kind of error for climate benchmarking.



- Standard dual frequency correction removes leading error term ( $1/f^2$ ).
- The remaining leading error is of order  $1/f^4$  and is due to the slightly different raypaths for different frequencies.

**Eq. (1)**  
**Bending angle correction**

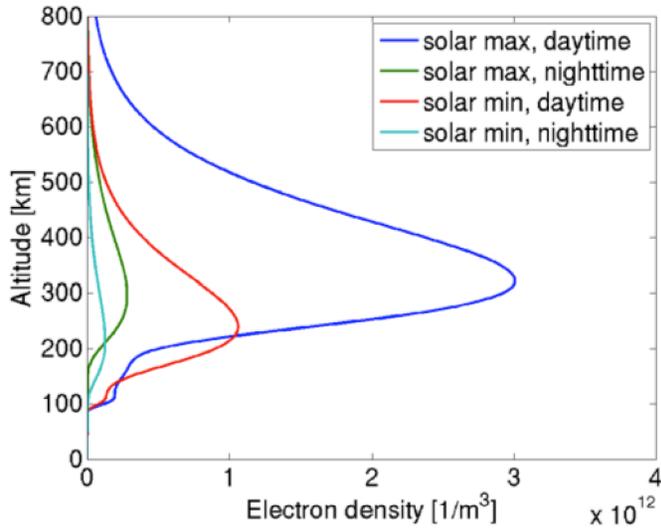
$$\alpha_c(a) = \left[ \frac{f_1^2}{f_1^2 - f_2^2} \right] \alpha_1(a) - \left[ \frac{f_2^2}{f_1^2 - f_2^2} \right] \alpha_2(a)$$

**Eq. (2)**  
**Residual error in bending**

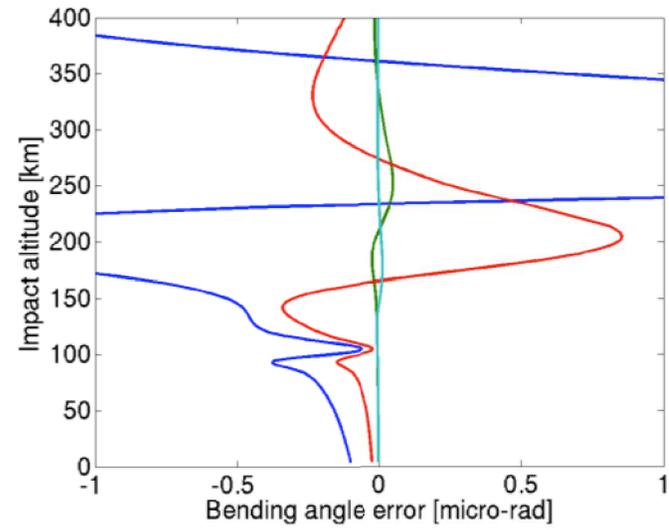
$$\Delta\alpha(a) = \frac{C^2}{f_1^2 f_2^2} a \frac{d^2}{da^2} \int_a^\infty \frac{x N_e^2 dx}{\sqrt{x^2 - a^2}} \quad [\text{Syndergaard, 2000}]$$

**Eq. (3)**  
**Residual error in refractivity**

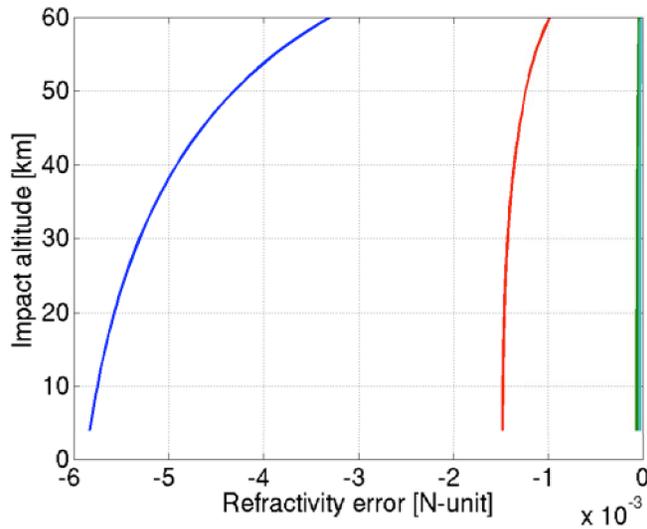
$$\Delta N = \frac{10^6}{\pi} \int_a^\infty \frac{\Delta\alpha(x) dx}{\sqrt{x^2 - a^2}}$$



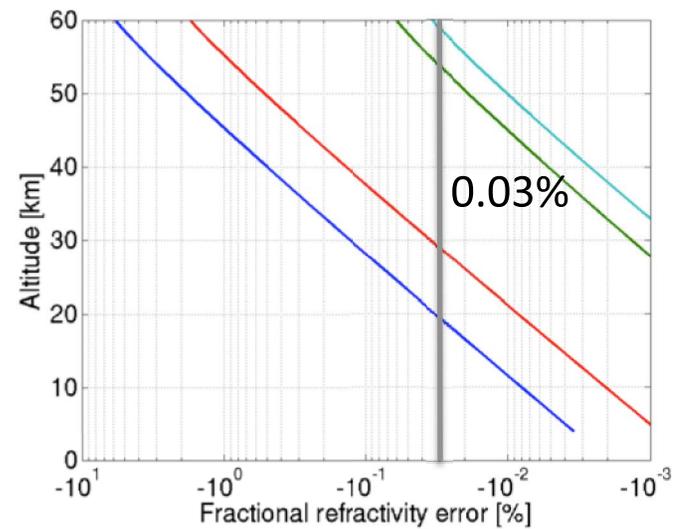
(a)



(b)



(c)



(d)

# New GNSS Frequencies

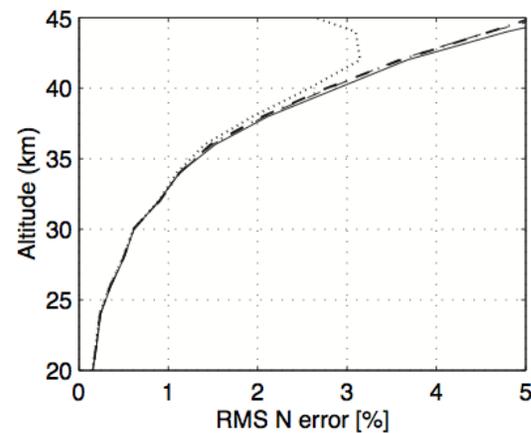
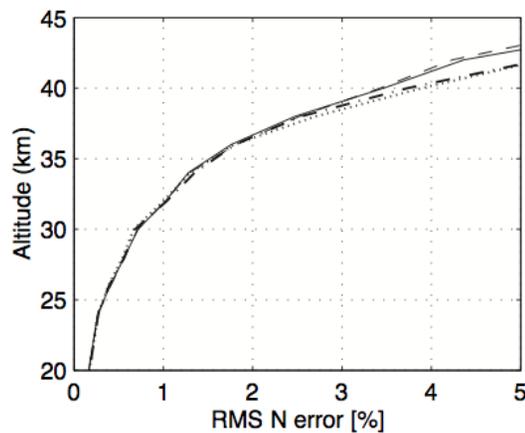
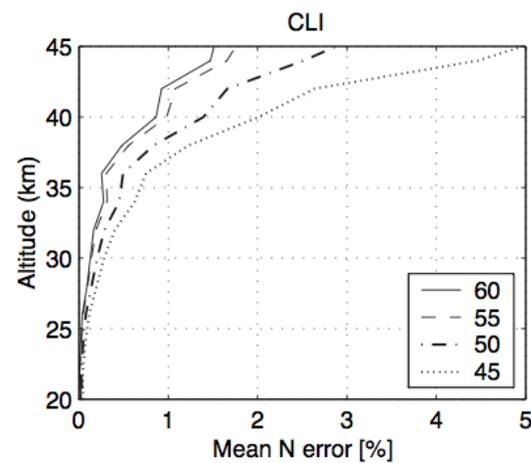
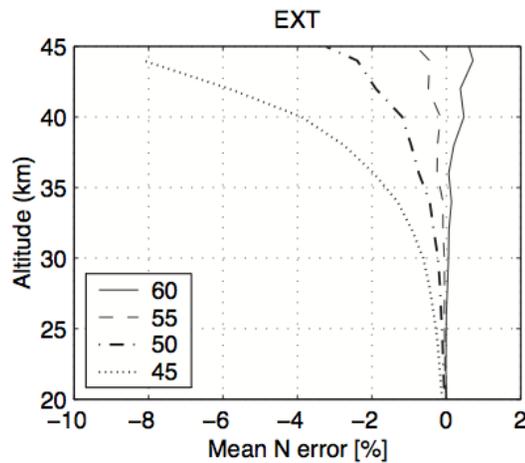
- Will new GNSS signals (e.g. L5=1176.45 MHz) be useful in reducing the ionosphere residual error?
- The leading residual error will cancel out with the combination

$$\frac{f_2^2}{f_2^2 - f_5^2} \alpha_{12}(a) - \frac{f_5^2}{f_2^2 - f_5^2} \alpha_{15}(a)$$

But small denominator will lead to >10x increase in noise.

# Upper Boundary Condition (UBC)

$$\ln n(a) = \frac{1}{\pi} \int_a^{h+R} da' \frac{\alpha_{obs}(a')}{\sqrt{a'^2 - a^2}} + \frac{1}{\pi} \int_{h+R}^{\infty} da' \frac{\alpha_{mod}(a')}{\sqrt{a'^2 - a^2}}$$



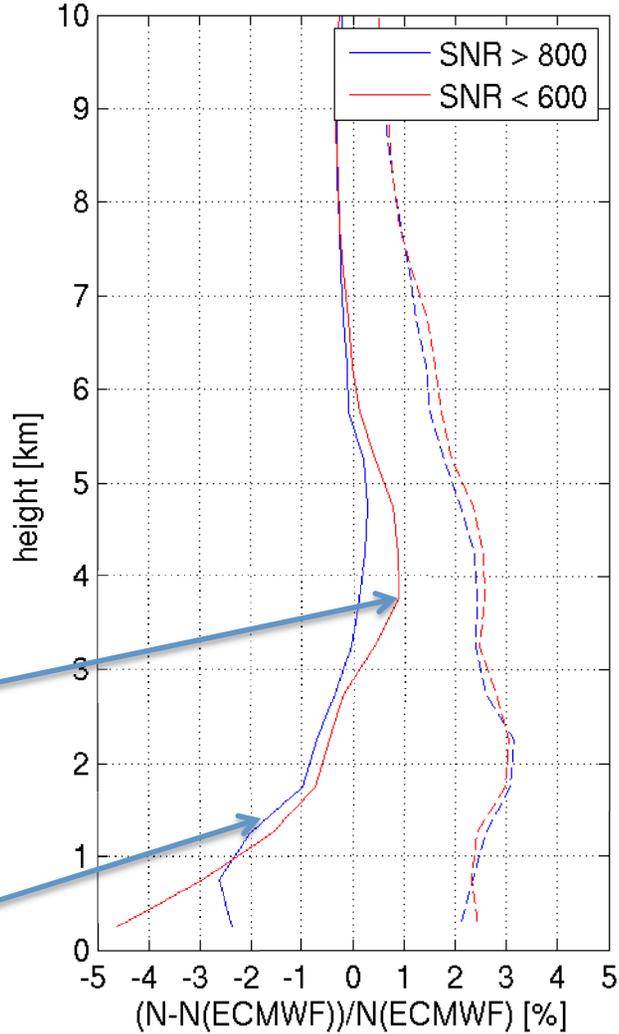
# UBC For Climate

- Use data as high as possible to reduce systematic error.
- Reduce random error through vertical smoothing (sacrifice vertical resolution).
- Don't use variable upper boundary heights based on noise level (statistical optimization approach): difficult to assess model influence.

# Lower Troposphere

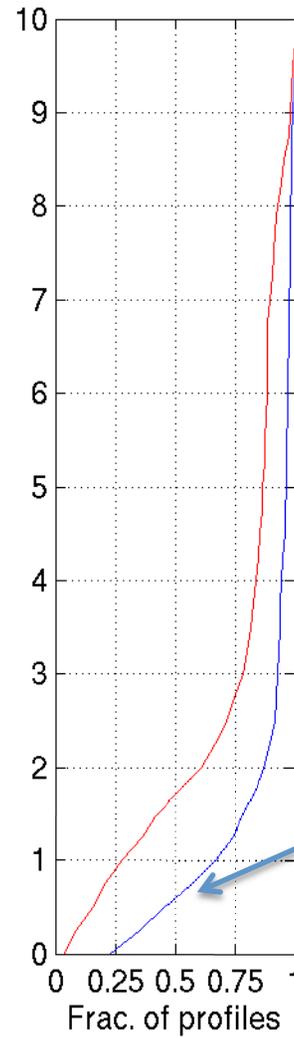
- **Fine-scale water vapor structure create challenging condition for signal tracking and retrieval.**
- Negative bias mainly below  $\sim 2$  km altitude.
- Noise-dependent positive bias as high as 5 km.
- Depth penetration: not all profiles are retrieved down to the surface.

COSMIC4 setting 30S-30N Aug.2007



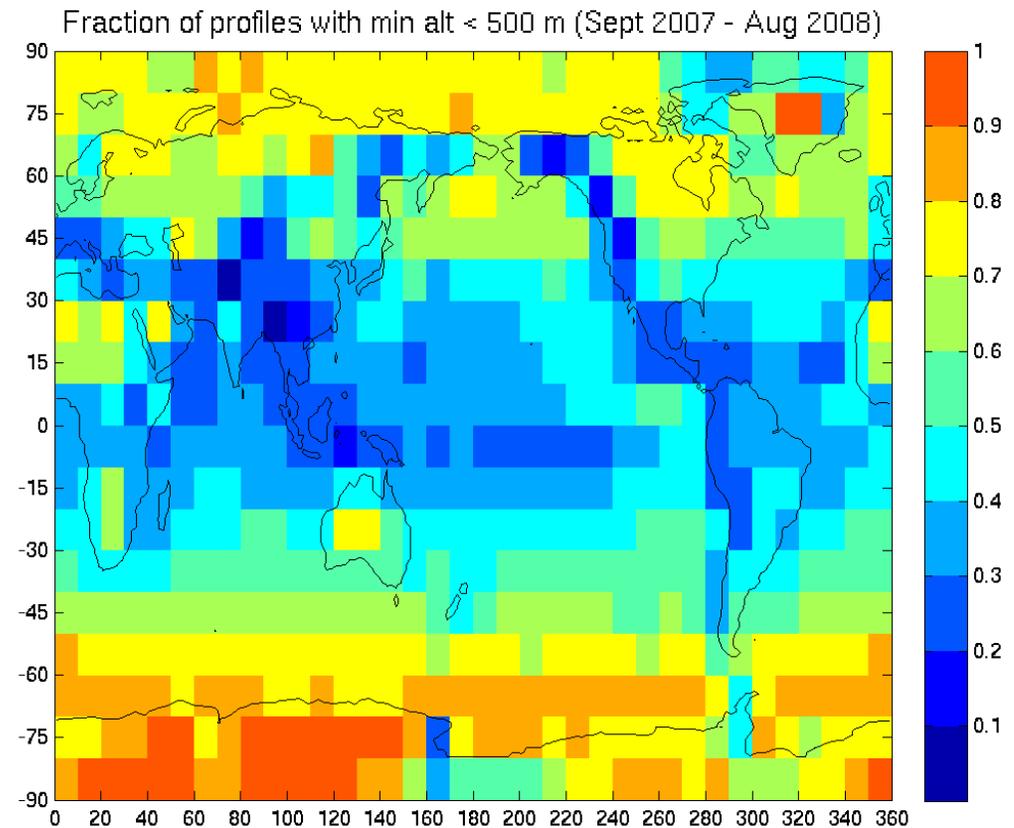
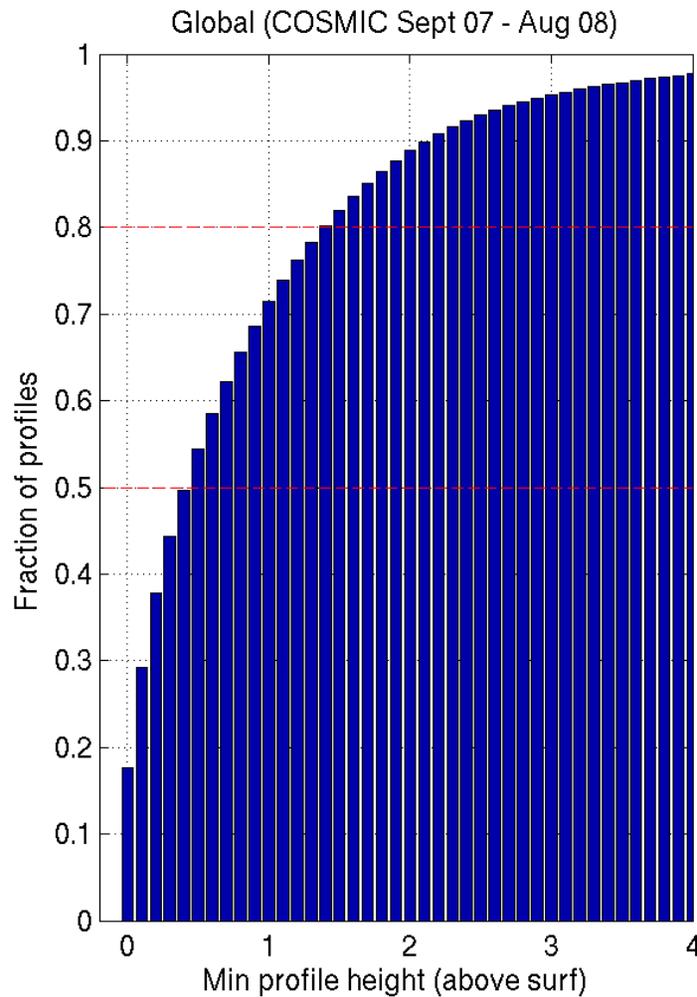
Positive bias  
when SNR is  
low

Negative bias  
below ~ 1-2  
km



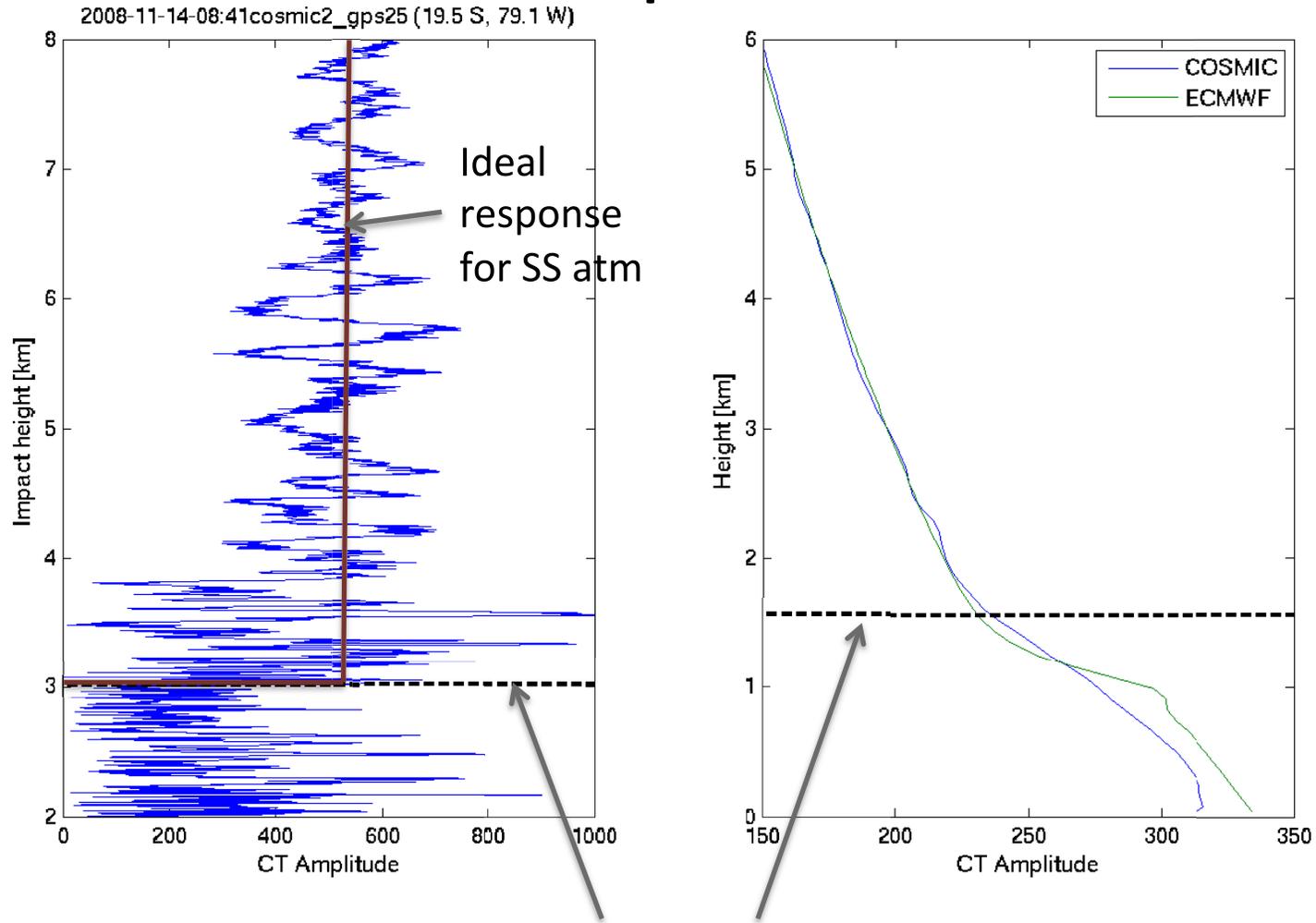
Not all  
profiles  
reach  
surface due  
to ret/qc

# Penetration Depth



(Time-dependent) biased sampling  
inhomogeneity problematic for CLARREO

# Minimum Altitude Based on CT Amplitude

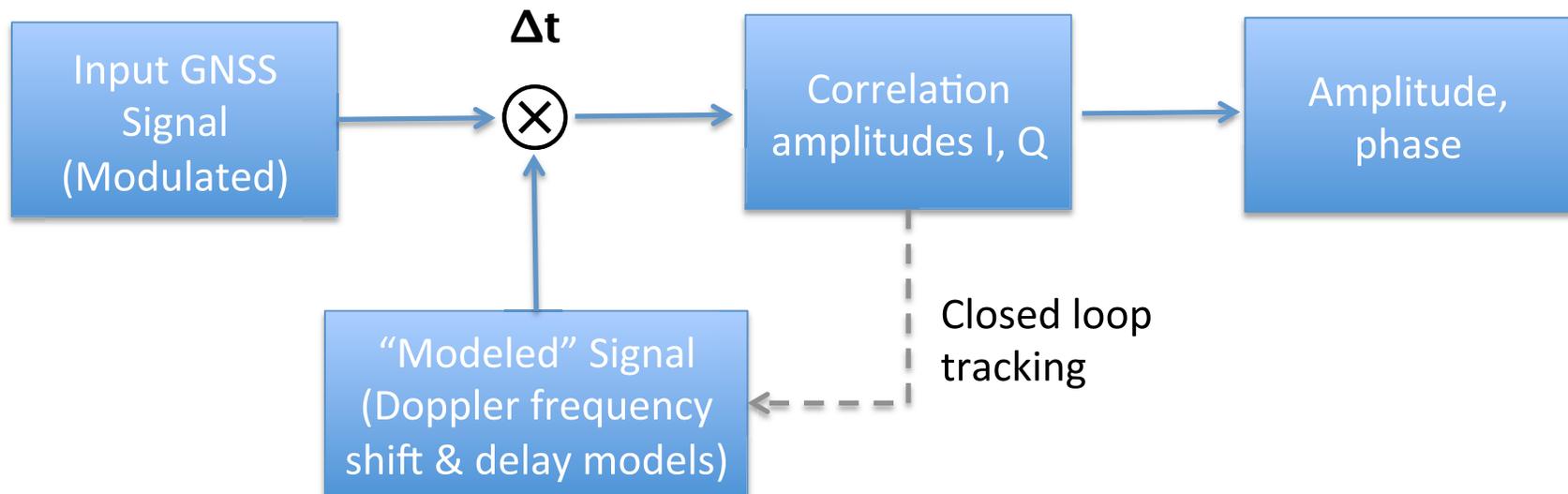


Cutoff heights with current algorithm

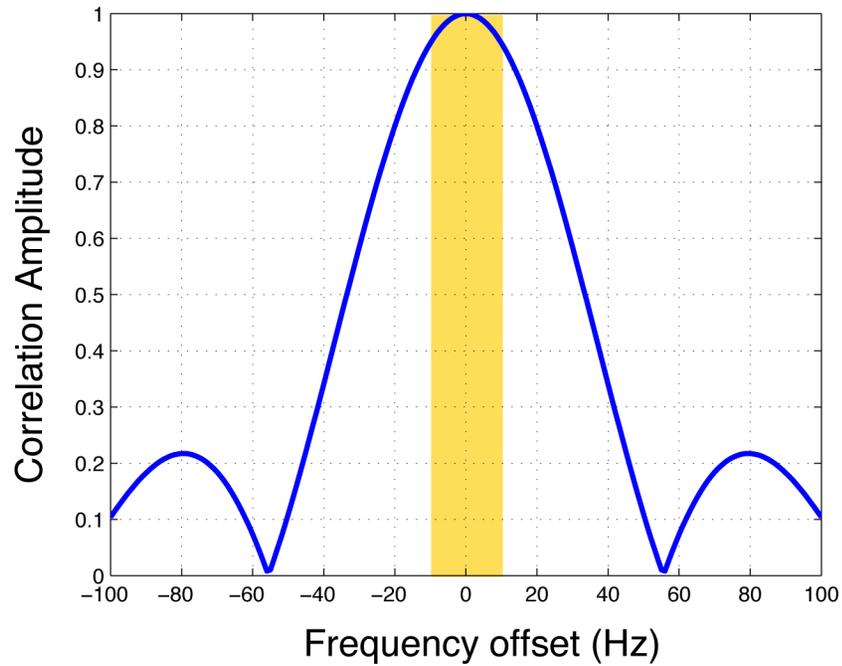
# Causes?

- 1. Signal tracking:** Drop in correlation amplitudes due to frequency & delay mismodeling in open-loop tracking.
- 2. Horizontal inhomogeneity:** horizontal gradients (in occ plane and/or out of plane) can lead to CT amplitude drop or fluctuation.

# Tracking GNSS RO Signals

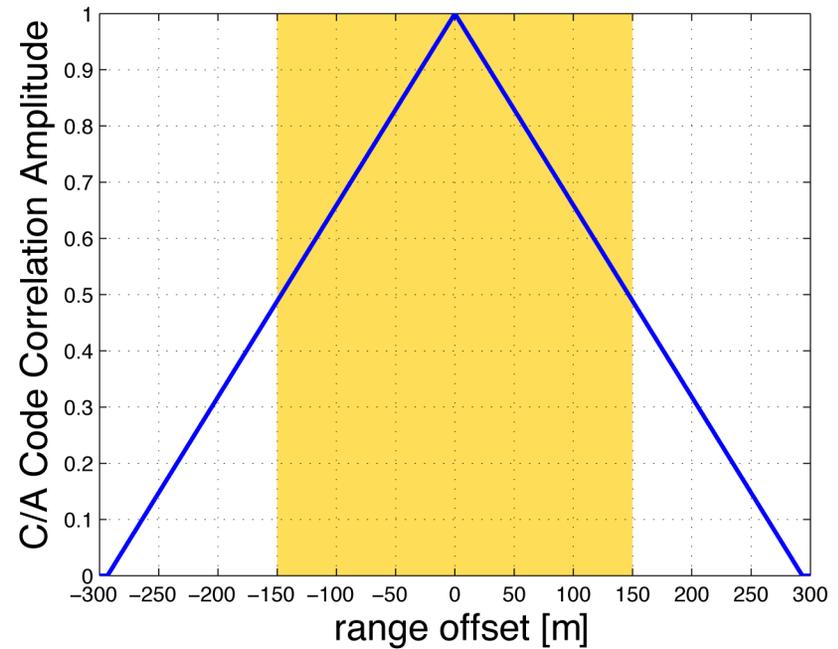


- In close loop tracking, the frequency and delay models are generated based on previous measurements.
- In open loop tracking, a priori frequency and delay models are supplied.



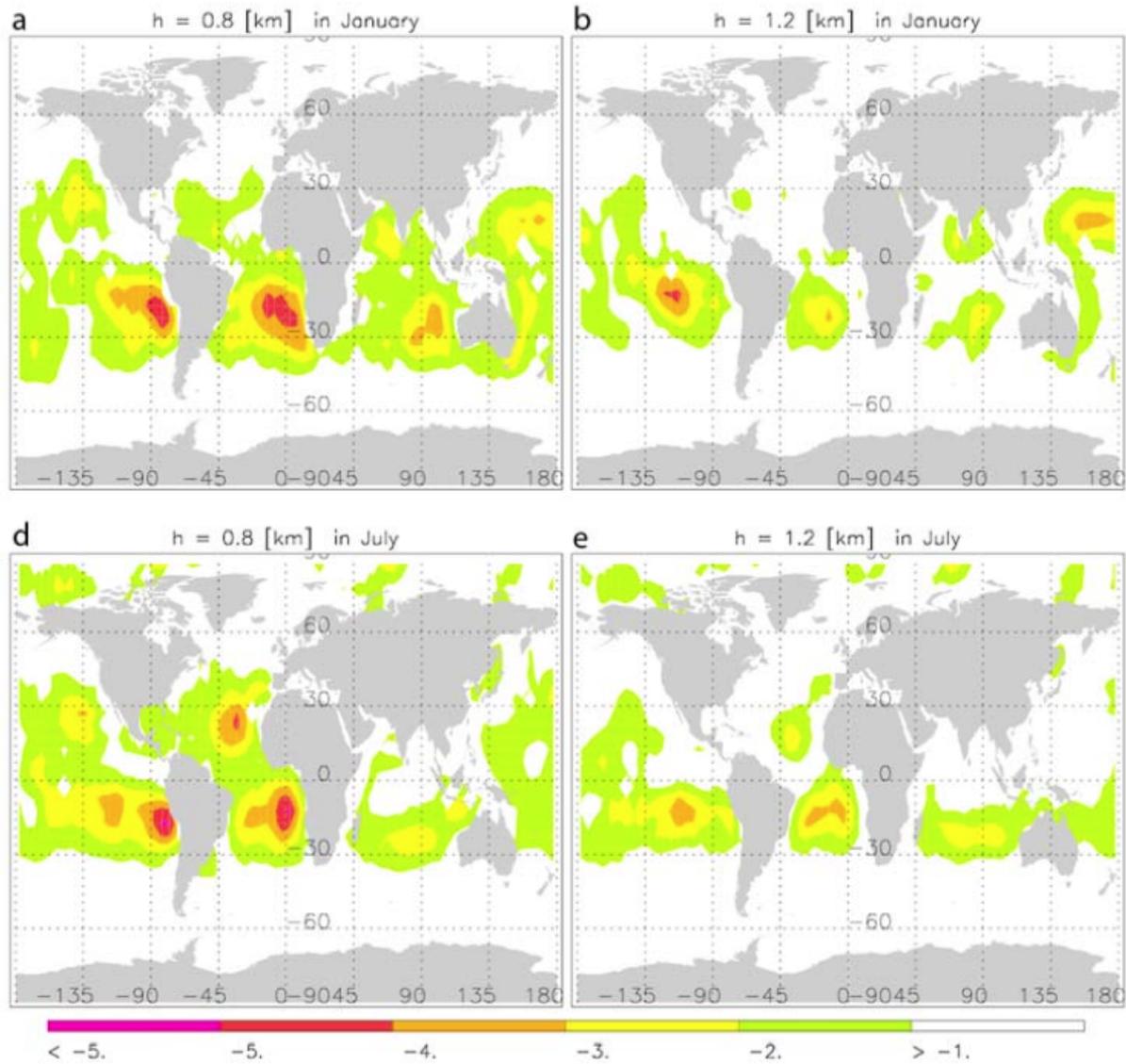
Frequency model offset causes amplitude reduction & cycle slips.

Delay model offset causes amplitude reduction



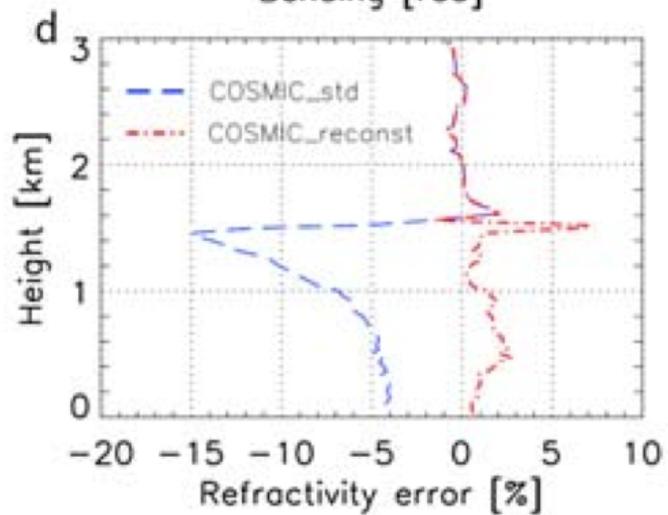
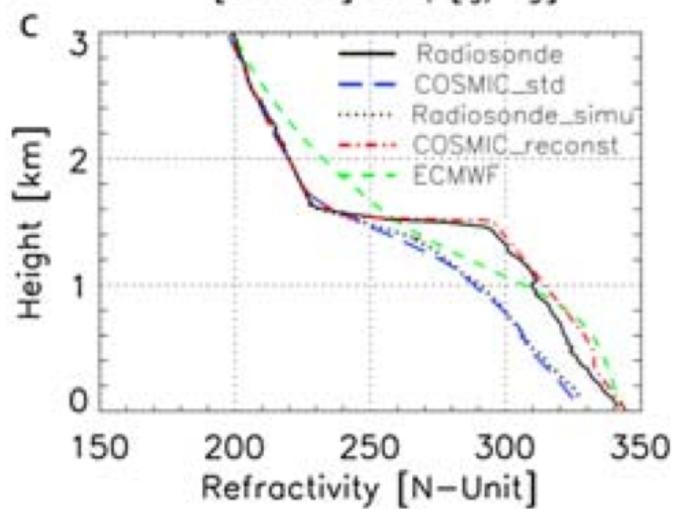
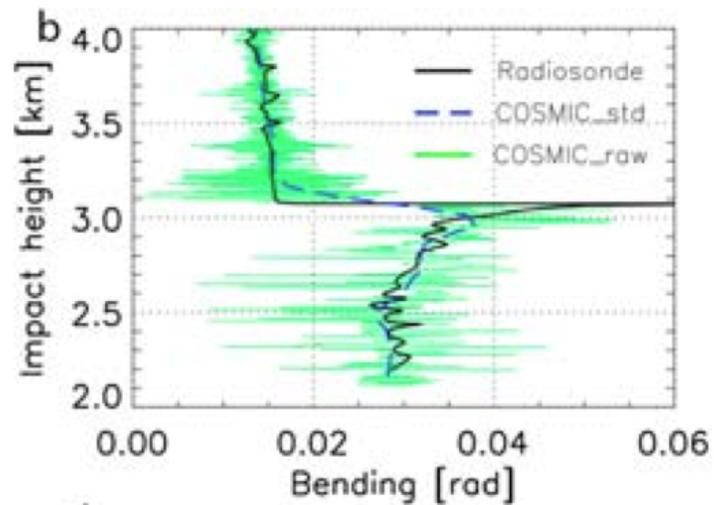
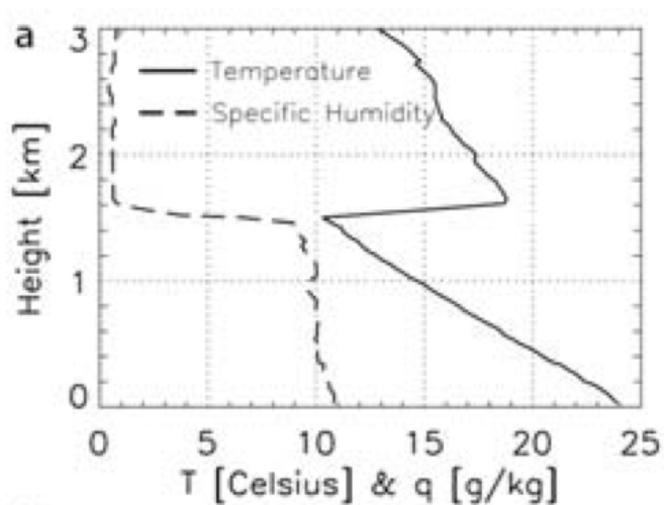
# Negative N-Bias

- There exists a negative bias below  $\sim 2$  km altitude.
  - Bending angle bias: insufficient tracking depth (large bending systematically missing), horizontal inhomogeneity (vertical features are smoothed out).
  - Refractivity bias not due to bending bias: in the presence of critical refraction layer, Abel-retrieved refractivity is systematically smaller below the layer.



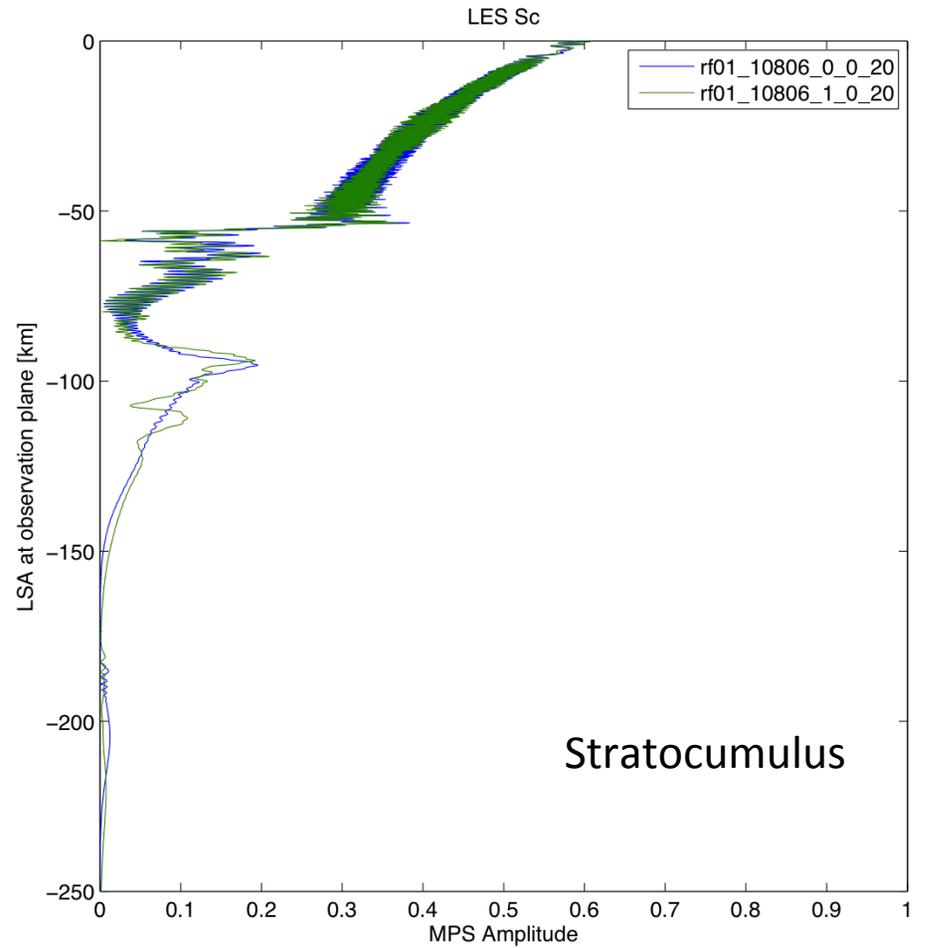
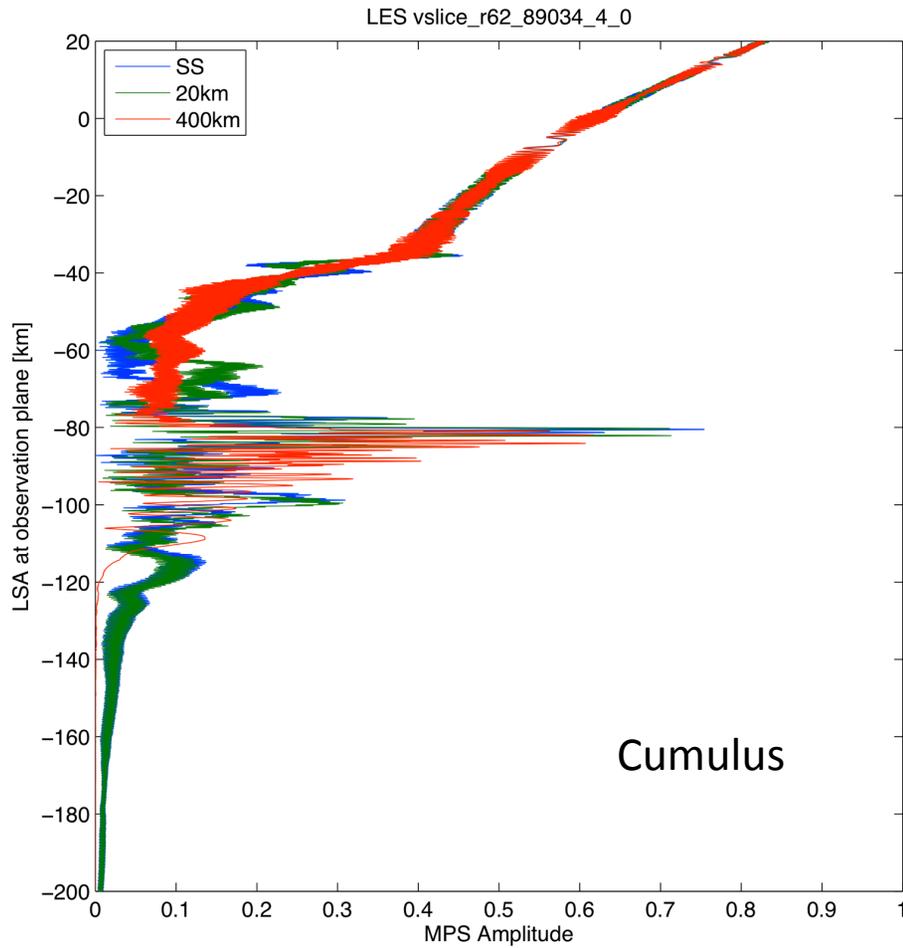
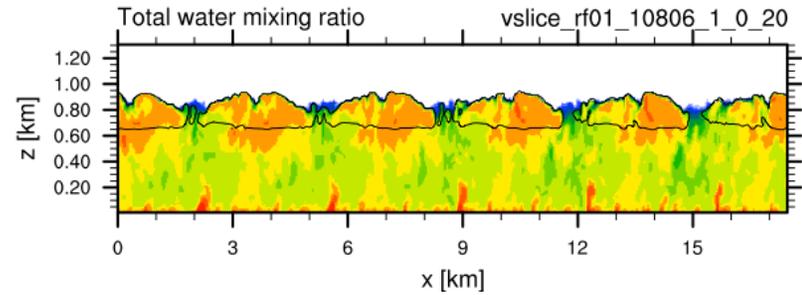
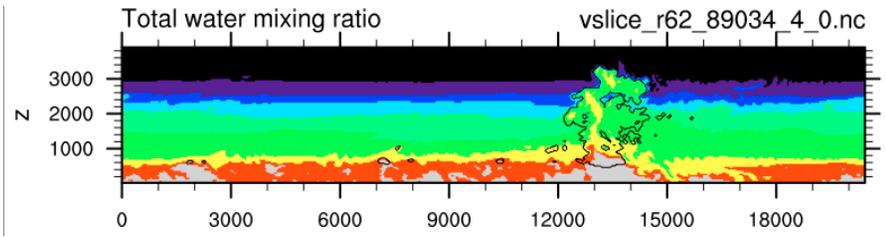
Xie et al. 2010

Fractional Refractivity difference (RO-ECMWF) in %



Xie et al. 2010

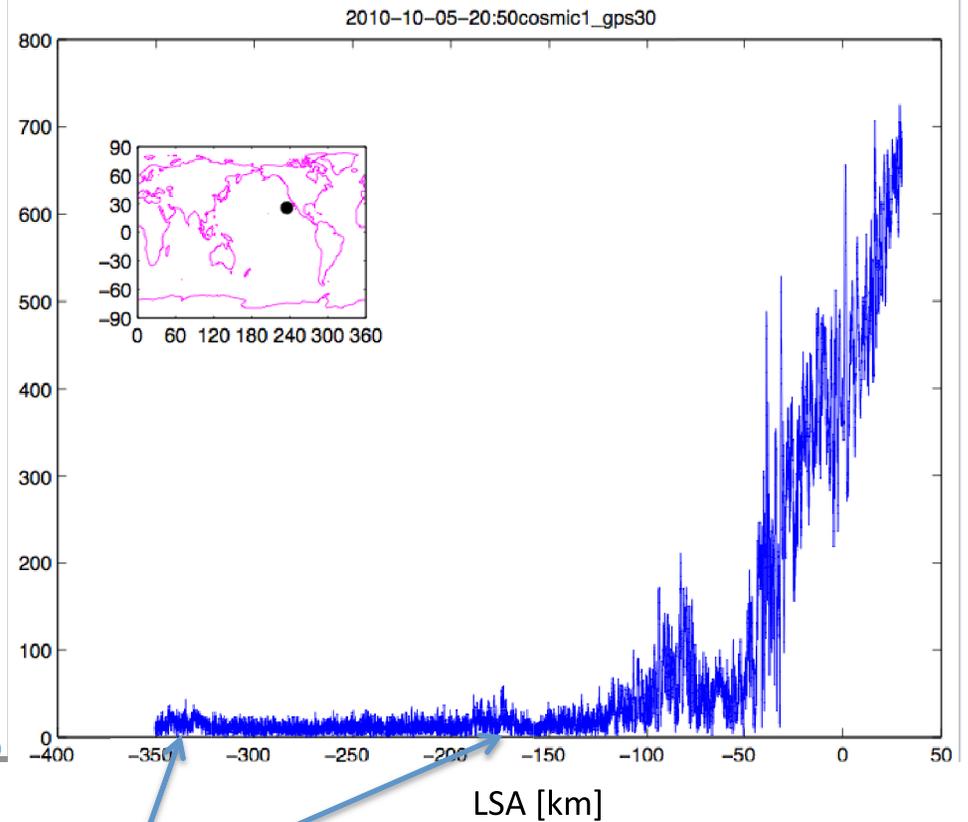
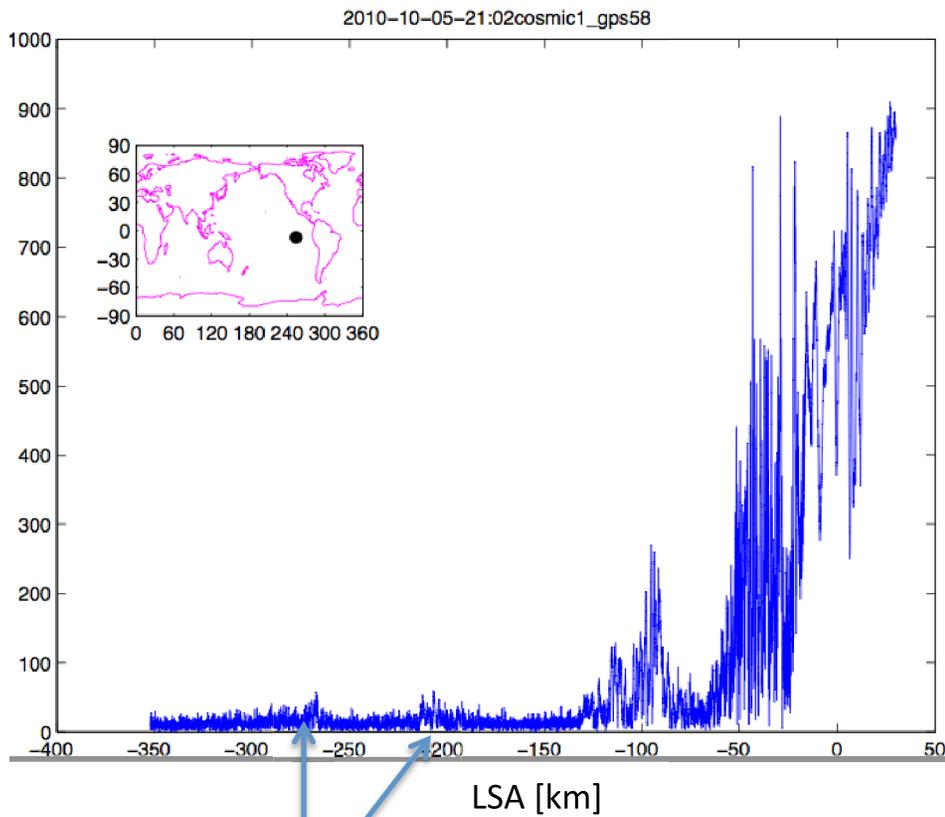
# LES Simulations (From George Matheou, JPL)



# Deep Tracking Experiment

- To evaluate possible bending angle bias due to truncation of measurement, COSMIC FM1 receiver firmware was modified to track setting tropical ROs down to -350 km line-of-sight altitude (normally  $\sim$  -180 km) for  $\sim$  1 day in Oct 2010.
- There are  $\sim$  40 cases, with a few cases showing signals below -200 km LSA.
- More data (longer experiment) needed!

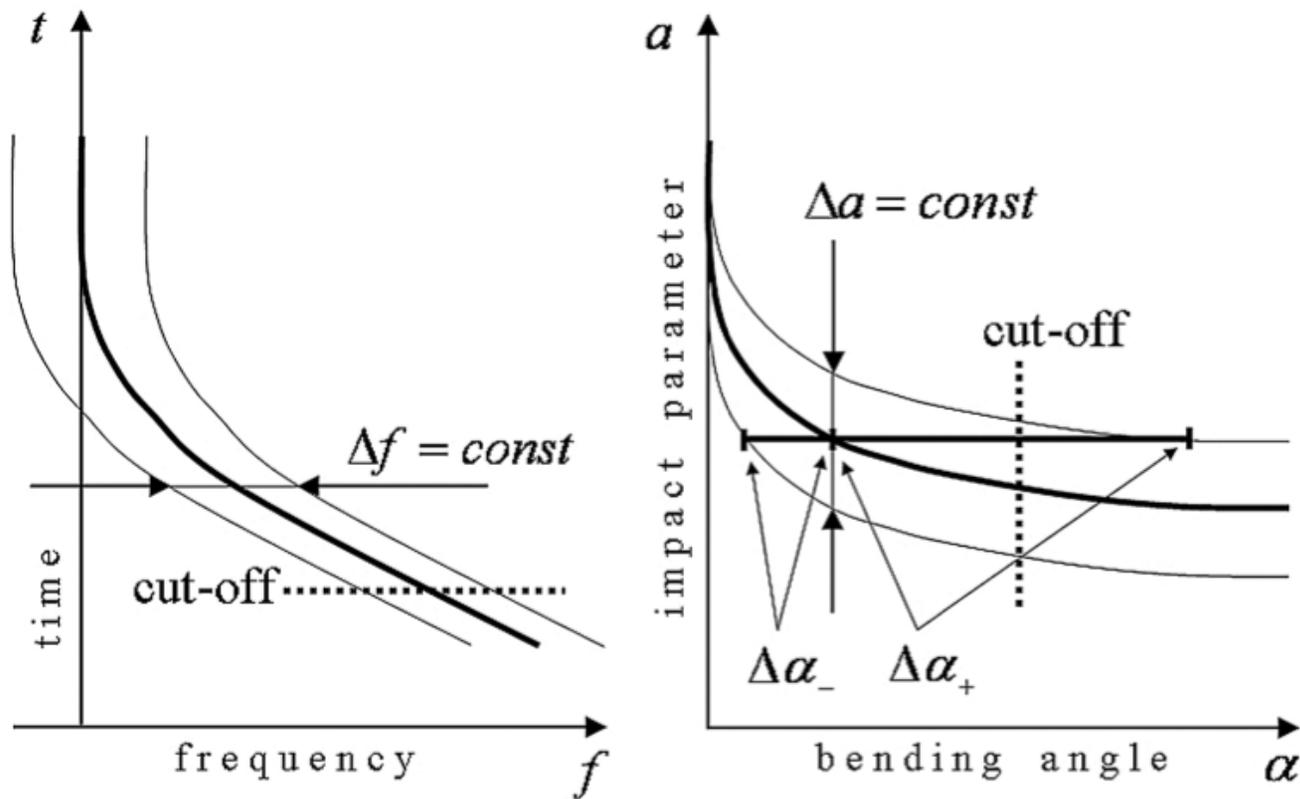
# Some Interesting Cases



Appreciable signals at very low altitudes

# Positive N-Bias

- Refractivity from low SNR tropical occ is found to be positively biased relative to high SNR occ ( $\sim 1\%$  at 3-4 km altitude) [Sokolovskiy et al. 2010].
- Believed to be caused by nonlinear noise propagation in the retrieval process (random phase noise  $\rightarrow$  + biased bending angle).
- Higher SNR and higher sampling bandwidth should reduce this bias.



**Figure 4.** The noise band of RO signal in time-frequency and impact parameter-bending angle representations (for details, see text).

Sokolovskiy et al. 2010

# Summary

- We plan to perform uncertainty analysis beyond the baseline 5-20 km and investigate mitigation methods.
- For stratosphere, ionospheric residual error is likely to have solar and diurnal variability and thus most problematic for climate. The refractivity uncertainty due to this (and other errors) depends on how the Abel upper boundary condition is imposed.

# Summary (Cont'd)

- In the lower troposphere, there are 2 regimes, 0-2 km and 2-5 km.
  - For 2-5 km, needs better understanding/constrain of the positive N bias due to noisy data.
  - For 0-2 km, needs better understanding of negative bending & refractivity biases, plus the issue of depth penetration.
- What levels of accuracy will be required by CLARREO science in these altitudes?

# Coupling to TriG Development

- TriG is designed to reduce the refractivity uncertainty in the stratosphere and lower troposphere:
  - Tracking of modern GPS, Galileo, and possibly GLONASS signals.
  - 3x higher phase precision relative to COSMIC from USO, higher antenna gain, L2C.
  - Higher sampling bandwidth (0.1 – 1 kHz) and more correlators mean better tracking and higher SNR.

# GRASP Mission Concept

- Geodetic Reference Antenna in Space: improves terrestrial and celestial reference frames accuracy by providing a geodetic “super-site” that colocates GPS, SLR, DORIS, VLBI sensors on a stable well-modeled platform above the atmosphere.
- Venture EV-2 proposal led by Yoaz Bar-Sever (JPL) and Steve Nerem (U. Colorado). Target launch 2016/7.

# CLARREO Connection

- A well-calibrated GPS receiver will be flown as part of GRASP. This will improve SI-traceability of the RO instrument by providing excellent transmit antenna phase center calibration, low local multipath, and very accurate orbits.
- RO is not part of the mission now, but could be put on as part of a broader CLARREO or climate-related initiative.