Systematic Error Analysis for GPS RO Refractivity in the Lower Troposphere

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Objectives

Identify, Evaluate, and Mitigate systematic errors in GPS RO refractivity

• Refractivity (“N”) most accurate over 5-20 km altitude (CLARREO baseline, < 0.03%)
• > 20 km (Stratosphere): AGU Fall Meeting
• < 5 km (Lower Tropo): this talk
GPS RO tracking and retrieval

**Received GNSS Signal**

- $\Delta t=20\text{msec}$

**Correlation amplitudes I, Q Sampled at 50 Hz**

- Closed loop tracking
- "Doppler" or geometric optics method (apply smoothing)

**“SNR”, phase time series at 50 Hz**

- Upsampled to ~3 kHz and applied "radio-holographic" inversion

**“Modeled” Signal (Doppler frequency shift & delay models Geo + Atmo)**

- Ray bending angles and impact parameters
- Differentiate transformed phase to derive bending (apply smoothing)

**Refractivity as a function of height**

- Abel inversion

**Integral-transformed “SNR”, phase in impact parameter space**
Transformation to a-space

Beyerle, Gorbunov, Ao, RS [2003]  
Ray manifold is single-valued in impact parameter
What make LT so tough

• Fine-scale water vapor structure creates challenging conditions for signal tracking and retrieval.
  – Large vertical gradient causes strong differential bending leading to atmospheric multipath (caustics).
  – Very large vertical gradient (“ducting condition”) makes inversion ill-posed.
  – 3D atmospheric turbulence causes strong signal dynamics (scintillations).
COSMIC4 setting 30S-30N Aug.2007

Positive bias when SNR is low?

Negative bias below ~ 2 km

Not all profiles reach surface due to ret/qc (worse for low SNR)
Noise-related bias

Sokolovskiy et al., JGR, 2010 [sok10] argued that a positive bias in $\alpha$ (N) can result from random phase noise in the tropical lower troposphere.

Figure 4. The noise band of RO signal in time-frequency and impact parameter-bending angle representations (for details, see text).
Main Results from Sok10

1. The bias affected tropical occultations.
2. The bias was demonstrated in 3 ways:
   i. Truncating noisy part of the data results in a negative bias.
   ii. Adding random noise results in a positive bias.
   iii. Average refractivity for low SNR is larger than for high SNR in the tropics (cf earlier slide).
3. The bias is highly sensitive to filtering/smoothing method used in calculating bending.
Key Questions

• Can these results be reproduced using JPL retrieval system?
• How does the bias vary with latitude (or longitude)?
• Given an accuracy requirement for N, what is the required SNR?
• What filtering/smoothing method (if any) works best in reducing the bias?
• Can we simulate this effect with end-to-end simulations?
"Noise" Cutoff Experiment

Sok10

Figure 6. Same as Figure 5 but for a tropical occultation.
• Similar bias below ~ 1 km but none above 2 km.
• Are we throwing away noise or data?
Zonal N vs Lat

COSMIC 2007 Zonal Mean at 3 km

\[
\frac{(N(RO) - N(ECMWF))/N(ECMWF)}{N(RO)} \times 100 \%
\]

- SNR > 700
- SNR < 700

SNR [V/V]

-90 -60 -30 0 30 60 90

(\frac{(N(RO) - N(ECMWF))/N(ECMWF)}{N(RO)} \times 100 \%)
Zonal N vs SNR

COSMIC 2007 Zonal Mean [-10 0] latitude

Clear dependence on SNR, consistent with earlier slide and also Sok10.
- ECMWF (interpolated to COSMIC loc) shows similar SNR dependence to COSMIC!
- This is presumably due to sampling differences between high and low SNR occultations.
- Could sampling bias account for the observed low SNR bias in COSMIC?
Sampling vs. SNR

n(SNR > 700)

n(SNR < 700) - n(SNR > 700)
RO Simulations with LES Atmosphere (From George Matheou, JPL)
2D Simulations with Noise Added
Summary

- We examined the recent finding by Sok10 that random additive phase noise caused a large positive N bias at 3-4 km in the tropical LT.
- Our data analysis and simulations did not show conclusive evidence of this effect (due to different smoothing methods?).
- Observed positive bias > 3 km might be a result of sampling bias.
- More work (esp. simulations) needed to fully characterize the effects of SNR and data length on retrieval biases.