Lower-Troposphere Sounding with GPS Occultation: Challenges and Progress

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Overview

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   - Characteristics of the N-bias
   - Possible causes

2. Simulation study
   - Components of end-to-end system
   - Strategy

3. Numerical results
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   - Statistical comparisons
   - How does it compare with real data?

4. Conclusions
   - Pressing questions
Characteristics of the N-Bias

- Fractional refractivity difference with respect to ECMWF:

\[
\delta N = \frac{N(\text{retrieved}) - N(\text{ecwmf})}{N(\text{ecwmf})}
\]

ST = standard “Doppler” retrieval
CT = canonical transform retrieval

- The bias is most severe in the tropics and at altitudes below 2 km.

- The bias extends to mid-latitudes, and, for ST, reaches up to 8 km.

- CT significantly reduces the ST bias above 2 km.

- CT bias shows a well-defined latitudinal dependence.
Causes of the N-Bias

I. Occultation retrievals are wrong.

- *Retrieval errors*
  - Sharp refractivity structure in lower troposphere leads to atmospheric multipath, superrefraction, and ducting.
  - Breakdown of spherical symmetry.

- *Tracking errors*
  - Low SNR in the lower troposphere causes problems for the tracking loop.

II. NWP models are wrong.

- Insufficient data to assimilate in some regions.
- Low spatial and temporal resolution.
End-to-End Simulation

Input Refractivity → Forward Propagation (MPS) → Simulated Amplitude & Phase → Receiver Tracking

Retrieved Refractivity → Abel Inversion → Bending Angle & Impact Parameter → DOP, BP, CT, etc.

Global analyses, Other satellite data, In-situ measurements

Data from CHAMP, SAC-C, etc.
1. **24 simulated occultations from 24 high resolution radiosonde profiles** *
   - 2 datasets: one with receiver tracking and noise, one without.
   - 2 retrieval methods are used: ST & CT.

2. **Compare with true profiles to evaluate errors.**

3. **Compare with ECMWF to evaluate the N-bias.**

4. **Compare with observed N-bias from a selected list of CHAMP and SAC-C occultations.**

*Courtesy of R. Weller, Alfred Wegener Institute for Polar and Marine Research, Germany.*
Single Profile: Amplitude and Phase

![Graphs showing altitude, refractivity, and phase over time.](image-url)
Retrievals

- ST is plagued by multipaths and has vertical resolution limited by Fresnel diffraction.
- CT works extremely well above 2 km.
- Significant errors exist below 2 km.
Ducting & Abel Inversion

Ducting Condition:

\[ \frac{dn}{dr} < -\frac{1}{r} \]

\[ \ln n(r) = \frac{1}{\pi} \int_{a}^{\infty} \frac{\alpha(a')}{\sqrt{a'^2 - a^2}} \, da' \]

\[ a = r n(r) \]
- SNR large: PLL accurately reproduces the phase.

- SNR small (below 50): the receiver enters flywheeling (FW) mode. The model Doppler is constructed based on extrapolation of non-FW data.
Retrievals with Receiver

- **Above 2 km**, CT refractivity error is caused by half-cycle slips.

- **Below 2 km**, refractivity error is due to inaccuracy from the tail-end of the occultation.
Statistical Comparison without Receiver

(a) ST w/o rx

(b) CT w/o rx

Altitude (km)

Refractivity difference (%)
Statistical Comparison with Receiver

(a) ST w/ rx

(b) CT w/ rx

Altitude (km)

Refractivity difference (%)
Statistical Comparison with ECMWF

(a) CT - ECMWF (SIM)

(b) CT - ECMWF (CHAMP/SAC-C)

Refractivity difference (%)

Altitude (km)
Conclusions

- **The negative N-bias are investigated with simulations:**
  1. With perfect data, CT retrievals give a small negative N-bias below 2 km. This represents a fundamental limitation of Abel inversion when atmospheric ducting exists.
  2. Receiver errors increase the N-bias below 2 km. No bias is introduced above 2 km.
  3. NWP errors are non-negligible.

- **How often does ducting occur in real occultations? How well do the refractivity profiles used in the simulations represent reality?**

- **How can we identify these cases? Can we rescue Abel inversion?**

- **What are the effects of non-spherically symmetric structures?**

- **What modifications can we make to the receiver tracking algorithms that would reduce retrieval errors?**