Use of GNSS Radio Occultation data for Climate Applications

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Questions of Study

– How does the GNSS Radio Occultation technique observe atmospheric parameters?

– To what level are GNSS RO bending angles (BA) “Mission Independent”, i.e., no inter-satellite or inter-instrument biases?

– What is the impact of residual ionospheric errors when using GNSS RO data in climate applications?
Atmospheric excess phase

- Difference between true phase path between $\vec{r}_1$ and $\vec{r}_2$ and straight line (vacuum) path

$$S_{true} - S_{str} = \int ndl - |\vec{r}_1 - \vec{r}_2|$$

GNSS signals that are driven by atomic clocks enable measurement of precise (mm level) carrier phase. Computation of atmospheric excess phase requires Precise Orbit Determination at the level of 0.1 mm/sec for velocity (allows computation of BA at $\sim2e^{-8}$ rad).
Upper stratosphere and lower troposphere are the regions of maximum errors and uncertainty of the GPS RO inversions.

In the lower troposphere:  
the signal reduces below noise level in terms of the amplitude  
Additive noise - main error source

In the upper stratosphere:  
the signal reduces below noise level in terms of the exc. phase (Doppler)  
Multipliclicative noise - main error source
Bending Angle Calculation

Determining Bending from observed Doppler
(Geometric optics)

From orbit determination we know the location of source and
We know the receiver orbit $\nu$ . Thus we know $\Phi$

We measure Doppler frequency shift: $f_d = \frac{1}{\Delta t} = \frac{\nu}{\Delta x} = \frac{\nu}{\lambda} \cos \psi = f_T \frac{\nu}{c} \cos \psi$

Thus we know $\psi$ . And compute the bending angle $\alpha = \Phi - \psi$
Data Processing Procedure

Raw Phase/Amplitude

Precise Orbit Determination / excess phase process
no error propagation

Excess Phase (Doppler)

local transform
no error propagation

Bending angle

non-local transform (Abel inversion)
error propagation downward

Refractivity (density)

non-local transform (hydrostatic integration)
error propagation downward

Pressure, temperature
Mission Independence of Bending Angles

Here we investigate systematic differences in bending angle to evaluate the level at which RO bending angle data are mission independent.

Collocated raw bending angle profiles are differenced at common heights and statistical results are shown in the upper stratosphere and lower troposphere.

First we evaluate systematic differences between COSMIC3 (FM3) and COSMIC4 (FM4) early in the mission (satellites were < 100km apart), which evaluates the stability of one instrument on two similar satellites in close orbits.

Then we examine systematic differences between COSMIC and Metop/GRAS profiles, which evaluates the stability of two different instruments flying on two different satellites in different orbits.

The following results were computed from recent data available at the COSMIC Data Analysis and Archive Center (CDAAC) at UCAR in Boulder

Legend: Mean = Red, STD = Green, Count = Blue
Bending Angle Differences between 30 and 60 km height

Left Panel: Bending angle differences vs altitude between COSMIC3 and COSMIC4 collocated profiles (TPs < 10 km, same PRN). The average of the mean differences over the height range is \(~3.0\times10^{-8} +/- 4\times10^{-8}\) radians.

Right Panel: Bending angle differences vs altitude between Metop/GRAS and COSMIC collocated profiles (TPs < 150 km, within 1 hr). The average of the mean differences over the height range is \(~3.0\times10^{-9} +/- 2\times10^{-8}\) radians.
Bending Angle Differences in the Lower Troposphere

**Left Panel**: Bending angle differences vs altitude between COSMIC3 and COSMIC4 collocated profiles (Tangent Points < 10 km, same GPS satellite). The mean differences of up to ~0.5% below 4 km can be explained by systematically smaller L1 Signal-to-Noise Ratios observed for COSMIC3 as compared to COSMIC4.

**Right Panel**: Bending angle differences vs altitude between Metop/GRAS and COSMIC collocated profiles (TPs < 150 km, within 1 hr). The mean differences up to ~2% can be explained by Metop/GRAS receiver tracking limitations.

### COSMIC3 – COSMIC4

Global: Jul-Dec 2006

<table>
<thead>
<tr>
<th>MSL Alt (km)</th>
<th>Mean</th>
<th>STDev</th>
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### METOP – COSMIC

Global: 2009-2010

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<tr>
<th>MSL Alt (km)</th>
<th>Mean</th>
<th>STDev</th>
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(BA_C3 – BA_C4)/BA_C3

(BA_MET – BA_COS)/BA_MET
Impact of Small-Scale Ionospheric Irregularities

Small-scale ionospheric irregularities introduce fluctuating error of the ionospheric correction 100-1000 times larger than the large-scale (bias). For weather: main error source at heights > 30 km. For climate: must be reduced by zonal averaging.

- ray separation
- diffraction effects

**Left:**
larger electron density & residual bias error

**Right:**
larger small-scale residual error
Impact of Large-Scale Ionospheric Irregularities

Relationship between F10.7 and bending angle bias: (mean [obs.BA - clim.BA] between 60 and 80 km)

NmF2 during solar max. 2002 and solar min. 2007 (from CHAMP - retrieved electron density profiles)
Estimation (by ray tracing) of the residual ionospheric bending angle error (2nd order ionospheric effect) during daytime for solar max. 2002 and solar min. 2007: 
\(~ 0.1 \mu\text{rad}; \sim 0.02 \mu\text{rad}\) at 60 km.

Application of the estimated 2nd order ionospheric correction: removes much (but not all) of the bending angle bias.

A realistic assumption: we may correct BA bias to the level \(~ 0.05 \mu\text{rad}\).
Impact of Residual Ionospheric Error

We now estimate the effect of residual ionospheric errors on monitoring the climate signal by using an Observing System Simulation Experiment (OSSE):
- forward modeling of the climate signal in BA;
- inversion of the BA to N and T with different initialization heights;
- comparison of the inverted climate signal to ionospheric residual

Model of the climate signal: a piecewise-linear approximation of the 25 year temperature trend (2001-2025, low latitudes) from MAECHAM5 climate model (Foelsche et al., 2008)
The climate signal in RO bending angle (BA) and the effect of the residual ionospheric error 0.05 µrad

The climate signal in retrieved temperature with BA initialization starting at: 40 km; 50 km; 60 km; and the effect of residual ionospheric error 0.05 µrad
The main error of GNSS RO for climate applications in the stratosphere is residual ionospheric error. This error can be reduced by:

- modeling of the 2nd order correction by ray tracing and an ionospheric model;
- averaging of large amount of RO data.

The effect of the residual ionospheric error is smallest in BA, larger in N and further larger in T due to non-local transforms.

Errors of monitoring of the climate signal by RO:

<table>
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<tr>
<th>Variable/Altitude</th>
<th>20 km</th>
<th>30 km</th>
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<tbody>
<tr>
<td>Bending Angle</td>
<td>~0.003%</td>
<td>~0.015%</td>
</tr>
<tr>
<td>Refractivity</td>
<td>~0.010%</td>
<td>~0.045%</td>
</tr>
<tr>
<td>Temperature</td>
<td>~0.045% (0.1K)</td>
<td>~0.140% (0.3K)</td>
</tr>
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</table>

Assimilation of BA by climate models is preferable over assimilation of N, T. Requires specification of the atmospheric state well above the height of interest.
Conclusions

• To what level are GNSS RO bending angles “Mission Independent”, i.e., no inter-satellite or inter-instrument biases?
  – Between 30 and 60 km altitude, analysis of COSMIC3 and COSMIC4 collocated BA profiles show no statistically significant bias between two COSMIC satellites.
  – Between 30 and 60 km altitude, analysis of Metop/GRAS and COSMIC collocated BA profiles show no statistically significant bias.
  – In the lower troposphere, a small systematic BA bias of < ~0.5% exists between COSMIC3 and COSMIC4 due to receiver/antenna SNR differences.
  – In the lower troposphere, Metop/GRAS BA data are negatively biased compared to COSMIC with a maximum of several percent (tropics) due to GRAS receiver tracking limitations.

• What is the impact of residual ionospheric errors when using GNSS RO data in climate applications?
  – The effect of the residual ionospheric error is smallest in BA, larger in N and further larger in T due to non-local transforms.
  – At 20 km height, the errors of monitoring the climate signal with RO have magnitudes of ~0.003% in BA, ~0.01% in N, and ~0.045% (0.1K) in T.
  – Assimilation of BA by climate models is preferable over assimilation of N or T, but requires specification of the atmospheric state well above height of interest.