Radio Occultation Measurements in the Cloudy Boundary Layer

1Anthony J. Mannucci
1Chi Ao
2E. Robert Kursinski
1Feiqin Xie
1Byron Iijima
1Dong Wu

1Jet Propulsion Laboratory, California Institute of Technology
2University of Arizona, Tucson

KISS Workshop
“Innovative Satellite Observations To Characterize The Cloudy Boundary Layer”
September 22, 2010

Overview of Today’s Talk

• Measurement concept and recent results
• RO in the boundary layer
• Research directions
Geometry of an acquisition

Snell’s Law

\[ N = a_1 \frac{P}{T} + a_2 \frac{P_W}{T^2} \]
Atmospheric Refractivity at L-band

\[ N = (n - 1) \times 10^6 \]
\[ = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} - 40.3 \times 10^6 \frac{n_e}{f^2} \]
\[ + O \left( \frac{1}{f^3} \right) + a_w W_w + a_i W_i \]

\[ a_1 = 77.6 \text{ K/mbar} \]
\[ a_2 = 3.73 \times 10^5 \text{ K}^2/\text{mbar} \]

\( W_w \) and \( W_i \) are liquid water and ice content (g/m\(^3\))
\[ a_w = 1.4 \text{ m}^3/\text{g} \]
\[ a_i = 0.6 \text{ m}^3/\text{g} \]

\[ \frac{dP}{dh} = -g\rho \]

\[ \rho = \rho_d + \rho_w = \frac{m_d P}{TR} + \frac{(m_w - m_d)P_w}{TR} \]

L1 = 1.575 GHz  
L2 = 1.227 GHz
Spherically symmetric case:

\[
\alpha(a) = -2a \int_a^\infty \frac{1}{\sqrt{a'^2 - a^2}} \frac{d \ln(n)}{da'} da'
\]

Abel inversion

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

Melbourne et al., JPL Pub 94-18, 1994
Geophysical Retrieval

Doppler Measurement & spherical symm

Bending Angle vs Altitude

\[ \text{Abel transform} \]

Refractivity vs Altitude

Ideal gas, hydrostatic equilibrium

\[ N = a_1 \frac{P}{T} + a_2 \frac{P_W}{T^2} \]

\[ \frac{dP}{dh} = -\rho g \]

\[ \lambda \Delta f = [v_t \cdot \hat{k}_t - v_r \cdot \hat{k}_r - (v_t - v_r) \cdot \hat{k}] \]

Horizontal resolution: 50-300 km
Vertical resolution: 50m - 1 km

Minimally affected by liquid water, precipitation and ice
Geographical Coverage

Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs

COSMIC-Follow On: 12 satellites, GPS+Galileo, 2014 and 2016
RO versus Radiosonde
High Accuracy and Precision in UTLS

- Multi-year statistical profile comparison
- IGRA database
- CHAMP RO

Continents:
USA
Russia
Australia
India

- Statistically significant difference in daytime versus nighttime means

He et al., GRL 2009
JPL

September 22, 2010
GPS Radio Occultation
KISS Workshop
Humidity Versus Temperature Uncertainty

For a “typical” tropical sounding:

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Pressure (mbar)</th>
<th>1 K uncertainty</th>
<th>2 K uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>995</td>
<td>5%</td>
<td>6%</td>
</tr>
<tr>
<td>2.2</td>
<td>767</td>
<td>8%</td>
<td>9%</td>
</tr>
<tr>
<td>5.5</td>
<td>567</td>
<td>12%</td>
<td>20%</td>
</tr>
<tr>
<td>7.7</td>
<td>380</td>
<td>50%</td>
<td>-</td>
</tr>
</tbody>
</table>

Although not directly applicable to all BL cases because of temperature inversions – $q$ dominates refractivity

Assume a temperature from an analysis

Estimated RMS errors for $q$

RMS diff. in $N$ and $q$ wrt RAOB
Recent Results

GPS Radio Occultation

The Polar Summer Tropopause Inversion Layer
From Randel and Wu, submitted to Journal Of The Atmospheric Sciences

GPS profiles show excellent agreement with high resolution radiosondes, capturing the inversion layer

Many more COSMIC observations than high-resolution radiosondes (COSMIC: ~5,000 profiles per month poleward of 60°)

COSMIC provides 8 hours of gain in forecast skill starting at day 4

Details:
- Anomaly correlation scores (the higher the better) as a function of the forecast day for the 500 mb gph in Southern Hemisphere
- 40-day experiments:
  - expx (NO COSMIC)
  - cnt (old RO assimilation code - with COSMIC)
  - exp (updated RO assimilation code - with COSMIC)
ECMWF Results


(S. Healy)
ECMWF: Impact On Radiance Biases

Anchoring of radianace bias correction with GPSRO observations:

**Metop AMSU-A channel 9 departure & bias correction evolution**

- eykt (DA) : EUMETSAT_TOVS-1C metop-a_AMSU-A_Tb Ch 9 Southern Hemisphere
- Used data
- St. dev. and bias (K) OB-FG (red) OB-AN (blue) BIASCOR (mean)-0.056

---

**CONTROL (NO COSMIC MEASUREMENTS)**

---

**COSMIC MEASUREMENTS ASSIMILATED**

---

(S. Healy)

September 22, 2010  GPS Radio Occultation  KISS Workshop
RO in the Cloudy Boundary Layer

Useful

• Cloud penetration
• Sensitivity to water vapor
  – Wet term tends to dominate refractivity gradients in ABL
• Insensitive to liquid water and aerosol (complementary)
• High vertical resolution (50m-200m)

Less useful

• Limb measurement – horizontal averaging
  – Answer: combine RO with nadir-facing sensors
• Current technology: not all soundings reach the surface
  – Answer: increase antenna size, fly new receiver “TriG”, higher data rates and multiple delay processing
Boundary Layer Applications

NOTE: BL sensing requirements not levied on RO instruments for current constellations
How to compute the ABL height from GPS RO?

- **Local gradient methods**
  - Minimum gradient of refractivity profile [Sokolovskiy et al. 2006; Basha and Ratnam 2009]
  - Minimum gradient of specific humidity profile [Ao et al. 2008]

- **Bulk moisture method**: $q(pblh) = \frac{1}{2} q(surf)$

Seidel et al.: on comparative study of several ABL height definitions with *radiosonde* data shows that gradient based heights can be very different from traditional mixing heights.

Seidel, Ao and Li, *JGR* 2010
Defining the ABL Top

- **Local Gradient**: Define ABL top as height where $dq/dz$ is minimum

- **Bulk Moisture**: Define ABL top as height where $q = \frac{1}{2}q_{surf}$
Comparison with RAOB/Hi-Res

dq/dz method

All profiles < 300 km, 3 hr apart

• Restrict comparisons to profiles with min alt < 0.5 km above surface

• Exclude the lowest 200 m of both GPS and RAOB profiles

→ Need improved technology for RO to consistently reach surface
Minimum Profile Depth

Global (COSMIC Sept 07 - Aug 08)

Fraction of profiles with min alt < 500 m (Sept 2007 - Aug 2008)
cosmic 2007 data, 10x10 grids, seasonal averages

minimum dq/dz, no smoothing,
only include sharp profiles, defined as dq/dz < -5 g/kg/km and (dq/dz)/median(dq/dz) > 10

GPS Radio Occultation
“Sharp” PBL Tops

Distribution of top 25 %-tile in humidity gradients at PBL height

Vertical velocity from ERA-40 500 hPa (2000-2001)
GPS Radio Occultation

ERA-Interim

January 2007
Diurnal variations of the ABL depth
(thin lines – standard deviations of the mean)

**North Pacific**
lat(+20,+40) lon(-150,-120)

**South Atlantic**
latt(-35,-15) lon(-20,+10)

**South Pacific (I)**
lat(-35,-15) lon(-130,-100)

**South Pacific (II)**
lat(-35,-15) lon(-100,-70)

Based on bending angle lapse rate

Sokolovskiy et al.,
AMS Annual Meeting
2010
Validation of the diurnal variations of the ABL depth with atmospheric models is difficult because the models:
(i) do not provide sufficient vertical resolution at the ABL top
(ii) do not provide uniform sampling in local time

Internal validation: estimation of the diurnal variation over desert produces expected results (deeper ABL in the afternoon).

Sahara Desert

Sokolovskiy et al.,
AMS Annual Meeting
2010
Case Study: Lihue, Hawaii

Xie et al., GRL 2010

a) Temperature and Specific Humidity

b) Impact height [km]

RO-RAOB
10 min
85 km

Xie et al., GRL 2010

C) Refractivity [N-Unit]

D) Refractivity error [%]
RO Remote Sensing in Context

- **Passive (AIRS, MISR, …)**
  - A natural source provides the photons
    - Often this creates possibility to form a 2D image
  - Radiative transfer
    - Count photons of a specific frequency or spectral band

- **Active backscatter (Radar, LIDAR, …)**
  - Sensitive to particulates, scatterers
  - Range gating and discrimination of different scatterers

- **Active transmission (RO with GPS or other sources)**
  - Phase shifts sensitive to atmospheric density and water vapor
  - Interferometric: received signal is coherent superposition of phase shifts along the beam and vertically
The Forward Problem in RO

Source of phase shift
\[ \phi_n(x) = k \int_{z_n - \Delta z/2}^{z_n + \Delta z/2} [\mu(x, z) - 1] dz \]

Impact of phase shift
\[ u(x, z_n^+) = u(x, z_n^-) \exp [i\phi_n(x)] \]

Decomposition into plane waves
\[ U(k_x, z_n^+) = \int_{-\infty}^{\infty} u(x, z_n^+)e^{-ik_x x} dx \]

Free space propagation
\[ U(k_x, z_{n+1}^-) = U(k_x, z_n^+) \exp (ik_z \Delta z) \]

Signal reconstruction
\[ u(x, z_{n+1}^-) = \frac{1}{2\pi} \int_{-\infty}^{\infty} U(k_x, z_{n+1}^-)e^{ik_x x} dk_x \]

Scalar diffraction theory, polarization effects ignored at L-band
Measurement Physics

| Wavelength of the radiation | 0.19 | meters |
| Synthetic Aperture Size     | 100,000 | radius |
| Diffraction corrected resolution (vertical) | 6-60 | 6 reflects "ideal" |
| Distance traveled to shift phase 1/2 wavelength | 850 | at 2 km altitude |

“Backpropagation”, Karayel and Hinson, 1997 ➔
“Canonical Transform”, Gorbunov, 2002

Constructive and destructive interference

GPS Radio Occultation
Simulations demonstrate that the received signal is very sensitive to kinks in atmospheric density structure.
• The following results show simulated signal structure after propagation through simulated atmospheric fields with small-scale structure characteristic of BL features of interest

Acknowledgement: Research and Technology Development (R&TD) program, JPL
Recent Results Using Large Eddy Simulations and Mesoscale Models

40 m resolution LES simulation

Refractivity structure within and outside a convective plume

Acknowledgement:
Georgios Matheou, JPL

KISS Workshop
Simulated Signal Amplitude

350: smooth refractivity profile
SS: continue LES structure of x=0
20 km: LES structure embedded in a smoother background
400 km: LES structure repeated (periodic boundary conditions)

20 km and 400 km cases contain convective plume
SS “Spherical symmetry”

Lower “penetration” associated with less horizontal variability

LSA: Measure of vertical coordinate descending
Impact height ≈ altitude + 2 km

- 350: smooth refractivity profile
- SS: continue LES structure of $x=0$
- 20 km: LES structure embedded in a smoother background
- 400 km: LES structure repeated (periodic boundary conditions)
- 20 km and 400 km cases contain convective plume
- SS “Spherical symmetry”
WRF refractivity structure

ret: retrieved refractivity assuming spherical symmetry

inp at tp: refractivity at tangent point location

inp 1 deg avg: WRF refractivity average within ± 1 degree

inp 1 deg min: WRF refractivity displaced -1 degree from tp

inp 1 deg max: WRF refractivity displaced +1 degree from tp

Acknowledgement:
Svetla Hristova-Veleva, JPL
• **50 m vertical retrieval resolution** ⇒ **50 km horiz resolution**

RO as a Tool for BL Remote Sensing

• Science objective: thermodynamic conditions and water vapor within and above the boundary layer. This provides a constraint on the processes that result in the distribution of hydrometeors.

• Develop new retrieval techniques that:
  – Increase use of information in the signal
  – Can be combined with other sensors that detect liquid water, ice, etc.

• New retrieval methods will (perhaps):
  – Use a forward model that includes diffraction effects
  – Use \textit{a priori} atmospheric information in some form
  – Use information from complementary sensor systems
  – Account for refractive index variations along the raypath
Radio occultation link penetrating this structure, providing information on the thermodynamic and water vapor vertical structure.

Accurate forward modeling and the sensitivity of RO provide a very strong constraint on scientific hypotheses regarding such regions.

“If we can solve the forward problem, we can solve the inverse problem.” (!)
Next Generation Radio Occultation Instrument

TriG

IGOR GNSS BASEBAND PROCESSOR

L1, L2, L5 RFDC (10)

SCIENCE PROCESSOR (multiple correlators?)

Reconfigurable Digital Processor

1000 Hz

RF from Antennas

BIG

30x20x20 cm
~35W
50kRad
~6kg + Antennas

4 processors total: 2 CPU, 2 FPGA

New Obs Types

GPS Radio Occultation

COSMIC Workshop T.K.Meehan; Oct 29, 2009
Summary

• What is the revolution? Integrating radio occultation information content into a combined retrieval
• We have tools to make significant progress now
• Critical to increase depth penetration
  – SNR and multiple correlation
• Long term “vision”: increase fraction of computer time spent doing retrievals
  – Measurements with increased sensitivity (higher spatial resolution, additional radar frequencies, camera angles, wavelengths, etc.)
  – Retrievals with increased physical content
• GNSS systems are proliferating: GPS, Galileo, GLONASS – 3x number of measurements
Despite all the structure in the signal, one can smooth the data to obtain meaningful results in specific limits:

- Doppler shift from phase rate: bending angle
- Spectral content: multiple bending angles
- Integral transforms: decomposition into unique bending angle for each impact parameter
- Spherical symmetry: bending angle to refractivity
- Spherical asymmetry: input impact parameter $\neq$ output impact parameter
Atmospheric Multipath

Figure 1. The geometry of multipath propagation.