Precise Orbit Determination and Radio Occultation Retrieval Processing at the UCAR CDAAC: Overview and Results

Bill Schreiner, Chris Rocken, Sergey Sokolovskiy, Stig Syndergaard, Doug Hunt, Karl Hudnut, Maggie Sleziak, T.K. Wee, and Bill Kuo

UCAR COSMIC Project Office
www.cosmic.ucar.edu
Outline

• COSMIC and CDAAC Overview
• POD Overview and Results
• RO Retrieval Overview and Results
  – Neutral Atmosphere
  – Ionosphere
• All six satellites stacked and launched on a Minotaur rocket

• Initial orbit altitude ~500 km; inclination ~72°

• Will be maneuvered into six different orbital planes for optimal global coverage (at ~800 km altitude)

• Satellites are in relatively good health and providing data-up to 2000 soundings per day to NOAA
COSMIC at a Glance

- **Constellation Observing System for Meteorology Ionosphere and Climate (ROCSAT-3)**
- 6 Satellites launched in 2006
- Orbits: alt=800km, Inc=72deg, ecc=0
- Weather + Space Weather data
- Global observations of:
  - Pressure, Temperature, Humidity
  - Refractivity
  - TEC, Ionospheric Electron Density
  - Ionospheric Scintillation
- Demonstrate quasi-operational GPS limb sounding with global coverage in near-real time
- Climate Monitoring
- Geodetic Research
GPS Antennas on COSMIC Satellites

2 Antennas POD, TEC_pod (1-sec), EDP, 50Hz clock reference

- GPS receiver developed by JPL and built by Broad Reach Eng.
- Antennas built by Haigh-Farr

High-gain occultation antennas for atmospheric profiling (50 Hz)

COSMIC s/c

V_{leo}

Upto 9 GPS

Upto 4 GPS

Nadir
CDAAC Processing Flow

- **Atmospheric processing**
  - Excess Phase
  - Abel Inversion
  - 1-D Var Moisture Correction

- **Ionospheric processing**
  - Excess Phase
  - Abel Inversion
  - Combination with other data

- **Real time Task Scheduling Software**

- **Input data**
  - LEO data
  - Fiducial data
  - Orbits and clocks

- **Profiles**
Impact of Velocity Errors on RO Retrievals

• Kursinski et al. (1997)
  ~0.05% error in N at 40km due to 0.05 mm/s velocity error

• UCAR simulation
  ~0.1% in N at 40km due to 0.1 mm/s velocity error
LEO POD at CDAAC with Bernese v5.0

**LEO POD**

- Developed by Markus Rothacher and Drazen Svehla at TUM
- Zero-Difference Ionosphere-free carrier phase observables with reduced-dynamic processing (fully automated in CDAAC)
- Real-Time (~70 ground stations)
- Dynamic Model: Gravity - EIGEN1S, Tides - (3rd body, solid Earth, ocean)

**State Parameters:**
- 6 initial conditions (Keplerian elements)
- 9 solar radiation pressure parameters (bias and 1 cycle per orbital revolution accelerations in radial, transverse, and normal directions)
- pseudo-stochastic velocity pulses in R-T-N directions every 12 minutes
- Real ambiguities

**Quality Control**
- Post-fit residuals
- Internal overlaps

---

- GPS Orbits/EOPs/Clocks(Final/IGU)
- IGS Weekly Station Coordinates
- 30-sec Ground GPS Observations

- 30-sec LEO GPS Observations
- LEO Attitude (quaternion) data

- 1-Hz Ground GPS Observations
- 50-Hz LEO Occultation GPS Obs.

---

- Estimate Ground Station ZTD’s and Station Coordinates
- Estimate 30-sec GPS Clocks OR use CODE/IGS clocks
- Estimate LEO Orbit And Clocks

---

- Single/Double Difference Occultation Processing
- Excess Phase Data

---

- Estimate LEO Orbit And Clocks
- Post-fit residuals
- Internal overlaps
ZTD Processing

DataFlow

- Post-Process monthly batches of data into DD 1-hr Neq’s
- Use IGS Final Orbits/EOPs, IGS Weekly Reference station coordinates
- Geodetic Datum defined by minimum constraint (no-net trans, no-net rot) to IGS coords
- Estimate Non-IGS station coords: pre-eliminate ZTD’s before stacking Neq’s
- Estimate troposphere ZTD’s every hour: pre-eliminate station coords before stacking Neq’s (Quality: < 1 cm rms vs IGS/CODE)
The Bernese CLKEST program is used to generate ground station and GPS satellite clock corrections as described in [Bock et al, 2000].

The ground network carrier phase observation equation for a given receiver $i$ and satellite $j$ and epoch $l$ are modeled as

$$
\phi_{il}^j = \rho_{il}^j - c \cdot \Delta t_i^l + c \cdot \Delta t_{il}^j + \Delta \rho_{il,ion}^j + \Delta \rho_{il,trop}^j + \lambda \cdot N_i^j + \epsilon_{\phi}
$$

If ionosphere-free observations are considered, and previously solved for GPS orbits, station coordinates, and ZTDs are used to subtract known terms, then the modified observations are only a function of clock terms

$$
LC_{il}^j = -c \cdot \Delta t_i^j + c \cdot \Delta t_{il}^j + \epsilon_{\phi}
$$

Estimate precise phase-derived clock offset differences from epoch to epoch

Align precise epoch to epoch GPS clock offsets to IGS clocks
High-Rate GPS Clock Comparison

CDAAC 1-s GPS clocks
CDAAC 30-s GPS clocks
IGS 15-min GPS clocks

GPS Cesium clocks

GPS Rubidium clocks
Zero-Difference Observables with Reduced-Dynamic processing (fully automated in CDAAC)
Data cleaning (first two columns in fig above) requires a priori orbit (arc length = 6 hrs)
Orbit Improvement (arc length = 24 hrs)
Dynamic Model: Gravity - EIGEN1S, Tides - (3rd body, solid Earth, ocean)
Model State:
- 6 initial conditions (Keplerian elements)
- 9 solar radiation pressure parameters (bias and 1 cycle per orbital revolution accelerations in radial, transverse, and normal directions)
- pseudo-stochastic velocity pulses in R-T-N directions every 12 minutes
CPU time: ~5 minutes on P4 2.4 GHz machine
POD Results - Near Real-Time

- Internal overlaps for 2006.200-280
  - Average: ~24 cm 3D RMS
  - Median: ~16 cm 3D RMS

- External overlaps with preliminary GFZ rapid science orbits (courtesy of G. Michalak)
  - ~ 23 cm 3D RMS (5-10cm bias in cross/along track components)
  - ~ 0.24 mm/s 3D RMS
Orbit differences at day boundaries (3-hour overlap)

### CHAMP (2007 May, 2007.121-151)

<table>
<thead>
<tr>
<th></th>
<th>Radial POS [cm] (VEL: [mm/s])</th>
<th>Along-Track POS [cm] (VEL: [mm/s])</th>
<th>Cross-Track POS [cm] (VEL: [mm/s])</th>
<th>3-D RSS POS [cm] (VEL: [mm/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.1 (0.04)</td>
<td>3.7 (0.03)</td>
<td>3.7 (0.04)</td>
<td>5.9 (0.07)</td>
</tr>
</tbody>
</table>

### COSMIC (2006 Aug 4-6, 2006.216-218)

No data gaps, Good attitude control

<table>
<thead>
<tr>
<th></th>
<th>Radial POS [cm] (VEL: [mm/s])</th>
<th>Along-Track POS [cm] (VEL: [mm/s])</th>
<th>Cross-Track POS [cm] (VEL: [mm/s])</th>
<th>3-D RSS POS [cm] (VEL: [mm/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.5 (0.04)</td>
<td>4.5 (0.04)</td>
<td>4.0 (0.04)</td>
<td>7.2 (0.07)</td>
</tr>
</tbody>
</table>
### COSMIC (2006.111-2007.212)

<table>
<thead>
<tr>
<th>FM#</th>
<th>Radial POS [cm] (VEL: [mm/s])</th>
<th>Along-Track POS [cm] (VEL: [mm/s])</th>
<th>Cross-Track POS [cm] (VEL: [mm/s])</th>
<th>3-D RSS POS [cm] (VEL: [mm/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM1</td>
<td>5.8 (0.08)</td>
<td>8.4 (0.07)</td>
<td>6.2 (0.06)</td>
<td>12.5 (0.12)</td>
</tr>
<tr>
<td>FM2</td>
<td>4.2 (0.05)</td>
<td>5.7 (0.05)</td>
<td>4.7 (0.05)</td>
<td>9.0 (0.09)</td>
</tr>
<tr>
<td>FM3</td>
<td>5.4 (0.07)</td>
<td>7.7 (0.06)</td>
<td>5.3 (0.06)</td>
<td>11.2 (0.12)</td>
</tr>
<tr>
<td>FM4</td>
<td>5.1 (0.07)</td>
<td>7.2 (0.06)</td>
<td>5.1 (0.05)</td>
<td>10.7 (0.11)</td>
</tr>
<tr>
<td>FM5</td>
<td>4.0 (0.05)</td>
<td>5.3 (0.05)</td>
<td>4.0 (0.04)</td>
<td>8.1 (0.08)</td>
</tr>
<tr>
<td>FM6</td>
<td>4.8 (0.06)</td>
<td>6.9 (0.06)</td>
<td>4.9 (0.05)</td>
<td>10.2 (0.10)</td>
</tr>
</tbody>
</table>
### CHAMP Post-Processed External Overlaps

#### UCAR - GFZ(RSO) (2006.241-243)

<table>
<thead>
<tr>
<th></th>
<th>Radial POS [cm] (VEL: [mm/s])</th>
<th>Along-Track POS [cm] (VEL: [mm/s])</th>
<th>Cross-Track POS [cm] (VEL: [mm/s])</th>
<th>3-D RSS POS [cm] (VEL: [mm/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>-5.6 (-0.08)</td>
<td>4.7 (0.06)</td>
<td>-4.8 (0.00)</td>
<td>-</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td>7.0 (0.12)</td>
<td>7.5 (0.13)</td>
<td>7.4 (0.08)</td>
<td>12.7 (0.20)</td>
</tr>
</tbody>
</table>

#### UCAR - JPL(QUICK) (2006.241-243)

<table>
<thead>
<tr>
<th></th>
<th>Radial POS [cm] (VEL: [mm/s])</th>
<th>Along-Track POS [cm] (VEL: [mm/s])</th>
<th>Cross-Track POS [cm] (VEL: [mm/s])</th>
<th>3-D RSS POS [cm] (VEL: [mm/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>-4.1 (-0.05)</td>
<td>-0.5 (-0.01)</td>
<td>-2.1 (0.00)</td>
<td>-</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td>7.5 (0.10)</td>
<td>8.4 (0.15)</td>
<td>6.7 (0.11)</td>
<td>13.1 (0.21)</td>
</tr>
</tbody>
</table>
COSMIC Post-Processed External Overlaps

- Inter-Agency (UCAR, NCTU, GFZ, JPL) orbit differences
- FM’s 1-6, no data gaps, good attitude control

**UCAR - NCTU (2006.216-218)**

<table>
<thead>
<tr>
<th></th>
<th>Radial POS [cm] (VEL: [mm/s])</th>
<th>Along-Track POS [cm] (VEL: [mm/s])</th>
<th>Cross-Track POS [cm] (VEL: [mm/s])</th>
<th>3-D RSS POS [cm] (VEL: [mm/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>0.6 (0.01)</td>
<td>-3.0 (-0.03)</td>
<td>0.8 (0.00)</td>
<td>-</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td>8.8 (0.13)</td>
<td>10.1 (0.14)</td>
<td>10.5 (0.18)</td>
<td>17.0 (0.26)</td>
</tr>
</tbody>
</table>

- Radial
- Along-track
- Cross-track
- Position
- Velocity
# COSMIC Post-Processed External Overlaps

## UCAR - GFZ (G. Michalak) (2006.216-218)

<table>
<thead>
<tr>
<th></th>
<th>Radial POS [cm] (VEL: [mm/s])</th>
<th>Along-Track POS [cm] (VEL: [mm/s])</th>
<th>Cross-Track POS [cm] (VEL: [mm/s])</th>
<th>3-D RSS POS [cm] (VEL: [mm/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>2.9 (0.00)</td>
<td>4.7 (0.05)</td>
<td>8.0 (0.00)</td>
<td>-</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td>9.4 (0.15)</td>
<td>13.9 (0.12)</td>
<td>12.7 (0.12)</td>
<td>21.3 (0.22)</td>
</tr>
</tbody>
</table>

## UCAR - JPL (Da Kuang) (2006.216-218)

<table>
<thead>
<tr>
<th></th>
<th>Radial POS [cm] (VEL: [mm/s])</th>
<th>Along-Track POS [cm] (VEL: [mm/s])</th>
<th>Cross-Track POS [cm] (VEL: [mm/s])</th>
<th>3-D RSS POS [cm] (VEL: [mm/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>2.9 (0.04)</td>
<td>3.0 (0.03)</td>
<td>-2.0 (0.00)</td>
<td>-</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td>7.7 (0.10)</td>
<td>12.8 (0.13)</td>
<td>9.6 (0.13)</td>
<td>18.0 (0.21)</td>
</tr>
</tbody>
</table>
Computation of excess atmospheric phase

- **Double Difference**
  - Advantage: Station clock errors removed, satellite clock errors mostly removed (differential light time creates different transmit times), general and special relativistic effects removed
  - Problem: Fid. site MP, atmos. noise, thermal noise

- **Single Difference**
  - LEO clock errors removed
  - use solved-for GPS clocks
  - Main advantage: Minimizes double difference errors
Neglecting ambiguities, multipath, and thermal noise, the observed occulting-link L1 phase path and the non-occulting L3 (ionosphere-free) phase paths can be written as

\[
L1^b_a(t_r) = \rho^b_a(t_r) + c \cdot \delta t_a(t_r) - \delta t_{a,rel}(t_r) - c \cdot \delta t^b_a(t_r) - \tau^b_a + \delta t_{rel,1}(t_r - \tau^b_a) + \delta \rho^b_{a,ion}(t_r) + \delta \rho^b_{a,trop}(t_r) + \delta \rho^b_{a,rel,2}(t_r)
\]

\[
L3^c_a(t_r) = \rho^c_a(t_r) + c \cdot \delta t_a(t_r) - \delta t_{a,rel}(t_r) - c \cdot \delta t^c_a(t_r) - \tau^c_a + \delta t_{rel,1}(t_r - \tau^c_a) + \delta \rho^c_{a,rel,2}(t_r)
\]

\[
L3^c_d(t_r) = \rho^c_d(t_r) + c \cdot \delta t_d(t_r) - \delta t_{d,rel}(t_r) - c \cdot \delta t^c_d(t_r) - \tau^c_d + \delta t_{rel,1}(t_r - \tau^c_d) + \delta \rho^c_{d,rel,2}(t_r) + \delta \rho^c_{d,rel,2}(t_r)
\]

\[
L3^b_d(t_r) = \rho^b_d(t_r) + c \cdot \delta t_d(t_r) - \delta t_{d,rel}(t_r) - c \cdot \delta t^b_d(t_r) - \tau^b_d + \delta t_{rel,1}(t_r - \tau^b_d) + \delta \rho^b_{d,rel,2}(t_r) + \delta \rho^b_{d,trop}(t_r)
\]

where \( \delta t_{d,rel}(t_r) \) and \( \delta t_{a,rel}(t_r) \) are the combined oscillator effects of general and special relativity at the ground station (constant) and LEO receiver, respectively, and \( \rho \) is the geometric distance and \( \tau \) is the signal travel time. The desired L1 excess phase path is shown in \textcolor{green}{\text{GREEN}}, and quantities computed from previous POD and ZTD estimates are shown in \textcolor{blue}{\text{BLUE}}.

Forming the Double-Difference and subtracting known quantities leaves the desired excess phase path and an error term of small magnitude due to incomplete cancellation of the GPS satellite clocks because each observation has a slightly different signal transmission time.

\[
\Delta L1^b_a = \delta \rho^b_{a,ion}(t_r) + \delta \rho^b_{a,trop}(t_r) - c \cdot (\delta t^b_a(t_r - \tau^b_a) - \delta t^b_a(t_r - \tau^b_a)) + c \cdot (\delta t^c_a(t_r - \tau^c_a) - \delta t^c_a(t_r - \tau^c_a))
\]

Forming the \textcolor{blue}{\text{Single}}-Difference and subtracting known quantities, including the GPS solved-for clocks at transmit time leaves the desired excess phase. The GPS clocks are not solved for perfectly and contribute some residual errors.

\[
\Delta L1^b_a = \delta \rho^b_{a,ion}(t_r) + \delta \rho^b_{a,trop}(t_r)
\]
Additional Details

- CDAAC currently uses single difference processing with 30-sec GPS clocks
- Apply L4 (=L1-L2) smoothing to reference satellite link to minimize impact of L2 thermal noise
  - \[ L3 = L1 + C(L1-L2) \]
  - \[ L3\text{smooth} = L1 + C<L1-L2> \]
  - <> denotes 2 second smoothing of ionospheric signal (L4)
  - (L1-L2) - <L1-L2> used to detect reference link cycle slips
- For open-loop processing, interpolate reference link data (on regular 20 ms timetag interval) onto irregular occultation link timetags
COSMIC POD Summary

- Current COSMIC POD quality ~ 15-20 cm (0.15-0.2 mm/s) 3D RMS
- Significant error sources
  - Attitude knowledge errors
  - Phase center offsets and variations
  - Local spacecraft multipath
  - Changing center of mass location
  - Dynamic modeling
  - Use both POD antennas
- Data gaps and latency improving with time
Occultation Geometry

• During an GPS occultation a LEO ‘sees’ the GPS rise or set behind Earth limb while the signal slices through the atmosphere

• The GPS receiver on the LEO observes the change in the delay of the signal path between the GPS SV and LEO

• This change in the delay includes the effect of the atmosphere which delays and bends the signal
Input (phase, amplitude, LEO/GPS position and velocity)

1a) Open-Loop Data Processing
NDM Removal, Phase connection

1) Detection of L1 PLL tracking errors and truncation of the signal

2) Filtering of raw L1 & L2 Doppler

3) Estimation of the “occultation point”

4) Transfer of the reference frame to the local center of Earth’s curvature

5) Calculation of L1 and L2 bending angles from the filtered Doppler

6) Calculation of the bending angle from L1 raw complex signal, FSI

7) Combining (sewing) (5) and (6) L1 bending angle profiles

8) Ionospheric calibration of the bending angle

9) Optimal estimation of the bending angle

10) Abel inversion

11) Retrieval of P,T

Output

(Kuo et al., 2004)
Open-loop tracking of RO signals described by Sokolovskiy (2001)

Tracking firmware for COSMIC receivers implemented by JPL.

L1 and L2 signals are recorded in PLL mode above ~10 km.

Below ~10 km L1 is recorded in OL mode. L2 is not recorded.

The UCAR COSMIC program has deployed a global ground network of 6 GPS receivers ("data bit grabbers" that collect the GPS navigation data messages (NDMs) for demodulation of open-loop occultation signals.
In receiver:
(1) modeling of the atmospheric Doppler and down-conversion
(2) low-pass filtering (integration)
I and Q
output signal is a sequence of complex samples with un-connected phase and un-removed NDM

In post-processing:
(1) up-conversion with rec. model
(2) down-conversion with more accurate Doppler model*)
(3) removal of NDM
(4) connection of the phase (resolving cycle ambiguities)

\[
\begin{align*}
\Phi_{out} &= ATAN_2(<Q>,<I>) \\
A_{out} &= \sqrt{<I^2> + <Q^2>} \\
u_{down} &= A \exp(i\Phi - i\Phi_{rec\_mod}) \\
u_{up} &= A_{out} \exp(i\Phi_{out} + i\Phi_{rec\_mod}) = A_{out} \exp(i\Phi_{up}) \\
u_{down} &= A \exp(i\Phi_{up} - i\Phi_{post\_mod}) \\
\Phi_{i+1} &= \Phi_i + 0 \text{ or } \pm 2\pi \\
|\Phi_{i+1} - \Phi_i| &= \text{min}
\end{align*}
\]

*) the Doppler model is based on \(\alpha(h)\) climatology and orbits [Radio Sci., 2001]
Raw Signal Truncation in Closed-Loop Mode
Detection of L1 closed-loop tracking errors

- Using LEO/GPS position and velocities, and CIRA+Q climatology, predict atmospheric Doppler
- Compare predicted Doppler with measured L1 Doppler (smoothed)
- Tracking error exists if difference > 10 Hz
- Truncate signal where difference > 5 Hz L1
- Signal truncated at Point A
Raw Signal Truncation in Open-Loop Mode
Detect when L1 SNR rises above noise

- Compute magnitude of noise of L1 SNR for bottom 3 s, \( \sigma_{SNR}^{L1} \)
- Truncate L1 signal when smoothed (0.5 s win) L1 SNR > 1.5 \( \sigma_{SNR}^{L1} \)
Filtering of raw L1 and L2 signals

• Use Fourier filtering of phase to simultaneously low-pass filter and differentiate to get filtered Doppler
• L1 filter bandwidth of 2 Hz (0.5 s), provides vertical resolution of ~ 1 km at tropopause
• (L1-L2) filter bandwidth of 0.5 Hz (2 s) to minimize impact of L2 noise. Some ionospheric residuals remain
• Complex RO L1 signals used for RH inversions not subjected to filtering
Determining Bending from observed Doppler (I)

From orbit determination we know the location of source and We know the receiver orbit $\vec{v}$. Thus we know $\Phi$

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

Thus we know $\psi$. And compute the bending angle $\alpha = \Phi - \psi$
The goal is to determine impact parameters and bending angles for all rays arriving at receiver during RO.

When only one ray arrives at each point, the arrival angle is determined from the derivative of phase (Doppler).

This is not possible when several rays are arriving at one point.

Multi-path propagation almost always occurs the moist troposphere.

RH methods allow to find arrival angles for individual rays under multi-path propagation.

RH methods use both phase and amplitude of RO signal.
In the LT, the complex RO signals (phase and amplitude) are inverted by RH methods, such as the canonical transform (CT) [Gorbunov 2002] or the full spectrum inversion (FSI) [Jensen et al. 2003].

The RH methods transform RO signal from time or space to impact parameter representation under the assumption of spherical symmetry of N.

This allows solving for multiple rays that are uniquely defined by their impact parameters.

The derivative of the phase of the complex transformed signal defines the arrival angle and thus the bending angle of a ray with a given impact parameter.

CDAAC currently uses FSI method.
The disagreement between radio-holographic methods is much smaller than between any of them and the Doppler method.
Ionospheric calibration

Is performed by linear combination of L1 and L2 bending angles at the same impact parameter (by accounting for the separation of ray tangent points).

\[ \alpha(a) = \frac{f_1^2 \alpha_1(a) - f_2^2 \alpha_2(a)}{f_1^2 - f_2^2} \]

- \( \alpha \) bending angle
- \( a \) impact parameter

Effect of the small-scale ionospheric irregularities with scales comparable to ray separation is not eliminated by the linear combination, thus resulting in the residual noise on the ionospheric-free bending angle.
Ionospheric Calibration
Determination of L2 cut-off altitude, Znid

• L2 occulting link data are discarded below the altitude (Znid) where they are determined to be of poor quality
• Two Doppler checks performed
  – 1) Mean deviation
    \[ \langle f_{L1}^{Dop} \rangle - c \cdot \langle f_{L2}^{Dop} \rangle > 1 \text{ Hz} \]
  – 2) Fluctuations
    \[ \langle f_{L2}^{Dop} \rangle - \langle f_{L2}^{Dop} \rangle > 6 \text{ Hz} \]
• Ionospheric calibration below Znid is based on an extrapolation of the difference \( \alpha_{L1} - \alpha_{L2} \) from last 3 seconds of data above Znid

\[ \alpha_{iono-free} = \alpha_{L1} + C \langle \alpha_{L1} - \alpha_{L2} \rangle \]
\( \langle \ \rangle \) denotes mean over last 3 sec
Optimization of the observation bending angle

The magnitude of the residual noise can be very different for different occultations, but it almost does not depend on height for a given occultation. Above a certain height, climatology provides better estimate of the atmospheric state than RO observation. The observed bending angle is optimally weighted with climatology. This does not improve the value of the bending angle at large heights, but results in reduction of error propagation downward after the Abel inversion.

\[ \alpha_{opt} = w\alpha_{obs} + (1 - w)\alpha_{clm} \]

where
\[ w = \frac{\sigma_{clm}^2}{\sigma_{clm}^2 + \sigma_{obs}^2} \]

The weighting function is calculated individually for each occultation.
Truncation of Bending Angle

- Transformed CT amplitude should look like step function, but differs in reality due to noise and turbulence.

- Perform least squares fit of step function to CT amplitude to determine impact height cutoff.
Total bending angle of a plain curved ray is \( \alpha = \int dl / \rho \) where \( dl \) is the differential path length, and \( \rho \) is the local curvature radius of the ray.

With account for expression for \( \rho \) in polar coordinates and the Snell's law:

\[
\alpha(a) = -2a \int_a^\infty \frac{dn}{dx} \frac{1}{n \sqrt{x^2 - a^2}} dx
\]

where \( x = r \) is the "refractive radius". This equation can be inverted by substitution of the variables \( u = x^2, v = a^2 \) and by use of the Abel transform:

\[
n(x) = \exp \left[ \frac{1}{\pi} \int_x^\infty \frac{\alpha(a)}{\sqrt{a^2 - x^2}} da \right] - \text{the so-called "Abel inversion"}
\]

Now the refractivity \( n \) is retrieved as the function of refractive radius \( x \) and can be readily converted to the function of radius \( r = x / n(x) \) (\( r \) is the distance from the center of curvature of the refractivity).
Deriving Pressure Temperature Humidity

• After converting GPS Doppler $\Rightarrow \alpha(a) \Rightarrow N(r)$ we have a profile of dry refractivity for altitudes from $\sim 150$ km down to the 240K level in the troposphere.

• Using ideal gas law,

$$\rho(z) = \frac{N(z)}{77.6R}$$

• We use the hydrostatic equation to derive a vertical profile of pressure versus altitude over this altitude interval.

$$P(z) = \int_{z_{\text{top}}} g \rho dz + P(z_{\text{top}})$$

• If we start high enough, $P(z_{\text{top}}) = 0$ with negligible error.

• Given $P(z)$ and $N(z)$, we can solve for $T(z)$.

• Below the 240k level we need additional information (usually temperature from a weather model) to obtain water vapor pressure and humidity.
Quality Control Checks

• During retrieval
  – Detection of L1 tracking errors
  – Detection of L2 tracking errors
    • Determination of Znid (L2 cutoff altitude)

• After retrieval, marked bad if
  – difmaxref > 0.5, maximal fractional Refractivity difference between retrieved N and N from climatology
  – Stdv > 1.5e-4 rad, standard deviation of bending angle difference (retrieved - climatology) between 60 and 80 km alt
  – Smean > 1e-4 rad, mean of bending angle difference (retrieved - climatology) between 60 and 80 km alt
  – Znid > 20 km
Over 775,000 Neutral Atmospheric Profiles

Processed data for cosmicrt

Currently ~60% of profiles delivered in < 3 hours

Nov 13, 2007  CCAR Seminar  Boulder, CO
RO Retrieval Error Estimates - Previous Results

- First estimates: Yunck et al. [1988] and Hardy et al. [1994]
- Detailed analysis: Kursinski et al. [1997]
  - ~0.2 % error in N at 20 km (horizontal along track variations)
  - ~1 % at surface and ~1 % at 40 km
- ROSE inter-agency (GFZ, JPL, UCAR) comparison [Ao et al., 2003; Wickert et al., 2004] and GFZ-UCAR [von Engeln, 2006]
- Experimental validation: Kuo et al. [2004]
  - Errors slightly larger than Kursinski et al. [1997]
- Experimental precision estimates: Hajj et al. [2004]
  - ~0.4 % fractional error (0.86K) between 5 and 15 km
Inversions of pairs of collocated COSMIC occultations with horizontal separation of ray TP < 10 km.

Upper panel: tropical soundings, 2006, DOY 154, 15:23 UTC, 22.7S, 102.9W.

Lower panel: polar soundings: 2006, DOY 157, 13:14 UTC, 72.6S, 83.5W.
• Only precision (not accuracy) can be estimated from collocated soundings
• Thermal noise (uncorrelated for any two occultations) affects precision and accuracy
• Horizontally inhomogeneous irregularities whose correlation radii are less than TP separation affect precision and accuracy
• Systematic ionospheric residual errors degrade accuracy
• Errors due to calibration of excess phase (POD and single-differencing) affect precision and accuracy
• Insufficient tracking depth (including loss of L2) degrades accuracy
• Different tracking depths for a pair of occultations degrades precision
Statistics of Collocated Soundings

- Setting Occultations with Firmware > v4.2
- Tangent Point separations < 10km
- Same QC for all retrievals
- One outlier removed
- Near real-time products used

**FM3-FM4 (2006.111-300)**

- All collocated pairs
- Pairs with similar straight-line tracking depths

Real-Time vs Post-Processed (CDAAC v2.0) Results

FM3-FM4 (2006.111-300)
The Effect of Open Loop Tracking (UCAR-ECMWF)

28Aug-22Sep 2006  30S<Lat<30N
(From Anthes et al., 2007)
Penetration of setting/rising soundings

(From Anthes et al., 2007)
Southern Hemisphere Forecast Improvements from COSMIC Data

control normalised ox01 minus oetyg
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
Date: 20060914 00UTC to 20061125 12UTC
100hPa Temperature
Confidence: 95%
Population: 100

Sean Healey, ECMWF
Impact study with COSMIC at NOAA

- 500 hPa geopotential heights anomaly correlation (the higher the better) as a function of forecast day for two different experiments:
  - PRYnc (assimilation of operational obs ),
  - PRYc (PRYnc + COSMIC)
- We assimilated around 1,000 COSMIC profiles per day
- Results with COSMIC are very encouraging
66-hr predictions of integrated cloud liquid with WRF model

With COSMIC

Without COSMIC

(Chen et al., 2007)
Using COSMIC for Hurricane Ernesto Prediction

With COSMIC

GOES Image

(Chen et al., 2007)
Comparison of AMSU Channel 9 brightness temperature with that derived from COSMICH GPS RO soundings.

This shows variations of Tb from different NOAA satellites.
Assuming straight-line propagation, $TEC = T-T_0$, where $L_1, L_2$ are phase measurements, $m$ and $f_1, f_2$ are GPS frequencies, Hz and $C = 40.3082$.

$T - T_0 \approx \frac{f_1^2 f_2^2 (L_1 - L_2)}{C(f_1^2 - f_2^2)}$.

Compute calibrated TEC below LEO:

$\tilde{T}(r_0) = T_{BC}(r_0) = T_{AC}(r_0) - T_{AB}(r_0)$

Assuming spherical symmetry and straight-line propagation:

$\tilde{T}(p) = 2 \int_p^{p_{top}} \frac{r N(r)}{\sqrt{r^2 - p^2}} dr$.  \hspace{1cm} (1)

Where $p$ is the distance from Earth’s center to the tangent point of straight-line, and is $p_{top} \equiv p_{leo}$ the radius of the LEO.

Above equation inverted by Schreiner et al. (1999) to obtain

$N(r) = -\frac{1}{\pi} \int_r^{r_{LEO}} \frac{dT}{dp} dp \sqrt{p^2 - r^2} dp$. \hspace{1cm} (2)
First collocated ionospheric profiles


183 pairs with tangent point separation < 5 km
Comparisons with ISR data
[Lei et al., submitted to JGR 2007]
Absolute TEC processing

- Correct Pseudorange for local multipath
- Fix cycle slips and outliers in carrier phase data
- Phase-to-pseudorange leveling of TEC
- GPS satellite DCB’s from CODE used
- LEO Differential code bias correction
Pseudorange multipath calibration

C003.2006.284.04.46.0016.G11.00 --- without multipath calibration

C003.2006.284.04.46.0016.G11.00 --- with multipath calibration

P2 - P1 pseudo-range
L1 - L2 phase levelled to P2 - P1
LEO Differential Code Bias estimation

- Weighted average of paired observations

- Assumption:
  \[ \text{TEC}_A \mathcal{M}(\theta_A) = \text{TEC}_B \mathcal{M}(\theta_B) \]

- Foelsche-Kirchengast (2002) geometric mapping function:
  \[ \mathcal{M}(\theta) = \frac{\sin \theta + \sqrt{\hat{r}^{-2} - \cos^2 \theta}}{1 + \hat{r}^{-1}} \]

\[
\text{DCB}_{\text{leo}} = \frac{\sum (\mathcal{M}(\theta_B) - \mathcal{M}(\theta_A)) (\hat{\text{TEC}}_A \mathcal{M}(\theta_A) - \hat{\text{TEC}}_B \mathcal{M}(\theta_B))}{\sum (\mathcal{M}(\theta_B) - \mathcal{M}(\theta_A))^2}
\]
An example of comparison of calibrated TEC between JPL and UCAR
There appears to be a 2-3 TECU bias between JPL and UCAR slant TEC
Negative TEC differences between UCAR and JPL shown above have been reduced after s/w change on date of previous slide
Similar data volumes between JPL and UCAR

From presentation by Brian Wilson, JPL
Scintillation Sensing with COSMIC

No scintillation
S4=0.005

Scintillation
S4=0.113

GPS/MET SNR data

Where is the source
Region of the scintillation?
Scintillation Index > 0.1 from COSMIC

S4 > 0.1 (6627 Occultations), COSMICRT, 2006.111–365

Local Time (hours)

Sun-fixed Latitude (deg)

-50

0

50

0.2

0.4

0.6

0.8

S4, Scintillation Index
Acknowledgments

• NSF
• Taiwan’s NSPO
• NASA/JPL, NOAA, USAF, ONR, NRL
• Broad Reach Engineering
References


