Data Processing Overview and Current Results from the UCAR COSMIC Data Analysis and Archival Center

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UCAR COSMIC Project Office
Outline

• COSMIC and CDAAC Overview
• POD Overview and Results
• RO Retrieval Details and Results
  – Neutral Atmosphere
  – Ionosphere
• Summary and Future Work
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 good health and providing data-up to 2200 soundings per day to NOAA
GPS Antennas on COSMIC Satellites

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

- High-gain occultation antennas for atmospheric profiling (50 Hz)
- GPS receiver developed by JPL and built by Broad Reach Eng.
- Antennas built by Haigh-Farr

COSMIC s/c

V_{leo}

Nadir
Data available to weather centers within < 180 minutes of on-orbit collection
CDAAC Processing Flow

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

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

**Real time Task Scheduling Software**

**LEO data**
- Level 0→level 1

**Fiducial data**
- Orbits and clocks

**Profiles**
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 (~50 ground stations) and Post-Processed (~100 stations) Soln's
- Dynamic Model: Gravity - EIGEN-1S, 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
  - 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 LEO Orbit And Clocks

Estimate 30-sec GPS Clocks OR use CODE/IGS clocks

Estimate Ground Station ZTD’s and Station Coordinates

Single/Double Difference Occultation Processing

Excess Phase Data
### COSMIC Post-Processed External Overlaps:
Stochastic Parameters: Every 12 min, Larger a priori errors

#### UCAR - NCTU  2006.216-218  FM1-6

<table>
<thead>
<tr>
<th></th>
<th>Radial</th>
<th>Along-Track</th>
<th>Cross-Track</th>
<th>3-D</th>
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<tr>
<td><strong>Mean [cm]</strong></td>
<td>1.2 (0.01)</td>
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<td>1.1 (0.00)</td>
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<tr>
<td>(Vel: mm/s)</td>
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<tr>
<td><strong>STD [cm]</strong></td>
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<td>10.4 (0.14)</td>
<td>10.7 (0.18)</td>
<td>18.1 (0.26)</td>
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<td>(Vel: mm/s)</td>
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#### UCAR - GFZ  2006.216-218  FM1-6

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<th>3-D</th>
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<td>8.4 (0.00)</td>
<td>-</td>
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<tr>
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<td>10.7 (0.15)</td>
<td>14.3 (0.12)</td>
<td>13.2 (0.12)</td>
<td>22.4 (0.22)</td>
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<td>(Vel: mm/s)</td>
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• External Orbit Overlaps with initial orbits from Univ. of Texas-CSR for FM1-3 on 2006.216-217 (courtesy Rick Pastor). Some orbits show mean cross-track and along-track differences (upto 50 cm). Under investigation

• External Orbit Overlaps with JPL orbits for FM1-6 on 2006.216-218 (courtesy Da Kuang). Some orbits show mean along track differences (~50cm). Under investigation

• CDAAC Internal Orbit Overlaps for 2006.216-218 (27-hr arcs)
  – Average: ~9 cm (~0.1 mm/s) 3D RMS for 12 overlaps
Current 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

- External overlap with NCTU post-processed orbit (courtesy of Cheinway Hwang)
  - ~ 20 cm 3D RMS

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<th>cross-track</th>
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<tbody>
<tr>
<td>mean</td>
<td>-0.032900</td>
<td>0.029426</td>
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<td>stdev</td>
<td>0.113286</td>
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<td>rms</td>
<td>0.117965</td>
<td>0.128087</td>
<td>0.093761</td>
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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
• 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
• Reference link data used to provide precise time tags of occulting link data
• 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 (0.2 mm/s) 3D RMS

• Significant error sources
  – Attitude errors
  – Phase center offsets and variations
  – Local spacecraft multipath
  – Changing center of mass location
  – Dynamic modeling

• Data gaps and latency will improve with time
Neutral Atmosphere Results
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

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
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

- Noise in raw signals causes the phase of the RO signals to be taken out of the space restricted under the assumption of spherically symmetric refractivity.
- This causes the bending angle, calculated from the Doppler under the spherically symmetric assumption, to become a multi-valued function of the impact parameter.
- 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
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.
Reconstruction of L1 bending angle by all radio-holographic methods for GPS/MET occultation in tropics.

The disagreement between radio-holographic methods is much smaller than between any of them and the Doppler method.
• 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
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
     \[ \left( \langle f_{L1}^{Dop} \rangle - c \cdot \langle f_{L2}^{Dop} \rangle \right) > 1 \text{ Hz} \]
  - 2) Fluctuations
     \[ \left( f_{L2}^{Dop} - \langle f_{L2}^{Dop} \rangle \right) > 6 \text{ Hz} \]
- Ionospheric calibration below Znid is based on an extrapolation of the difference \( \alpha_{L1} - \alpha_{L2} \) from last 3 seconds of data above Znid

\[ \alpha_{\text{iono-free}} = \alpha_{L1} + C \langle \alpha_{L1} - \alpha_{L2} \rangle \]

\( \langle \rangle \) denotes mean over last 3 sec
Atmospheric bending compared to observation noise

The main source of noise in the neutral atmosphere is the residual noise after the ionospheric calibration (induced by small-scale ionospheric irregularities).

The magnitude of the ionospheric noise typically is in the range $10^{-6}$-$10^{-5}$ rad, but for certain occultations can be as large as $10^{-4}$ rad.

![Diagram showing atmospheric bending compared to observation noise](image)

- **Quiet ionosphere**: $70 \div 75 km$
- **Disturbed ionosphere**: $50 \div 55 km$
- **Very disturbed ionosphere**: $30 \div 35 km$

- **Noise**: $10^{-6} \text{ rad}$
- **Max. atmos. bending**: $2 \div 3 \cdot 10^{-2} \text{ rad}$
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.

\[ \alpha_{opt} = w\alpha_{obs} + (1 - w)\alpha_{clm} \quad \text{where} \quad w = \frac{\sigma_{clm}^2}{\sigma_{clm}^2 + \sigma_{obs}^2} \]

The weighting function is calculated individually for each occultation.
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 400,000 Neutral Atmospheric Profiles

Processed data for cosmicrt

Currently \(~60\%\) of profiles delivered in \(< 3\) hours
Vertical profiles of “dry” temperature (black and red lines) from two independent receivers on separate COSMIC satellites (FM-1 and FM-4) at 00:07 UTC April 23, 2006, eight days after launch. The satellites were about 5 seconds apart, which corresponds to a distance separation at the tangent point of about 1.5 km. The latitude and longitude of the soundings are 20.4°S and 95.4°W.
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)**

![Graph showing number of occultation pairs vs MSL altitude (km) for FM3-FM4 (2006.111-300).](image)

- **ALL Collocated pairs**
- **Pairs with similar straight-line tracking depths**

The Effect of Open Loop Tracking

CHAMP
0% penetration 100%

COSMIC
0% penetration 100%

mean N, rms N (%)
Penetration of setting/rising soundings

- high latitude, rising
- tropical, rising
- high latitude, setting
- tropical, setting
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
Using COSMIC for Hurricane Ernesto Prediction

With COSMIC

Without COSMIC

Results from Hui Liu, NCAR
Using COSMIC for Hurricane Ernesto Prediction

With COSMIC

GOES Image

GOES Image from Tim Schmitt, SSEC
Ionosphere and Space Weather
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
Comparison of Calibrated Slant TEC Measurements for June 26, 2006

- 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
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:

\[
\tilde{T}(p) = 2 \int_p^{p_{top}} \frac{r N(r)}{\sqrt{r^2 - p^2}} \, dr.
\]  

(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

\[
N(r) = -\frac{1}{\pi} \int_r^{r_{LEO}} \frac{d\tilde{T}}{dp} \sqrt{p^2 - r^2} \, dp.
\]  

(2)
First collocated ionospheric profiles

Comparisons with ISR data
[Lei et al., submitted to JGR 2007]
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

$S_4 > 0.1$ (6627 Occultations), COSMICRT, 2006.111-365

[Graph showing the distribution of scintillation index across different local times and sun-fixed latitudes.]
Future Work

• Perform additional orbit overlap differences with other centers and understand differences
• Improve dynamic modeling (gravity field and non-conservative forces)
• Tune stochastic velocity pulses
• Apply COSMIC POD antenna PCV’s
• Use both COSMIC POD antennas simultaneously
• Investigate ways to mitigate spacecraft multipath
• Better understand errors related to single/double-difference processing
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- Broad Reach Engineering
Some References

R. A. Anthes\(^1\), P. A. Bernhardt\(^2\), Y. Chen\(^3\), L. Cucurull\(^1,4\), K. F. Dymond\(^2\), D. Ector\(^1\), S. B. Healy \(^5\), S.-P. Ho\(^1,3\), D. C. Hunt\(^1\), Y.-H. Kuo\(^1,\ast\), H. Liu\(^3\), K. Manning\(^3\), C. McCormick\(^6\), T. K. Meehan\(^7\), W. J. Randel\(^3\), C. Rocken\(^1\), W. S. Schreiner\(^1\), S. V. Sokolovskiy\(^1\), S. Syndergaard\(^1\), D. C. Thompson\(^8\), K. E. Trenberth\(^3\), T.-K. Wee\(^1\), N. L. Yen\(^9\), and Z. Zeng (2007) The COSMIC/FORMOSAT-3 Mission: Early Results, submitted to BAMS


