FORMOSAT-3/COSMIC ionospheric data processing and availability for data assimilation systems

Stig Syndergaard

UCAR COSMIC Project Office

COSMIC/CDAAC:
Karl Hudnut  Doug Hunt  Bill Kuo  Chris Rocken  Bill Schreiner
Maggie Sleziak  Sergey Sokolovskiy  Tae-Kwon Wee  Zhen Zeng

IUGG XXIV General Assembly, Perugia, Italy, July 2–13, 2007
COSMIC – a six satellite constellation

- FORMOSAT-3/COSMIC is a joint Taiwan-US mission
- Formosa satellite mission #3 in Taiwan
- Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) in US
- Launched April 15, 2006, from Vandenberg AFB
• All six satellites stacked and launched on a Minotaur rocket

• Initial orbit altitude $\sim 500$ km; inclination $\sim 72^\circ$

• Currently spacecraft are being maneuvered into six different orbital planes for optimal global coverage (at $\sim 800$ km altitude)

• Satellites are providing a large amount of high-quality data

• COSMIC data were officially released to the public on July 28, 2006
All six satellites in the same orbit flying close to each other
• Four satellites (FM2, FM4, FM5, FM6) have reached their final orbit

• By the end of 2007, all satellites will be at ~800 km in final orbits separated by 30°
GPS receiver (GOX): \{ TEC & S_4 scintillation index along links to GPS satellites \\
Ionospheric radio occultations (profiles) & scintillations \}

Tiny Ionospheric Photometer (TIP): Ultra-violet emission from ionosphere

Tri-Band Beacon (TBB): TEC & scintillations on satellite-to-ground links
Total Electron Content data

GPS-COSMIC trans-ionospheric radio links for a period of 100 minutes on June 29, 2007

- COSMIC TEC data are potentially of great value for data assimilation in space weather models
Absolute TEC processing

• A four-step process involving:
  
  – Pseudo-range local multipath calibration
  
  – Correction for phase cycle-slips & outliers (basically following Blewitt, 1990)
  
  – Phase-to-pseudorange leveling
  
  – Differential code bias estimation and calibration
Pseudo-range local multipath

Depends on:

- Off boresight angle to GPS satellites (need orbits and attitude data)

- Solar array drive angle (solar panels constantly move back and forth)

Pseudo-range multipath data collected over months or years for calibration
Pseudo-range local multipath calibration

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

P2 - P1 pseudo-range
L1 - L2 phase levelled to P2 - P1

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

- DCB due to receiver hardware delay difference between P1 and P2
- Weighted average of paired observations
- Assumption:
  \[ TE_{\text{CA}} \mathcal{M}(\theta_A) = TE_{\text{CB}} \mathcal{M}(\theta_B) \]
- Foelsche-Kirchengast (2002) geometric mapping function:
  \[ \mathcal{M}(\theta) = \frac{\sin \theta + \sqrt{\tilde{r}^{-2} - \cos^2 \theta}}{1 + \tilde{r}^{-1}} \]

\[
DCB = \frac{\sum [\mathcal{M}(\theta_B) - \mathcal{M}(\theta_A)][\widehat{TE}_{\text{CA}} \mathcal{M}(\theta_A) - \widehat{TE}_{\text{CB}} \mathcal{M}(\theta_B)]}{\sum [\mathcal{M}(\theta_B) - \mathcal{M}(\theta_A)]^2}
\]
LEO Differential Code Bias estimation

- DCB due to receiver hardware delay difference between P1 and P2
- Weighted average of paired observations
- Assumption:
  \[ \text{TEC}_A \cdot M(\theta_A) = \text{TEC}_B \cdot M(\theta_B) \]
- Foelsche-Kirchengast (2002) geometric mapping function:
  \[ M(\theta) = \frac{\sin \theta + \sqrt{\tilde{r}^{-2} - \cos^2 \theta}}{1 + \tilde{r}^{-1}} \]

\[
DCB = \frac{\sum [M(\theta_B) - M(\theta_A)][\widehat{\text{TEC}}_A \cdot M(\theta_A) - \widehat{\text{TEC}}_B \cdot M(\theta_B)]}{\sum [M(\theta_B) - M(\theta_A)]^2}
\]
• DCB due to receiver hardware delay difference between P1 and P2

• 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:

\[ \mathcal{M}(\theta) = \frac{\sin \theta + \sqrt{\tilde{r}^{-2} - \cos^2 \theta}}{1 + \tilde{r}^{-1}} \]

\[ \text{DCB} = \frac{\sum [\mathcal{M}(\theta_B) - \mathcal{M}(\theta_A)][\widehat{\text{TEC}}_A \mathcal{M}(\theta_A) - \widehat{\text{TEC}}_B \mathcal{M}(\theta_B)]}{\sum [\mathcal{M}(\theta_B) - \mathcal{M}(\theta_A)]^2} \]
Solving for two antennas simultaneously

- DCB due to receiver hardware delay difference between P1 and P2
- 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:
  \[ \mathcal{M}(\theta) = \frac{\sin \theta + \sqrt{\tilde{r}^{-2} - \cos^2 \theta}}{1 + \tilde{r}^{-1}} \]

\[ \text{DCB}_B = \frac{\sum \mathcal{M}(\theta_B)[(\text{DCB}_A + \hat{\text{TEC}}_A)\mathcal{M}(\theta_A) - \hat{\text{TEC}}_B\mathcal{M}(\theta_B)]}{\sum[\mathcal{M}(\theta_B)]^2} \]
Daily averages — internal uncertainty estimate ≈ 0.2 ns (~0.57 TECU)

Day-to-day variability normally less than 1 TECU

Correlation between DCBs and SNR anomalies — not understood (e.g., FM5 Ant 00 @ yr = 2007.4)
Absolute TEC statistics

maximum elevation angle $> 45^\circ$, latitude $> 60^\circ$, $20 < $ local time $< 8$

- About 8% of arcs (red) have negative TEC at maximum elevation
- Statistics are indicative of accuracy and precision (a few TECU)
• Most data are downloaded within \( \sim 100 \) minutes of collection
• Transfer to CDAAC and processing usually takes 20–30 minutes
Tiny Ionospheric Photometer (TIP)

135.6-nm passes Sep 14, 2006 (FM1, FM3, FM6) 21:00 LT

Image provided by Clayton Coker, NRL
Data availability

- All data available in near real-time (http://www.cosmic.ucar.edu)
  - RINEX observation files (podObs)
  - Precise LEO orbits in SP3 format (leoOrb)
  - Receiver differential Code Biases (leoDcb)
  - Absolute TEC calibrated for DCBs (podTec)
  - Tiny Ionospheric Photometer (tipLv1) – remaining issues with timing and quality flag – radiances not yet calibrated