Ionosphere monitoring using NOAA’s CORS network

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National Geodetic Survey
National Oceanic and Atmospheric Administration

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Long Beach, CA
Topics of Discussion

- Geodetic need for Ionosphere
- Model/Equations
- Initial tests
- Full day solution
- Future directions
Geodetic need for ionosphere delays

• Frequency-dependent signals in GPS:
  – Ambiguities
  – Ionosphere
  – Multi-path (assumed zero initially)

• NOAA has developed an innovative new method for modeling absolute Ionosphere delays from ambiguous carrier phase data

• All data from NOAA’s CORS network

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Assumptions and model

- 2-D “condensed” TEC shell (epoch = pierce point)
- Focus on fast, accurate ionosphere delays; not on realistic 4-D electron distribution
- Mapping pierce points without loss of lock yields a track
- CORS yields about 20,000 tracks every day
Density of Electrons in Sat/Rcvr direction is TECS

Density of Electrons in direction normal to Ionosphere Shell is TECR

Normal to Ionosphere Shell

To GPS Satellite

Pierce Point

To GPS Receiver

Infinitesimally thin Ionosphere shell
• 5 (of ∞) possible TECS curves for track # 10,610
• Same shape, unknown bias
• 5 (of ∞) possible TECR curves for track # 10,610
• *Different* shapes!
Solving for biases with crossovers

• Solve:
  – 1 TECS bias per track

• Consider two tracks that pierce the ionosphere at the same place, at the same time (i.e. a “crossover”)
  – $\text{TECS}(\phi, \lambda, t, \text{track a}) \neq \text{TECS}(\phi, \lambda, t, \text{track b})$
  – $\text{TECR}(\phi, \lambda, t, \text{track a}) = \text{TECR}(\phi, \lambda, t, \text{track b})$
Using Crossovers

• By itself, one crossover has:
  – 1 condition (TECR equality)
  – 2 unknowns (TECS biases for 2 tracks)
  – Thus, unsolvable as is

• Need conditions $\geq$ unknowns

• Closed polygons is the solution
- 3 Tracks
- Crossovers A, B, C occur in sequential order
- Not as rare as it looks
- Forms a "closed polygon" of tracks
- *Uniquely* solvable in **absolute** TECS space
-4 Tracks (unknowns)
-5 Crossovers (conditions)
-Redundancy = Least Squares
Adjustment in *absolute* TECS space
Initial Tests

• Small “tracknets” of 10-12 tracks formed
• Proof-of-concept
• Absolute delays converted to double difference delays
• DD delays good to 0.1± 0.01 TECUs against “truth” (Ambiguity resolving software)
Full day solution

- Day 193 (July 12) of 2002
- 307 CORS stations
- 16,896 Crossovers (conditions)
- 8298 Tracks (unknowns)

Smith, D.A., Ionosphere from CORS, COSPAR 2004
Full day solution

• Unzip/read hundreds of RINEX.gz files
  – 2 hours
• Clean 11 Million data pts (cycle slips, etc)
  – 30 min
• Solve 8298 x 16896 sparse linear system
  – 30 seconds to get 8298 biases
  – 10 minutes to get $\sigma_{bias}$
Full day solution (cont)

• Post Fit Crossover stats (TECUs)
  – $-0.004 \pm 0.51$ (Min -3.7; Max +4.0)

• A-posteriori $\sigma_{bias}$ estimates:
  – $\text{Ave}(\sigma_{bias}) = \pm 1.1$ TECU (Min 0.22, Max 10.7)
Full day solution Animations

• Animation without tracks
  – gif
  – avi

• Animation with tracks
  – gif
  – avi
TECR (Phase only, Poly RCR (1/1/1) y2002 d193 Tension=0.1 t=00000 w/Raw Tracks shown)
Full day solution (cont)

- Average a-posteriori $\sigma_{\text{bias}}$ of ±1.1 TECU reasonable, but larger than hoped for
- Sub-TECU crossover residuals show tight “locking” or consistency of tracknet
- Overall noise in grids needs improvement
- General conclusion:
  - “Promising” but not by any means “done”
  - Initial analysis indicates near-horizon crossovers are the primary error source (TECS=TECR/$\cos z$’ unreliable)

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"Large" $z'$ makes the TECR equality questionable
TECS₁ x cos(z₁') = TECR₁ = TECR₂ = TECS₂ x cos(z₂')

“Small” z’ makes the TECR equality more reliable
Latest Results

- Ohio State University compared various Ionosphere estimates at Ohio CORS stations
- Crossovers restricted to 40 degrees above the horizon
  - Avoids erroneous biases from low-elevation crossovers
  - Reduces number of tracks immediately solvable from tracknets (unsolved tracks need interpolation from nearby solved tracks)

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Report for NOAA/NGS

On:

Accuracy analysis of various NGS ionosphere estimation models

Dorota Grejner-Brzezinska, Pawel Wielgosz, Israel Kashani

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Email: kashani.1@osu.edu
Email: wielgosz.1@osu.edu
This model

NOAA’s “Magic” model
Summary and Conclusions

• With certain assumptions, a model for the ionosphere can be computed as an entire network
  – to $\sim 1$ TECU (absolute)
  – to $\sim 0.3 \pm 0.06$ TECU (5 cm $\pm$ 1 mm on L1) agreement with Double Difference estimates, subject to cycle-slip fixing

• Interpolation can yield $\pm 5$ cm (L1) biases from nearby tracks
Summary and Conclusions (cont)

• Further sensitivity studies:
  – Removing near-horizon crossovers (nearly done)
  – Shell height
  – CORS thinning

• Independent tests forthcoming:
  – Against other ionosphere models
  – In ambiguity resolving software

• Production:
  – Daily solutions expected to begin in Fall 2004
This is an RINEX file, not strictly RINEX.
The difference is that an I1 variable, representing
the computed ionosphere delay on L1, in cycles of L1,
has been introduced. This value should generally
always be positive.
I1 was computed by Eric Smith, NOAA/NGS with the following
parameters (see D. Smith for details):
Year = 2004 Day of Year = 007
_height (km) = 0.000
Track Cleaning Criteria Index : 001
Crossover Spacing Criteria Index : 001
Track Formation Criteria Index : 009
LSA Weighting Scheme Index : 004
Flag for post-LSA interpolation : 000

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Contact Information

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Questions?

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Extra Slides

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CORS Network

Currently 400+ 24/7 receivers

- Dual frequency, carrier-phase
- Multi-agency
- Administered by NGS
- All 50 states, Central America, others
- Ideally suited to serve as an ionosphere monitoring network for geodetic applications in the USA

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Pierce Points and Tracks

- A pierce point occurs at ionosphere shell for each data epoch
- Mapping pierce points without loss of lock yields a track
- CORS yields about 20,000 tracks every day
TECS and TECR

- TECS is the TEC value seen in the satellite-receiver direction
- TECR is the vertical TEC value at the shell
  - $\text{TECS} = \text{TECR} / \cos z'$
    - Questionable usefulness at low elevation angles

Smith, D.A., Ionosphere from CORS, COSPAR 2004
\[ i R_k = b_k + i r + c(i \delta t) + i T + i I_k (+i m_k) = \lambda_k \Phi_k^{\text{RINEX}} \]  
(biased range, m, epoch "i", freq "k")

\[ I_k = -\frac{40.3}{f_k^2} \text{TECS} \quad \text{(m)} \]

\[ \therefore \lambda_1 \Phi_1^{\text{RINEX}} - \lambda_2 \Phi_2^{\text{RINEX}} = (b_1 - b_2) + (i_1 - i_2) \]

\[ \therefore \text{TECS} = \left( \frac{1}{40.3} \right) \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right)^{-1} \left[ \lambda_1 \Phi_1^{\text{RINEX}} - \lambda_2 \Phi_2^{\text{RINEX}} \right] \]

\[ - \left( \frac{1}{40.3} \right) \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right)^{-1} (b_1 - b_2) \]

\[ \therefore \text{i,j \Delta TECS} = \text{iTECS} - \text{jTECS} \]

\[ = \left( \frac{1}{40.3} \right) \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right)^{-1} \left( \lambda_1 \Phi_1^{\text{RINEX}} - \lambda_2 \Phi_2^{\text{RINEX}} \right) \]
Implications of Equations

• Knowing $\Delta$TECS:
  – Shape of “TECS vs time” curve known
  – Absolute level unknown

• Single, unknown bias per “track”
\[ \Delta TECR \text{ vs } \Delta TECS \]

\[ iTECS = iTECR / \cos^i z' \]

\[ i,j \Delta TECR = jTECR - iTECR \]

\[ \therefore \quad i,j \Delta TECR = i,j \Delta TECS \cos^j z' + iTECS(\cos^j z' - \cos^i z') \]
Implications

• Epoch-dependent cos z' in TECR:
  – Shape of “TECR vs time” curve is unknown
  – Absolute level unknown
Closed Polygons

• Altimetry or Leveling ($\Delta H$ & H-equality):
  – # conditions = # vertices – 1

• Ionosphere ($\Delta$TECS & TECR-equality)
  – # conditions = # vertices

• Any time that a closed polygon is formed on the ionosphere “shell” we have:
  – # Conditions = # Unknowns
## Polygon Crossover Equations

\[
\begin{bmatrix}
A \Delta TECS \cos A z' - A \Delta TECS \cos A z' \\
B \Delta TECS \cos B z' - B \Delta TECS \cos B z' \\
C \Delta TECS \cos C z' - C \Delta TECS \cos C z'
\end{bmatrix}
\]

\[
= \begin{bmatrix}
- \cos A z' & 0 & + \cos A z' \\
- \cos B z' & + \cos B z' & 0 \\
0 & - \cos C z' & + \cos C z'
\end{bmatrix}
\begin{bmatrix}
b_1 \\
b_2 \\
b_3
\end{bmatrix}
\]

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Polygon Crossover Equations

- The existence of the cos z' values on the RHS allows for matrix inversion
  - (as opposed to +1,0 and -1 for altimetry)
- Solvability
- Can we have redundancy?
  - YES
A good fit between P-R and carrier phase
A poor fit between P-R and carrier phase
Initial Tests

- Parameters:
  - Shell height = 300 km
  - Crossover definition: 0.1° x 0.1° x 1 min
  - Cut-off angle: 10° (for data and crossovers)
Initial Tests
(all contain the 4 base tracks)

- **Solution 1** (smallest tracknet possible containing the 4 base tracks)
  - 8 tracks, No polygons, PR-fit 6 of 8 tracks
- **Solution 2**
  - 10 tracks, 2 polygons, PR-fit 7 of 10 tracks
- **Solution 3**
  - 10 tracks, 2 polygons, no PR-fitting
- **Solution 4**
  - 10 tracks, 2 polygons, PR-fit 1 of 10 tracks
**Formal $\sigma_{bias}$ estimates for first tracknet tests (in TECU)**

<table>
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<th>Track #</th>
<th>Soln 1 (PR fit to 6 of 8; no polygons)</th>
<th>Soln 2 (PR fit to 7 of 10; 2 polygons)</th>
<th>Soln 3 (No PR fit; 2 polygons)</th>
<th>Soln 4 (PR fit to 1 of 10; 2 polygons)</th>
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Smith, D.A., Ionosphere from CORS, COSPAR 2004
Initial Tests (cont)

• Individual ionosphere delays for each SV/CORS combo were estimated:
  – $I_{4300}(SV1/GODE)$, $I_{4303}(SV2/GODE)$, $I_{9484}(SV1/RED1)$, $I_{9487}(SV2/RED1)$ all estimated individually (as well as for all other tracks in the tracknet)

• Double Difference delays were then computed:
  – $I_{DD}=(I_{4300}-I_{9484})-(I_{4303}-I_{9487})$ computed and compared to independent estimates from NGS ambiguity resolving software

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First tracknet tests

• Pseudo-range fitting tends to bias the tracknet

• Better fit to Double Difference estimated ionosphere by using just polygons and no P-R fitting
Full day solution (cont)

- Interpolation from tracks to grids and/or other tracks:
  - Track-to-grid-to-Track
    - Useful for grid-distributed Ionosphere model and animations
    - 0.00 ± 0.38 TECU (±6 cm on L1)
  - Track-to-Track
    - Useful for RINEX-distributed Ionosphere model
    - 0.00 ± 0.25 TECU (±5 cm on L1)

- Full day solution was gridded and animated
Example 2. 17:00-18:00 UT (day-time)

The “truth” DD ionospheric delays are presented in figure 14 with the corresponding satellite elevation map in figure 15. Figures 16–25 represents the derived DD ionosphere form each method and the difference from the “truth” (in pairs). The mean and standard deviation of the ionospheric residuals from the “truth” are shown in Table 2.

Fig. 14 “Truth” DD iono (day-time)  
Fig. 15 Satellite elevations
Smoothed Pseudorange Estimates

Fig. 16 P4 DD iono (day-time)

Fig. 17 P4 DD iono differences from the “truth” (day-time)

Fig. 18 GIM DD iono (day-time)

Fig. 19 GIM DD iono differences from the “truth” (day-time)

OSU’s MPGPS method
2.10 OBSERVATION DATA G (GPS) RINEX VERSION / TYPE
2000Jul20 CORS-ADM Account 20040106 05:10:00 UTC/CCIR / RUN BY / DATE

CORS/NGS/NOAA OAR/FSL OBSERVER / AGENCY
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3328186803 TRIM14532.00 ANT # / TYPE
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0.0600 0.0600 0.0600 ANTENNA: DELTA H/E/N
1 2 3 WAVELENGTH FACT L1/L2
8 C1 L1 L2 P1 F2 D1 D2 T1 # / TYPES OF OBSERV
30.0000 INTERVAL

This is an RINEX file, not strictly RINEX.

The difference is that an L1 variable, representing the computed ionospheric delay on L1, in cycles of L1, has been introduced. This value should generally always be positive.

It was computed by Eric Smith, NOAA/NGS with the following parameters:

Year = 2004 Day of Year = 007
Height (km) = 0120
Track Cleaning Criteria Index : 001
Crossover Spacing Criteria Index : 001
Array Formation Criteria Index : 009
LSA Weighting Scheme Index : 004
Flag for post-LSA interpolation : 000

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Five IGS Global Models

This model