Using GPS to Observe Crustal Loading Signals in the TibXS Region

- Analyze dNEU GPS position time series residuals
  - use latest IGS solutions for a global set of 706 stations
  - compare with 28 stations in Tibet-Xinjiang-Siberia region

- Quantify error budget using models for crustal loads

- Discuss sources for unmodeled contributions
  - especially non-load annual effects

Jim Ray, NOAA/National Geodetic Survey
Xavier Collilieux & Paul Rebischung, IGN/LAREG
Tonie van Dam, University of Luxembourg
Zuheir Altamimi, IGN/LAREG

4th International TibXS Workshop, YiNing, China, 28 July - 1 August 2013
Modeled Vertical Loading Deformation Signals

- Crustal loading is large across central Asia for all major fluid sources
- Height variations can reach 1 cm – at annual periods, mostly
- Signatures should be clear in IGS station position time series

(All plots from P. Gegout et al., EGU 2009)
• 28 stations in TibXS region with >100 weeks of IGS Repro1 results
Data Sets to Compare

• GPS station position time series from IGS 1st reprocessing
  – analysis consistent with IERS 2010 Conventions (more or less)
  – combined weekly frame results from up to 11 Analysis Centers
  – 706 globally distributed stations, each with >100 weeks
  – data from 1998.00 to 2011.29
  – Helmert alignment (no scale) w.r.t. cumulative solution uses a well-distributed subnetwork to minimize aliasing of local load signals
  – care taken to find position/velocity discontinuities

• Mass load displacement time series for the same stations
  – 6-hr NCEP atmosphere
  – 12-hr ECCO non-tidal ocean
  – monthly GLDAS surface ice/water, cubic detrended to remove model drift
  – all computed in CF frame
  – sum is linearly detrended & averaged to middle of each GPS week
  – data from 1998.0 to 2011.0

• Study dN, dE, dU non-linear weekly residuals (1998.0 – 2011.0)
  – bias errors not considered here!
GPS dUp Time Series in TibXS Region (1/3)

Red points = raw GPS
Turquoise = (GPS – Loads)
GPS dUp Time Series in TibXS Region (2/3)

Red points = raw GPS
Turquoise = (GPS – Loads)
GPS dUp Time Series in TibXS Region (3/3)

Red points = raw GPS
Turquoise = (GPS – Loads)
(GPS – Load) Comparison – WRMS Statistics

<table>
<thead>
<tr>
<th>WRMS Changes</th>
<th>median GPS WRMS (mm)</th>
<th>median Load RMS (mm)</th>
<th>median (GPS – Load) WRMS (mm)</th>
<th>median WRMS reduction (%)</th>
<th>% of stations with lower WRMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Network (706 stations)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dN</td>
<td>1.4</td>
<td>0.5</td>
<td>1.3</td>
<td>3.8</td>
<td>72.0</td>
</tr>
<tr>
<td>dE</td>
<td>1.45</td>
<td>0.4</td>
<td>1.4</td>
<td>1.6</td>
<td>62.9</td>
</tr>
<tr>
<td>dU</td>
<td>4.6</td>
<td>2.6</td>
<td>3.8</td>
<td>15.2</td>
<td>87.4</td>
</tr>
</tbody>
</table>

- Load corrections are globally effective to reduce WRMS
  - most stations show reduced WRMS scatter after load corrections
  - especially for dU
  - but most residual variation still remains after load corrections
  - especially for dN & dE
### (GPS – Load) Comparison – WRMS Statistics

#### WRMS Changes

<table>
<thead>
<tr>
<th></th>
<th>median GPS WRMS (mm)</th>
<th>median Load RMS (mm)</th>
<th>median (GPS – Load) WRMS (mm)</th>
<th>median WRMS reduction (%)</th>
<th>% of stations with lower WRMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global Network (706 stations)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dN</td>
<td>1.4</td>
<td>0.5</td>
<td>1.3</td>
<td>3.8</td>
<td>72.0</td>
</tr>
<tr>
<td>dE</td>
<td>1.45</td>
<td>0.4</td>
<td>1.4</td>
<td>1.6</td>
<td>62.9</td>
</tr>
<tr>
<td>dU</td>
<td>4.6</td>
<td>2.6</td>
<td>3.8</td>
<td>15.2</td>
<td>87.4</td>
</tr>
<tr>
<td><strong>TibXS Network (28 stations)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dN</td>
<td>1.9</td>
<td>0.8</td>
<td>1.6</td>
<td>10.9</td>
<td>78.6</td>
</tr>
<tr>
<td>dE</td>
<td>1.5</td>
<td>0.6</td>
<td>1.5</td>
<td>2.4</td>
<td>57.1</td>
</tr>
<tr>
<td>dU</td>
<td>6.75</td>
<td>4.4</td>
<td>4.5</td>
<td>33.6</td>
<td>100.0</td>
</tr>
</tbody>
</table>

- **Load corrections are globally effective to reduce WRMS**
  - esp for dU – but most residual variation remains, esp for dN & dE

- **Loads are larger & therefore corrections more effective in TibXS**
  - esp for dU – but smaller % improved for dE
### Annual Amplitude Changes

<table>
<thead>
<tr>
<th></th>
<th>median GPS annual (mm)</th>
<th>median Load annual (mm)</th>
<th>median (GPS – Load) annual (mm)</th>
<th>median annual (cor/no corr) ratio</th>
<th>% of stations with lower annual amp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Network (706 stations)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dN</td>
<td>0.9</td>
<td>0.45</td>
<td>0.65</td>
<td>0.78</td>
<td>70.7</td>
</tr>
<tr>
<td>dE</td>
<td>0.8</td>
<td>0.4</td>
<td>0.7</td>
<td>0.92</td>
<td>59.3</td>
</tr>
<tr>
<td>dU</td>
<td>3.6</td>
<td>2.4</td>
<td>1.7</td>
<td>0.52</td>
<td>87.1</td>
</tr>
</tbody>
</table>

- **Load corrections similarly effective globally to reduce annual amps**
  - most stations show reduced annual signals after load corrections
  - dU amplitude reduced by half
  - but most annual variation remains for dN & dE
### (GPS – Load) Comparison – Annual Amp Statistics

#### Annual Amplitude Changes

<table>
<thead>
<tr>
<th></th>
<th>Global Network (706 stations)</th>
<th>TibXS Network (28 stations)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>median GPS annual (mm)</td>
<td>median Load annual (mm)</td>
</tr>
<tr>
<td>dN</td>
<td>0.9</td>
<td>0.45</td>
</tr>
<tr>
<td>dE</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>dU</td>
<td>3.6</td>
<td>2.4</td>
</tr>
</tbody>
</table>

- Load corrections similarly effective globally to reduce annual amps
  - dU amp reduced by half – but most annual variation remains for dN & dE

- Loads are larger & therefore corrections more effective in TibXS
  - esp for dU – but less slightly effective for dE
A Generalized Model of Position WRMS

\[ WRMS^2 = WRMS_o^2 + (A_i \times \text{AnnAmp}_i)^2 + WRMS_i^2 \]

- **WRMS}_o^2 = \text{globally averaged error floor, including:}**
  - basement electronic & thermal noise
  - *a priori* modeling errors (tides & basic geophysics)
  - other large-scale random analysis errors (e.g., orbits)

- **AnnAmp}_i = \text{mean annual amplitude}**
  - \[ A_i = 1 / \sqrt{2} = 0.7071 \text{ or } A_i^2 = 0.5 \rightarrow \text{for stationary sinusoid} \]
  - \[ A_i^2 > 0.5 \rightarrow \text{for non-stationary seasonal variations} \]
  - includes loads + all other annual effects (e.g., technique errors)

- **WRMS}_i^2 = \text{local site-specific errors (non-annual part only), e.g.:}**
  - multipath + monument noise
  - antenna mis-calibration + GNSS hardware effects
  - thermal expansion of antenna installation & bedrock
  - tropo mis-modeling + orbit errors
  - non-annual loads (& residual load model errors, if corrected)
  - inter-AC analysis & station usage differences + RF realization
Model of Position WRMS – Global Error Floor
add variable amounts of annual variation: \( \text{AnnAmp}_i / \sqrt{2} \)
add variable amounts of local variations: \( \text{WRMS}_i \)
Load corrections have no impact on dN noise floor assessment
- local site & non-load errors overwhelmingly dominate
IGS Results – dE With/Without Loads

- Load corrections have no impact on dE noise floor assessment
  - local site & non-load errors overwhelmingly dominate
IGS Results – dU With/Without Loads

- Load corrections move results much closer to dU noise floor
  - but local site & non-load errors still dominate
IGS Results – dU With/Without Loads

- “Best” 2 stations in dU (WRMS = 2.2 mm) are:
  - LAGO (S. coast, Portugal) & GLPS (island, Pacific Ocean)
  - loading effects moderated by nearby oceans due to inverted barometer
Evaluation of Error Sources: Error Floor

\[ \text{WRMS}^2 = \text{WRMS}_o^2 + (A_i \times \text{AnnAmp}_i)^2 + \text{WRMS}_i^2 \]

- \( \text{WRMS}_o^2 = \) globally averaged error floor, including:
  - basement electronic & thermal (receiver) noise
  - \textit{a priori} modeling errors (tides & basic geophysics)
  - other large-scale random analysis errors (e.g., orbits)

- Estimate thermal noise from differences between station pairs with shared antennas (19 globally)

- Infer modeling + analysis error floors by quadratic differencing

<table>
<thead>
<tr>
<th>Decomposition of Weekly WRMS Error Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal noise (via 19 global pairs with shared antennas)</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>dN</td>
</tr>
<tr>
<td>dE</td>
</tr>
<tr>
<td>dU</td>
</tr>
</tbody>
</table>
Evaluation of Error Sources: Annual Signals

\[ \text{WRMS}^2 = \text{WRMS}_o^2 + (A_i \times \text{AnnAmp}_i)^2 + \text{WRMS}_i^2 \]

- \( \text{AnnAmp}_i = \text{mean annual amplitude} \)
  - includes loads + all other annual effects (e.g., technique errors)
  - \( A_i^2 \approx 0.6 \) \( \to \) from empirical IGS results

- Most horizontal annual motions probably not caused by loads
  - technique errors are probably most important sources

- \( dU \) load modeling seems fairly reliable (see next slide)
  - but non-load & technique errors are also significant for \( dU \)

### Decomposition of Annual Signals (global medians)

<table>
<thead>
<tr>
<th></th>
<th>median load annual amp (mm)</th>
<th>median non-load annual amp (mm)</th>
<th>observed median GPS raw annual amp (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( dN )</td>
<td>0.45</td>
<td>0.65</td>
<td>0.9</td>
</tr>
<tr>
<td>( dE )</td>
<td>0.4</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>( dU )</td>
<td>2.4</td>
<td>1.7</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Effectiveness of dU Annual Load Models

- dU load corrections appear rather effective at annual periods
  - e.g., no scale defect seen
  - but residual non-load annual signals also clearly remain

- dN, dE load corrections have essentially no effect
  - non-load sources dominate annual signals

- Need to identify sources for non-load annual signals
  - see following slides

- But no doubt that model load must have some errors too
  - probably largest errors from land water & ice/snow hydrology
  - e.g., inter-annual hydrology variations (see next slide)
Some Inter-Annual Signals Possibly Mismodeled

- KIT3 (Kitab, Uzbekistan) & SELE (Almaty, Kazakhstan) both show significant inter-annual dU variations
  - load corrections partially effective
  - but inter-annual signals remain

- Both stations also sit in basins in mountainous regions
  - unmodeled water/snow load signals appear plausible
Non-load Annual Signals: 1. Draconitic Errors

- **Draconitic year** = 351.2 d
  - or frequency = 1.04 cpy
  - 1\textsuperscript{st} & 2\textsuperscript{nd} harmonics overlay seasonal signals

- **Strong spatial correlations in IGS position time series**
  - fit $(1.0 + 2.0 + 3.12 + 4.16)$ cpy
  - plot significant dU 4\textsuperscript{th} harmonics ($\phi$ clockwise from N wrt 2000)
  - very striking in most regions
  - also seen in dN distribution
  - esp coherent in Europe
  - Amiri-Simkooei (2013) found mean 1\textsuperscript{st} harmonic amps of: 1.4 (dN), 1.3 (dE), 2.8 (dU) mm

- **Implies orbit-related source**
  - also seen in all other products
Non-load Annual Signals: 2. Temperature Cycle

- **Thermal dU expansion of antenna monument structures**
  - \[ \Delta U (\text{mm}) \approx 0.015 \times \left( \frac{\text{Hgt}}{\text{m}} \right) \times \left( \frac{\Delta T}{\degree \text{C}} \right) \]
  - for \( \text{Hgt} = 3 \text{ m} \) + annual \( \Delta T = 30 \degree \text{C} \) \( \Rightarrow \) annual \( \Delta U (\text{mm}) = 1.35 \text{ mm} \)
  - so annual \( \Delta T \) cycle probably significant for most stations outside tropics

- **Thermal dU expansion of surrounding bedrock**
  - H. Yan et al. (GRL, 2009) predict max annual amps \( \sim 1.3 \text{ mm} \) in NE Asia

- **Horizontal tilting of antenna structures**
  - S. Bergstrand et al. (2013) measured diurnal tilting of \( \pm 1 \text{ mm} \) for shallow drill-braced monument
  - tilting for other types usually larger
  - probably explains most \( dN/dE \) annual signals for stations outside tropics
Non-load Annual Signals: 3. IERS Models

• Unmodeled ocean pole tide deformation
  – to account for centrifugal effect of polar motion variations on oceans
  – amps reach ~ 0.5, 0.5, 1.8 mm in dN, dE, dU, mostly near annual & Chandler (433 d) periods
  – IERS model in Conventions 2010, but not yet implemented

• Aliases of errors in subdaily EOP tide model
  – K1, P1, T2 lines alias to annual periods
  – coupling through resonant 12-hr GPS orbits leads to draconitic errors
  – magnitude of position effects not yet quantified

• Seasonal variations of low-degree geopotential terms
  – frame origin might shift by ~1 mm, mainly in Z component
  – WRMS orbit differences might reach few-mm level

• Unmodeled S1/S2 atmosphere pressure loading
  – dU amps reach 1.5 mm in tropics with 12/24 hr periods
  – but should mostly average out for daily data processing
Non-load Annual Signals: 4. Antenna-Related Effects

- **Local multipath errors**
  - especially due to near-field reflectors & environment changes
  - GPS ground tracks repeat with K1 (sidereal) period
  - can alias to GPS draconitic year (352 d) for daily processing

- **Snow, ice cover, rain on or near antennas**
  - can add annual signals to data quality & sky visibility
  - most serious for stations at higher latitudes

- **Antenna calibration errors**
  - similar alias effects possible, as with local multipath
Non-load Annual Signals: 5. Receiver Hardware

- Receiver artifacts sometimes seen
  - e.g., receiver changed: AOA Rogue SNR-8000 → Trimble 4000SSI on 2005-08-02
    - dU annual amp clearly increased after receiver swap
    - non-load annual amp also increased afterwards
    - no obvious impact for dN, dE

- Such effects can occur due to improved/degraded sky coverage, SNR change, etc

- While not unique, such receiver effects are not very common
Non-load Annual Signals: 6. Other Effects

- **Troposphere delay mismodeling**
  - due to errors in *a priori* dry zenith delay & dry/wet mapping functions
  - also errors in treatment of troposphere horizontal gradients
  - continuous progress being made
  - but ultimate solution of accurate, independent line-of-sight delays remains remote

- **Aliasing in long-term time series stacking**
  - local position variations (including load effects) can alias into Helmert frame parameters to derive long-term positions & residuals
  - methods used to minimize effects but residual errors still not eliminated

- **Processing differences among Analysis Centers (ACs)**
  - clear differences between ACs are sometimes seen for the same stations
  - effects include different draconitics but also more random variations
  - causes are unknown & probably diverse
### Summary of Weekly GPS Position Errors

**IGS Error Budget for Weekly Integrations**

<table>
<thead>
<tr>
<th></th>
<th>WRMS$_o$ (mm)</th>
<th>median Annual Amps (mm)</th>
<th>median site WRMS$_i$ (mm)</th>
<th>median total WRMS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>thermal (via pairs)</td>
<td>models + analysis</td>
<td>total</td>
<td>loads</td>
</tr>
<tr>
<td>dN</td>
<td>0.4</td>
<td>0.5</td>
<td>0.65</td>
<td>0.45</td>
</tr>
<tr>
<td>dE</td>
<td>0.4</td>
<td>0.6</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>dU</td>
<td>1.3</td>
<td>1.7</td>
<td>2.2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

- Noise floor WRMS$_o$ & local site errors WRMS$_i$ dominate over loads
  - especially for dN & dE components
  - unless load models missing about half of total signal

- Local site WRMS$_i$ inferred by quadratic differencing
  - residual load model errors largest at inland stations
  - plus, high-frequency contributions from all other sources listed

- Loads larger in TibXS region & corrections more effective for dU

- Significant technique improvements still needed in many areas
Thank You !