EOP and Scale from Continuous VLBI Observing

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Overview

- Continuous (CONT) Campaigns (2 weeks)
  - EOP and Scale Precision
  - Compare with weekly operational VLBI series

- Future Networks
  - Continuous broadband observing
  - Comparison with current observing
  - NASA Space Geodesy Project:
    VLBI+SLR TRF combination simulation

- Simulations of current versus future performance
CONT Campaign History

- Five IVS CONT R&D Campaigns since 2000 (CONT17 soon)
  - CONT02, CONT05, CONT08, CONT11, CONT14
- CONT94, CONT95, CONT96 observed before IVS creation
- Goals of these campaigns:
  - Acquire state-of-the-art VLBI data over a 2-week period
  - Provide high quality data for study of geophysical problems
    - High frequency EOP
    - Comparisons with collocated techniques
    - Reference frame stability
    - Subdaily site motion
Evolution of the CONT Networks

CONT02, 8 sites

CONT08, 11 sites

CONT11, 14 sites

CONT05, 11 sites

CONT14, 16 sites
How do we measure the precision of VLBI EOP?

⇒ Compare with independent GNSS measurements

GNSS EOP series are based on measurements from a large global network of several hundred of receivers

How do the VLBI networks differ?

• CONT networks are constant during each 2-week campaign

• R1 on Mondays and R4 on Thursdays

• ~6 sites in 2002 ⇒ 8-12 sites currently

• Core set of 4-5 sites + remaining sites differ between weeks ⇒ Inhomogeneous observing
Differences between VLBI and GNSS EOP

Residual differences after removing an overall offset/rate between the CONT+R1+R4 series and the IGS Finals series.

~15 meters
Are CONT EOPs more precise than R1/R4s?

- WRMS of R1/R4 sessions before and after CONT14 better than the rest of the year
  \[ \Rightarrow \text{Are there periods when operational series have much better precision?} \]

- Number of operational sessions in 2 months ~ number of CONT sessions

Running WRMS of operational differences for each 2 month window

- CONT values below envelope of the operational series
- Operational values are much better in the timeframe of CONT14
- Clear improvement of CONT polar motion precision since 2002
### EOP Precision

<table>
<thead>
<tr>
<th></th>
<th>Xp</th>
<th>Yp</th>
<th>Xpr</th>
<th>Ypr</th>
<th>LOD</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>µas</td>
<td>µas</td>
<td>µas/d</td>
<td>µas/d</td>
<td>µs/d</td>
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<tr>
<td>CONT02</td>
<td>63</td>
<td>52</td>
<td>188</td>
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<tr>
<td>CONT05</td>
<td>57</td>
<td>37</td>
<td>287</td>
<td>167</td>
<td>19.9</td>
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<tr>
<td>CONT08</td>
<td>50</td>
<td>48</td>
<td>131</td>
<td>122</td>
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<tr>
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<td>35</td>
<td>30</td>
<td>116</td>
<td>121</td>
<td>5.8</td>
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<tr>
<td>CONT14</td>
<td>26</td>
<td>35</td>
<td>82</td>
<td>98</td>
<td>5.2</td>
</tr>
<tr>
<td>R1 2014</td>
<td>85</td>
<td>82</td>
<td>200</td>
<td>215</td>
<td>14.8</td>
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<tr>
<td>R4 2014</td>
<td>67</td>
<td>82</td>
<td>205</td>
<td>271</td>
<td>12.9</td>
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</tbody>
</table>

VLBI EOP precision = wrms (VLBI – IGS differences) after removing VLBI-IGS bias(offset/rate)

- Precision of CONT14 better than R1 and R4 by factor of 2-3
- Precision of CONTs improved by factor of ~2 since 2002
• Estimate a scale factor $\beta$ for each 24-hour observing session

• $\beta$ is a factor that all lengths have to be adjusted by relative to an a priori terrestrial reference frame

• An priori reference frame is a set of station positions and velocities for a global distribution of sites

=> For an 8000 km baseline 1 ppb = 8 mm
For site vertical change 1 ppb = 6.4 mm
Scale and EOP Precision

<table>
<thead>
<tr>
<th></th>
<th>Scale</th>
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</tr>
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<tbody>
<tr>
<td></td>
<td>ppb</td>
<td>mm</td>
</tr>
<tr>
<td>CONT02</td>
<td>0.43</td>
<td>2.7</td>
</tr>
<tr>
<td>CONT05</td>
<td>0.31</td>
<td>2.0</td>
</tr>
<tr>
<td>CONT08</td>
<td>0.24</td>
<td>1.5</td>
</tr>
<tr>
<td>CONT11</td>
<td>0.23</td>
<td>1.5</td>
</tr>
<tr>
<td>CONT14</td>
<td>0.20</td>
<td>1.3</td>
</tr>
<tr>
<td>R1 2014</td>
<td>0.55</td>
<td>3.5</td>
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<tr>
<td>R4 2014</td>
<td>0.47</td>
<td>3.0</td>
</tr>
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</table>

Scale precision = wrms repeatability (scale time series)
VLBI Scale Series and Hydrology Loading

- Longer term scale stability

Annual with amplitude (~0.4-0.5 ppb)

CONTs occurred (Aug-Oct) [except Cont14 (May)] at series ± peaks

WRMS: 0.8 ppb -> 0.7 ppb

CONT08 and CONT11 biggest reduction of bias

Applying a monthly hydrology loading series based on the GLDAS model removes much of annual signal
Based on expected VLBI station availability in +5 years and +10 years

Stations will have broadband (2-14 GHz) receivers

Most antennas are “very-fast”

=> Slew at 12 deg/sec in azimuth and 6 deg/sec in elevation

Several antennas are “fast”

=> Slew at 5-6 deg/sec in azimuth and 1-2 deg/sec in elevation (GGAO12M, 3 Australian + 1 New Zealand antennas)

Legacy antenna at Westford (MA) slews at 3 deg/sec in azimuth

Average azimuth slew rate of legacy antennas ~ 1.3 deg/sec
Projected Broad Band Networks:
- +5 years (17 sites)
- +10 years (27 sites)
# Observing Session Comparison

<table>
<thead>
<tr>
<th>Session Type</th>
<th>Number of Stations</th>
<th>Site average scans/hr</th>
<th>Range of scans/hr</th>
<th>Number of Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekly R1</td>
<td>8-10</td>
<td>12</td>
<td>12-21</td>
<td>5100</td>
</tr>
<tr>
<td>CONT11</td>
<td>14</td>
<td>16</td>
<td>12-20</td>
<td>10900</td>
</tr>
<tr>
<td>CONT14</td>
<td>17</td>
<td>19</td>
<td>14-24</td>
<td>20300</td>
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<tr>
<td>+5yr</td>
<td>17</td>
<td>79</td>
<td>58-97</td>
<td>141800</td>
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<td>+10yr</td>
<td>27</td>
<td>76</td>
<td>61-86</td>
<td>274200</td>
</tr>
</tbody>
</table>

- Station scan: all pairwise observations of a specific radio source at a given epoch made by the station and other stations in the network

- CONT14 to +5yr: Faster antennas, higher bandwidth => observations x 7

- +5yr to +10yr: increased number of network baselines => obs x 2
Simulation Modeling

- Monte Carlo simulation using observing schedule for a given network

- Perform multiple repetitions of a 24-hr observing session with different realizations of the model delay noise (O-C) for each repetition

- Precision of an estimated parameter is the repeatability of the estimates

- Delay model includes:
  - Clock delays for each station modeled as random walk + integrated random walk processes corresponding to clock Allan standard deviation
  - Wet troposphere delay contribution based on site-dependent Kolmogorov turbulence delay model based
  - White noise contribution corresponding to the observation uncertainty
Validation of Simulation Model

CONT11: Sept. 15-29, 2011

Simulated WRMS/observed WRMS = 0.97 ± 0.32
Simulation Modeling

EOP and Scale Precision From Simulation

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>UT1</th>
<th>LOD</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONT11</td>
<td>33.4</td>
<td>31.2</td>
<td>2.35</td>
<td>4.61</td>
<td>0.43</td>
</tr>
<tr>
<td>CONT14</td>
<td>26.7</td>
<td>28.5</td>
<td>1.86</td>
<td>5.16</td>
<td>0.30</td>
</tr>
<tr>
<td>+5 yr</td>
<td>16.3</td>
<td>19.2</td>
<td>0.79</td>
<td>2.6</td>
<td>0.16</td>
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<tr>
<td>+10yr</td>
<td>12.8</td>
<td>11.5</td>
<td>0.74</td>
<td>2.1</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Improvement by a factor of 2-3 going from CONT14 -> +10yr
Conclusions

• CONT11 and CONT14 scale precision ~ 0.2-0.23 ppb
  - more than twice as good as operational R1 and R4 sessions

• CONT11 and CONT14 Polar Motion precision ~ 25-35 µas
  ~ same as long-term GNSS (IGS finals) precision (internal)
  GNSS short-term precision is probably better?

• Simulations of future observing (+10yr) =>
  Precisions of 12 µas PM, 0.7 µs UT1, 0.1 ppb scale
Using the speed of light, the delay is interpreted as a distance.

A network of antennas observes a Quasar.

The delay between times of arrival of a signal is measured.

3 picosec (10^{-12} sec) -> 1 mm

- Light travel time between 2 baseline stations ~ 20 msec
- Measurement precision ~10-20 psec.
- Very precise clocks - 1 sec error in 3 million years.