IGS Workshop on GNSS Biases 2015

Multi-GNSS Differential Code Biases (DCB)
Process at IGG

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Presented by Oliver Montenbruck

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Outline

- Background and motivation
- GPS and GLONASS DCB process within IGS network
- Multi-GNSS DCB process within MGEX network
- Determination of GNSS DCBs with uncombined PPP
- Summary and conclusions
Background and motivation (1/3)

- GNSS differential code biases (DCBs) include
  - Intra- and inter-frequency biases
  - Broadcast TGD/BGD and ISC parameters, as well as post-processed DCB products
- DCBs are needed for
  - Code based positioning, ionospheric TEC extracting, etc.
- Most DCB products focus on legacy GPS and GLONASS signals currently
- Multi-GNSS DCB products are needed with the new emerging constellations (BDS and Galileo) and new signals
- Multi-GNSS tracking networks offer a basis for an independent determination of multi-GNSS DCB parameters, e.g.
  - IGS multi-GNSS Experiment (MGEX) project
  - International GNSS Monitoring and Assessment System (iGMAS)
Summary of current GNSS tracking networks

- Green: IGS, G+R, ~400 sites
- Blue: MGEX, G+R+C+E, ~140 sites
- Red: iGMAS, G+R+C+E, ~15 sites
Current status for GNSS DCB determination

<table>
<thead>
<tr>
<th>GNSS sys.</th>
<th>Data sources</th>
<th>DCB type</th>
<th>Organization</th>
<th>Process strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS+GLO</td>
<td>IGS</td>
<td>Intra-frequency bias</td>
<td>CODE(^1)</td>
<td>GPS clock analysis and GNSS direct determination</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inter-frequency bias</td>
<td>IGS IAACs(^2)</td>
<td>Global ionospheric modeling + DCB estimation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>iGMAS ACs</td>
<td></td>
</tr>
<tr>
<td>GPS+GLO+</td>
<td>MGEX</td>
<td>Multi-GNSS DCB</td>
<td>DLR(^3)</td>
<td>DCB determination using GIM</td>
</tr>
<tr>
<td>BDS+GAL</td>
<td></td>
<td></td>
<td>IGG(^4)</td>
<td>IGGDCB (station-based ionospheric modeling + DCB estimation)</td>
</tr>
</tbody>
</table>

\(^1\) Schaer, GNSS bias workshop 2012.
\(^2\) Hernández-Pajares et al., J Geod, 2009.
\(^3\) Montenbruck et al., Navigation, 2014.
\(^4\) Wang et al., J Geod (online), 2015.
GPS and GLONASS DCB process within IGS network (1/3)

- GPS and GLONASS P1P2 DCBs are determined with IGGDCB method, as one of the steps for GIM generation\(^{(1)}\).

- Generalized triangular series (GTS) function is used for station-based ionospheric modeling and satellite-plus-receiver DCB estimation\(^{(2)}\).

\[
\begin{align*}
STE C(z, \varphi, h) &= VTEC(\varphi, h) \cdot M(z) \\
VTEC(\varphi, h) &= \sum_{n=0}^{n_{\text{max}}} \sum_{m=0}^{m_{\text{max}}} \left\{ E_{nm} (\varphi - \varphi_0)^n \cdot h^m \right\} + \sum_{k=0}^{k_{\text{max}}} \left\{ C_k \cos(k \cdot h) + S_k \sin(k \cdot h) \right\} \\
M(z) &= [1 - \sin^2 z \cdot (1 + H_{ion}/R_E)]^{-1/2}
\end{align*}
\]

\(^{(1)}\) Li et al., J Geod, 2015; \(^{(2)}\) Yuan et al., Prog Nat Sci, 2004
• RMS of GPS satellite P1P2 DCB estimates of different IAACs relative to CODE under different levels of solar activity (all values in [ns])

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>ESA</td>
<td>0.30</td>
<td>0.17</td>
<td>0.14</td>
<td>0.35</td>
</tr>
<tr>
<td>IGG</td>
<td>0.14</td>
<td>0.06</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>JPL</td>
<td>0.15</td>
<td>0.09</td>
<td>0.13</td>
<td>0.26</td>
</tr>
<tr>
<td>UPC</td>
<td>0.40</td>
<td>0.18</td>
<td>0.18</td>
<td>0.26</td>
</tr>
</tbody>
</table>
GPS and GLONASS DCB process using IGS network (3/3)

- GLONASS data contributes to IGG’s GIM since the third quarter of 2013

RMS of IGGDCB-based GPS C1WC2W and GLONASS C1PC2P bias estimates relative to CODE within IGS network (July, 2014)
• IGGDCB method is extended to estimate the intra- and inter-frequency biases of GPS, GLONASS, BeiDou and Galileo within MGEX network.

• Intra-frequency biases are directly determined from GNSS observations:

$$SPR_{s_1-s_2} = \frac{1}{N} \sum_{k=1}^{N} \left( P_{s_1,k} - P_{s_2,k} \right)$$

(a) Satellite plus receiver (SPR) biases  
(b) Pseudoranges of the selected signals through the data arc

• Inter-frequency biases are estimated together with station ionospheric modeling:

$$\tilde{P}_{4,k} = v \cdot STEC_k + c \cdot (B^s + B_r) + \epsilon$$

(a) Ionospheric observables depending on the selected signal pairs  
(b) Modeled with local GTS function  
(c) Estimated SPR inter-frequency biases

• A zero-mean condition is applied to separate the satellite- and receiver-specific DCBs for each individual signal pairs.
Residual distribution of ionospheric delay in local GTS solution at WUH2 and CUT0 sites (July 24, 2014)
Selected Set of multi-GNSS DCBs within DLR (22) and IGG (18) depending on current MGEX code observations

<table>
<thead>
<tr>
<th>GNSS sys.</th>
<th>DCB type</th>
<th>DLR</th>
<th>IGG</th>
<th>GNSS sys.</th>
<th>DCB type</th>
<th>DLR</th>
<th>IGG</th>
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</thead>
<tbody>
<tr>
<td>GPS</td>
<td>C1C-C1W</td>
<td>✓</td>
<td>✓</td>
<td>GLONASS</td>
<td>C1C-C1P</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>C2W-C2L</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>C2C-C2P</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td></td>
<td>C2W-C2S</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>C1C-C2C</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>C2W-C2X</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>C1C-C2P</td>
<td>✓</td>
<td>-</td>
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<tr>
<td></td>
<td>C1W-C2W</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>C1P-C2P</td>
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<td>✓</td>
</tr>
<tr>
<td></td>
<td>C1C-C5X</td>
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</tr>
<tr>
<td></td>
<td>C1C-C5Q</td>
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<td>✓</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>C1C-C2W</td>
<td>✓</td>
<td>-</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Galileo</td>
<td>C1C-C5Q</td>
<td>✓</td>
<td>✓</td>
<td>BeiDou</td>
<td>C2I-C7I</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>C1C-C7Q</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>C2I-C6I</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>C1C-C8Q</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>C7I-C6I</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>C1X-C5X</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C1X-C7X</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C1X-C8X</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
GPS and GLONASS intra-frequency bias results:

Consistency of GPS and GLONASS satellite intra-frequency biases of DLR/IGG with CODE for the year 2014 (unit in ns). The table provides the RMS for the differences of two DCB products after a zero-mean alignment.

<table>
<thead>
<tr>
<th>System</th>
<th>DCB type</th>
<th>IGG-CODE</th>
<th>DLR-CODE</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>C1CC1W</td>
<td>0.20</td>
<td>0.23</td>
<td>relative to CODE</td>
</tr>
<tr>
<td>GPS</td>
<td>C1CC1W</td>
<td>0.08</td>
<td>0.12</td>
<td>relative to CODERNX</td>
</tr>
<tr>
<td>GLO</td>
<td>C1CC1P</td>
<td>0.21</td>
<td>0.18</td>
<td>relative to CODERNX</td>
</tr>
<tr>
<td>GLO</td>
<td>C2CC2P</td>
<td>0.39</td>
<td>0.30</td>
<td>relative to CODERNX</td>
</tr>
</tbody>
</table>

GPS C1CC1W DCB estimates of CODE, DLR and IGG for December 2014

CODE: indirect GPS DCB products of CODE
CODERNX: direct GPS/GLONASS DCB products of CODE
GPS and GLONASS inter-frequency bias results:

Bias and STD of the MGEX-based C1WC2W and C1PC2P DCB estimates relative to CODE for the period 2013-2014

Consistency with CODE’s DCB products

IGGDCB
GPS → C1WC2W: 0.29 ns
GLONASS → C1PC2P: 0.56 ns

DLRDCB
GPS → C1WC2W: 0.24 ns
GLO → C1PC2P: 0.84 ns
BeiDou DCB results:

Time series of C2IC7I and C2IC6I DCBs of DLR during the period 2013-2014

RMS of the differences between BeiDou DCB solutions of IGG and DLR is limited to 0.4 ns, while that of broadcast TGD is about 1.4 ns
Monthly stability (std) of BDS C2IC7I DCB estimates determined by DLR and IGG for the year 2013 and 2014
Galileo DCB results:

RMS of the differences between Galileo DCB solutions of IGG and DLR performs at the level of 0.23 ns, while that of broadcast BGD is about 0.55 ns.
Determination of GNSS DCBs with uncombined PPP (1/3)

- Ionospheric observables, interpreted as line-of-sight ionospheric delays biased by satellite plus receiver DCB, are in general extracted from dual-frequency GNSS data using carrier-to-code leveling (CCL) method.

- An uncombined PPP, processing raw instead of ionosphere-free GNSS data, is developed to estimate ionospheric observables along with other geodetic parameters.

- Extraction of slant ionospheric information from undifferenced & uncombined PPP

\[
\begin{align*}
P_i &= \rho + c \cdot (d\tilde{I}_r - d\tilde{I}_s) + T_{rop} + \mu_i \cdot \tilde{I}_1 + \xi_{P_i} \\
L_i &= \rho + c \cdot (d\tilde{I}_r - d\tilde{I}_s) + T_{rop} - \mu_i \cdot \tilde{I}_1 + \tilde{N}_i + \xi_{\Phi_i}
\end{align*}
\]

where, \( \mu_i = f_i^2 / f_s^2 \) (\( i = 1, 2 \)), \( f_1 \) and \( f_s \) are the two frequencies of the selected signals;

\( \tilde{I}_i = I_i - \frac{c}{\mu_i - 1} (B + B^*) \) is the ionospheric observables containing satellite- and receiver-specific biases;

\( \tilde{N}_i \) is the phase ambiguity, which also contains satellite- and receiver-specific biases;

- Determination of DCBs with IGGDCB method from the input ionospheric observables
Determination of GNSS DCBs with uncombined PPP (2/3)

Uncombined PPP process scheme

<table>
<thead>
<tr>
<th>Item</th>
<th>Strategy/models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellites</td>
<td>G+R+C+E (MGEX + iGMAS tracking data)</td>
</tr>
<tr>
<td>Satellite orbit/clock</td>
<td>Final precise satellite orbit &amp; clock products of IGG’s iGMAS AC</td>
</tr>
<tr>
<td>Signal selection</td>
<td>G: L1+L2; R: L1+L2; C: B1+B2; E: E1+E5a</td>
</tr>
<tr>
<td>Elevation cut-off</td>
<td>8 deg.</td>
</tr>
<tr>
<td>Observation weight</td>
<td>G:R:C:E=5:4:2:2 &amp; elevation dependent weight</td>
</tr>
<tr>
<td>DCB correction</td>
<td>GPS P1-C1 DCB product of CODE</td>
</tr>
<tr>
<td>Station coordinate</td>
<td>Estimated as static parameters</td>
</tr>
<tr>
<td>Receiver clock</td>
<td>Modeled as white noise for each constellation</td>
</tr>
<tr>
<td>Tropospheric delay</td>
<td>UNB3m + GMF + random walk process</td>
</tr>
<tr>
<td>Ionospheric delay</td>
<td>Estimate as parameters</td>
</tr>
<tr>
<td>Phase ambiguity</td>
<td>Float solution for each arc</td>
</tr>
</tbody>
</table>
Multi-GNSS DCB results of uncombined PPP (DOY 106-112, 2015)

(a) GPS C1WC2W bias diff. relative to CODE

- PPP-CODE, IGG-CODE, DLR-CODE: 0.12ns, 0.27ns, 0.17ns

(b) GLO C1PC2P bias diff. relative to CODE

- PPP-CODE, IGG-CODE, DLR-CODE: 0.41ns, 0.49ns, 0.80ns

(c) BDS C2IC7I and GAL C1XC5X bias diff. relative to DLR

- PPP-DLR, IGG-DLR: 0.16ns, 0.24ns

(d) GAL C1XC5X

- PPP-DLR, IGG-DLR: 0.18ns, 0.22ns

Standard deviation of differences over each constellation:

(a) GPS C1WC2W

- PPP-CODE, IGG-CODE, DLR-CODE: 0.12ns, 0.27ns, 0.17ns

(b) GLO C1PC2P

- PPP-CODE, IGG-CODE, DLR-CODE: 0.41ns, 0.49ns, 0.80ns

(c) BDS C2IC7I

- PPP-DLR, IGG-DLR: 0.16ns, 0.24ns

(d) GAL C1XC5X

- PPP-DLR, IGG-DLR: 0.18ns, 0.22ns
Summary and conclusions

- Routine multi-GNSS DCB processing within IGS, MGEX and iGMAS network at IGG
  - IGGDCB: station-based ionospheric modeling instead of using priori ionospheric information
  - GPS and GLONASS P1P2 DCB process within IGS network for IGG GIM generation
  - Multi-GNSS DCB process and analysis within MGEX and iGMAS network
  - Routine CAS/IGG MGEX DCB products contribute to IGS MGEX project

- Good agreement of multi-GNSS DCB products with CODE/DLR DCBs (rms of differences)
  - Limits to 0.1ns, 0.2ns and 0.4ns for GPS C1CC1P, GLONASS C1CC1P and C2CC2P (w.r.t CODE)
  - Performs at the level of 0.29ns and 0.56ns for IGG’s GPS C1WC2W and GLONASS C1PC2P (w.r.t CODE)
  - 0.33ns and 0.39ns for BeiDou C2IC7I and C2IC6I, respectively (w.r.t DLR)
  - Overall agreement limits to 0.24ns for Galileo DCBs (w.r.t DLR)

- Multi-GNSS DCB determination based on uncombined PPP
  - Uncombined PPP scheme enables more reliable ionospheric observables extraction compared to carrier- to-code leveling (CCL) method
  - An alternative way for multi-GNSS DCB determination
Thanks for your attention.

Many thanks to Dr. Oliver Montenbruck, Bruno Garayt and Carey Noll for coordinating and helping with the delivery of CAS/IGG MGEX DCB products to IGN and CDDIS ftp archive.

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