L2 bandwidth correction for the Swarm Satellites

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Intro

- Slant TEC variations trigger artifacts in kinematic positions.
- Artifacts propagate into gravity field solutions derived from Swarm kinematic positions.
- Caused by the receivers loop filter settings.

(w.r.t. to the monthly JPL-GRACE-RL06 gravity field solution)
The Swarm L2 tracking loop filter

- L1-aided L2 tracking:
  - only the ionospheric induced difference (L1-L2) needs to be tracked.
  - L1 is assumed to be error-free.

- Third order digital phase lock loop, with computation delay of 100 ms.
- Rate-only feedback.
- Super-critically damped.

Input signal → Residual Phase → Phase Rate Estimation

\[ \phi_n \rightarrow \tilde{\phi}_n = \phi_n - \hat{\phi}_n \rightarrow \hat{\phi}_{n+1} T = K_1 \tilde{\phi}_{n-1} + K_2 \sum_{i=0}^{n-1} \tilde{\phi}_i + K_3 \sum_{i=0}^{n-1} \sum_{j=0}^{i} \tilde{\phi}_j \]

\[ \hat{\phi}_{n+1} = \hat{\phi}_n + 0.5T(\hat{\phi}_n + \hat{\phi}_{n+1}) \]

Adopted from Thomas (1998), An analysis of digital phase-locked loops

Model Phase
\[ \hat{\phi}_n \]
# L2 Loop filter updates

Bandwidth settings of the phase lock loops of the Swarm GPS receivers

<table>
<thead>
<tr>
<th>Since</th>
<th>Swarm-A</th>
<th>Swarm-B</th>
<th>Swarm-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>$B_{L1} = 10$ Hz</td>
<td>$B_{L1} = 10$ Hz</td>
<td>$B_{L1} = 10$ Hz</td>
</tr>
<tr>
<td></td>
<td>$B_{L2} = 0.25$ Hz</td>
<td>$B_{L2} = 0.25$ Hz</td>
<td>$B_{L2} = 0.25$ Hz</td>
</tr>
<tr>
<td>6 May 2015</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Oct 2015</td>
<td>$B_{L1} = 15$ Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$B_{L2} = 0.50$ Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Oct 2015</td>
<td></td>
<td>$B_{L1} = 15$ Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$B_{L2} = 0.50$ Hz</td>
<td></td>
</tr>
<tr>
<td>23 June 2016</td>
<td></td>
<td>$B_{L2} = 0.75$ Hz</td>
<td></td>
</tr>
<tr>
<td>11 Aug 2016</td>
<td>$B_{L2} = 0.75$ Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adopted from van den IJssel et. al. 2016, Impact of Swarm GPS receiver updates on POD performance.
Simulations

- Artificial 10s pulse with white noise

\[ \phi(t) = \begin{cases} 
-\cos((t - a)/(b - a) \cdot 2\pi) + 1, & a < t < b \\
0, & \text{else}
\end{cases} \]

Left: Artificial Pulse and loop filter output. Right: Tracking error of the loop filter.
Transfer function

- Transformation to frequency space.
- \(100\text{ms}\) computation delay too large for third order continuous update formulation → Approximation using a higher order transfer function.

\[ H(s) = \frac{b_2 s^3 + b_3 s^2 + b_4 s + b_5}{s^5 + a_1 s^4 + a_2 s^3 + a_3 s^2 + a_4 s + a_5} \]
Inversion

Which input phase is required to generate the observed output phase?

Issues and approaches:

- $1Hz$ observed data instead of $10Hz$
  $\rightarrow$ transformation to frequency space.

- Application of the inverse transfer function and re-transformation to time domain.

- Edge effects due to long response times and unknown initial conditions
  $\rightarrow$ Detrending and $60s$ extrapolation with $10s$ blending.
Inversion results

Corrections compared to ionosphere-free residuals (left) and ionosphere-free residuals before and after corrections were applied (right). Plots for Swarm A, 1st of March 2015.
Impact of the L2-correction on the post-fit RMS of the orbit adjustment (top), the number of Ambiguities set up (bottom, left) and number of observations (bottom, right)
SLR Residuals

SLR residual statistics for March 2015, Swarm reduced dynamic orbits

<table>
<thead>
<tr>
<th>March 2015</th>
<th># obs.</th>
<th>mean [mm]</th>
<th>std [mm]</th>
<th>RMS [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swarm A, Original</td>
<td>1433</td>
<td>4.93</td>
<td>26.09</td>
<td>26.54</td>
</tr>
<tr>
<td>Swarm A, L2-Cor.</td>
<td>1433</td>
<td>4.34</td>
<td>25.05</td>
<td>25.41</td>
</tr>
</tbody>
</table>

SLR residual statistics for March 2015, Swarm kinematic orbits

<table>
<thead>
<tr>
<th>March 2015</th>
<th># obs.</th>
<th>mean [mm]</th>
<th>std [mm]</th>
<th>RMS [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swarm A, Original</td>
<td>1408</td>
<td>2.47</td>
<td>30.02</td>
<td>30.12</td>
</tr>
<tr>
<td>Swarm A, L2-Cor.</td>
<td>1408</td>
<td>1.29</td>
<td>26.46</td>
<td>26.48</td>
</tr>
</tbody>
</table>

• Mostly the reduction of observational noise is seen in the residual statistics.
• The orbits using the L2-correction are not degraded compared to the original scenario.
• Only very few SLR observations exist for the equatorial region.
Gravity fields, Statistics (March 2015)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>wRMS(^1) (monthly) mm</th>
<th>wSTD(^1) (monthly) mm</th>
<th>No. kin. pos.</th>
<th>RMS kin. pos. mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Original</td>
<td>21.42</td>
<td>28.25</td>
<td>695673</td>
<td>2.61</td>
</tr>
<tr>
<td>A L2-correction</td>
<td>17.17</td>
<td>26.85</td>
<td>761586</td>
<td>2.27</td>
</tr>
<tr>
<td>A Weighting</td>
<td>11.67</td>
<td>23.06</td>
<td>706698</td>
<td>2.58</td>
</tr>
</tbody>
</table>

\(^1\) Compared to the monthly JPL-GRACE-RL06 gravity field solution

- The smallest difference to monthly GRACE solution is obtained using weighting strategies (second derivative and rate of TEC index based).
- Maximum number of kinematic positions and smallest post fit RMS for L2-correction scenario.
- The L2-correction scenario outperforms the original solution.
Conclusions

- Artifacts in L2 phase measurements can efficiently be corrected in frequency space using the inverse transfer function.
- 10 Hz sampling would be required for full reconstruction.
- Improvements could also be observed for the most recent L2 bandwidths (0.5 Hz, 0.75 Hz, 1 Hz).
- Phase arc boundaries need to be extrapolated. Limited accuracy of the corrections.

Thank you for your attention!

Paper submitted to GPS Solutions (under review): "Bandwidth correction of Swarm GPS carrier phase observations for improved orbit and gravity field determination"