L2 bandwidth correction for the Swarm Satellites

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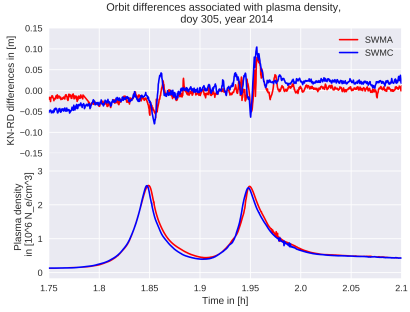
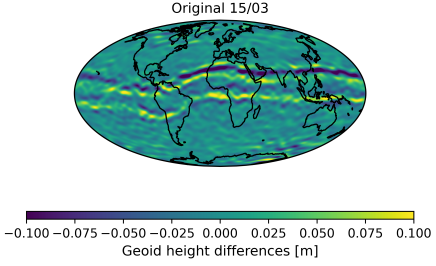
Intro

- 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.

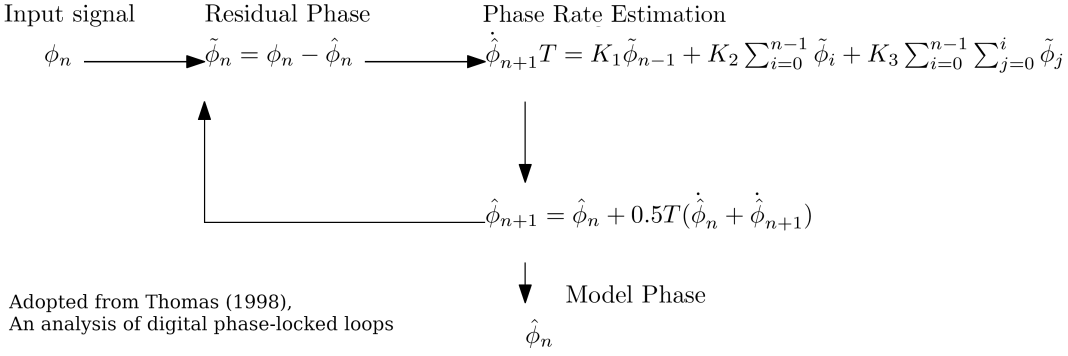




(w.r.t. to the monthly JPL-GRACE-RL06 gravity field solution)

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-criticaly damped.



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

L2 Loop filter updates

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

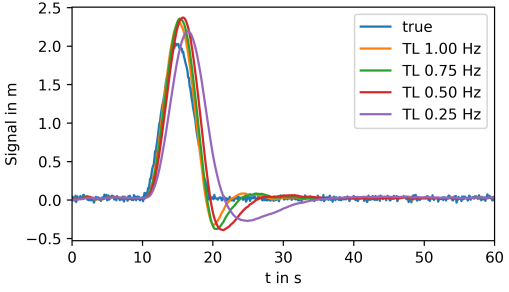
Since	Swarm-A	Swarm-B	Swarm-C
Launch	$B_{L1} = 10\,\text{Hz}$, $B_{L2} = 0.25\,\text{Hz}$	$B_{L1} = 10\,\text{Hz}$, $B_{L2} = 0.25\,\text{Hz}$	$B_{L1} = 10\,\text{Hz}$, $B_{L2} = 0.25\,\text{Hz}$
6 May 2015			$B_{L1} = 15\,\text{Hz}$, $B_{L2} = 0.50\,\text{Hz}$
8 Oct 2015	$B_{L1} = 15\,\text{Hz}$, $B_{L2} = 0.50\,\text{Hz}$		
10 Oct 2015		$B_{L1} = 15\,\text{Hz}$, $B_{L2} = 0.50\,\text{Hz}$	
23 June 2016			$B_{L2} = 0.75\,\text{Hz}$
11 Aug 2016	$B_{L2} = 0.75\,\text{Hz}$		$B_{L2} = 1.00\,\text{Hz}$

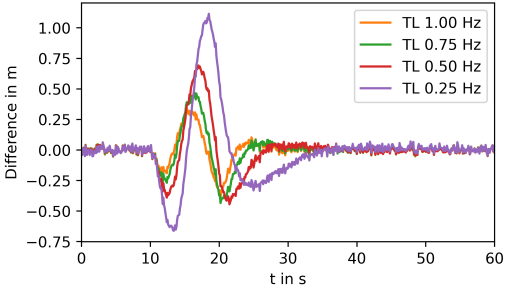
Adopted from van den IJssel et. al. 2016,
Impact of Swarm GPS receiver updates on POD performance.

Simulations

- Artificial 10s pulse with white noise

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



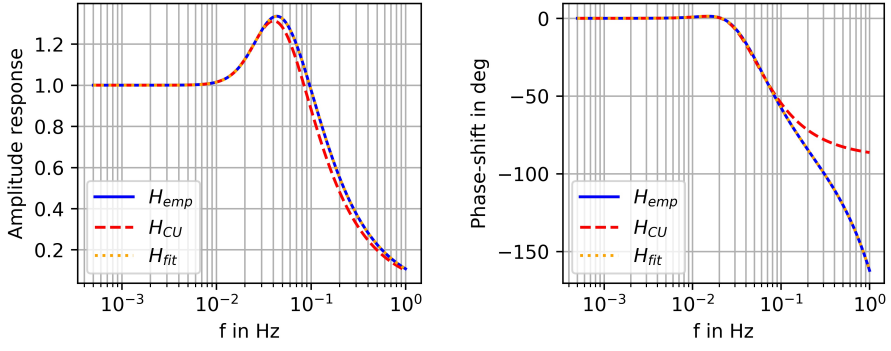


Left: Artificial Pulse and loop filter output. Right: Tracking error of the loop filter.

Transfer function

- Transformation to frequency space.
- $100ms$ computation delay too large for third order continuous update formulation
  $\rightarrow$ Approximation using a higher order transfer function .
- Empirical approximation of order 4/6 (Aguirre and Hurd, 1984).

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



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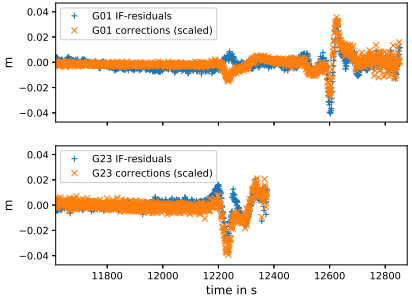
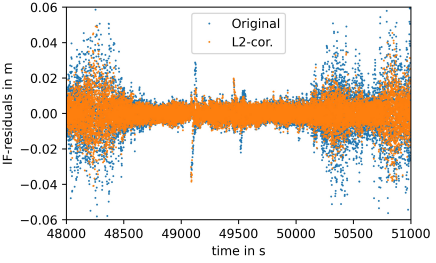
Inversion

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.

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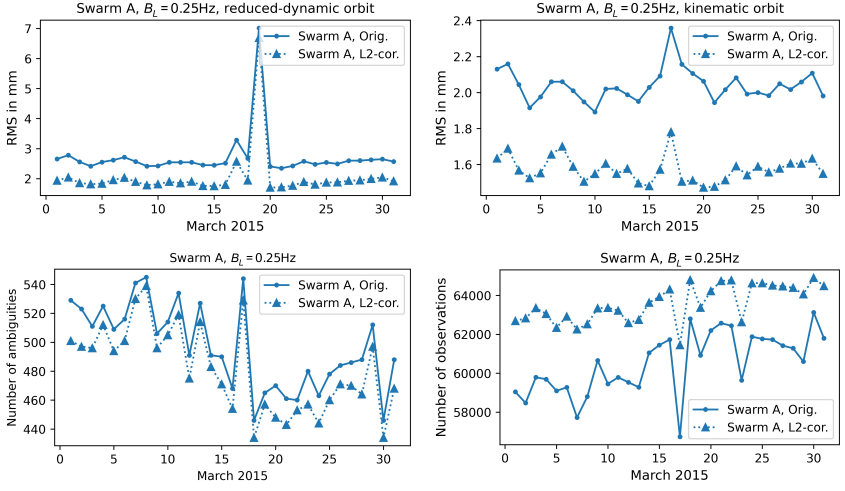
Orbit statistics



Impact of the L2-correction on the post-fit RMS of the obit adjustment (top), the number of Ambiguities set up (bottom, left) and number of observations (bottom, right)

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SLR Residuals

SLR residual statistics for March 2015, Swarm reduced dynamic orbits

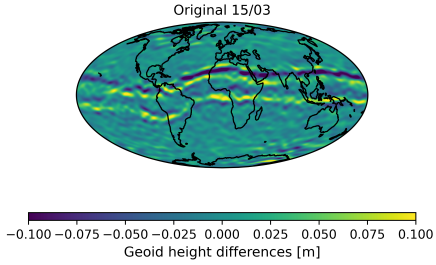
March 2015	# obs.	mean [mm]	std [mm]	RMS [mm]
Swarm A, Original	1433	4.93	26.09	26.54
Swarm A, L2-Cor.	1433	4.34	25.05	25.41

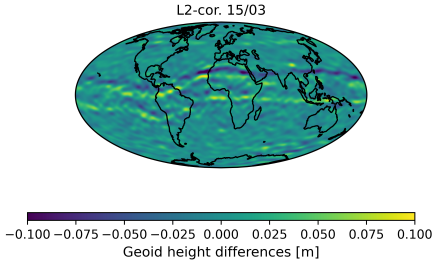
SLR residual statistics for March 2015, Swarm kinematic orbits

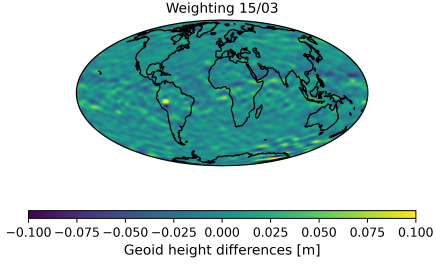
March 2015	# obs.	mean [mm]	std [mm]	RMS [mm]
Swarm A, Original	1408	2.47	30.02	30.12
Swarm A, L2-Cor.	1408	1.29	26.46	26.48

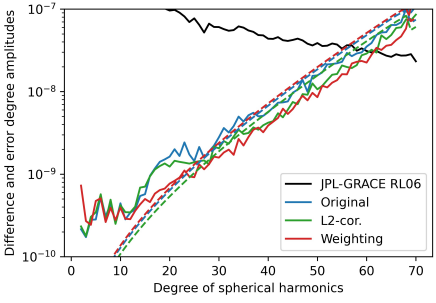
- Mostly the reduction of observational noise is seen in the residual statistics.
- The orbits using the L2-correction are not degraded compared to the original scenario.
- Only very few SLR observations exist for the equatorial region.

Gravity fields March 2015









Gravity fields, Statistics (March 2015)

Scenario	wRMS[1] (monthly) mm	wSTD[1] (monthly) mm	No. kin. pos.	RMS kin. pos. mm
A Original	21.42	28.25	695673	2.61
A L2-correction	17.17	26.85	761586	2.27
A Weighting	11.67	23.06	706698	2.58

[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"