Ionospheric Filtering: Improving Swarm Orbits and Studying Ionospheric Fluctuations

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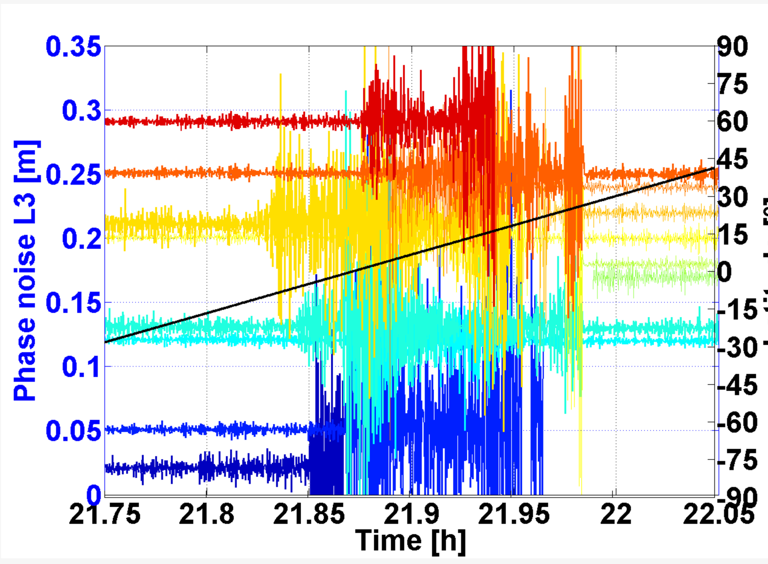
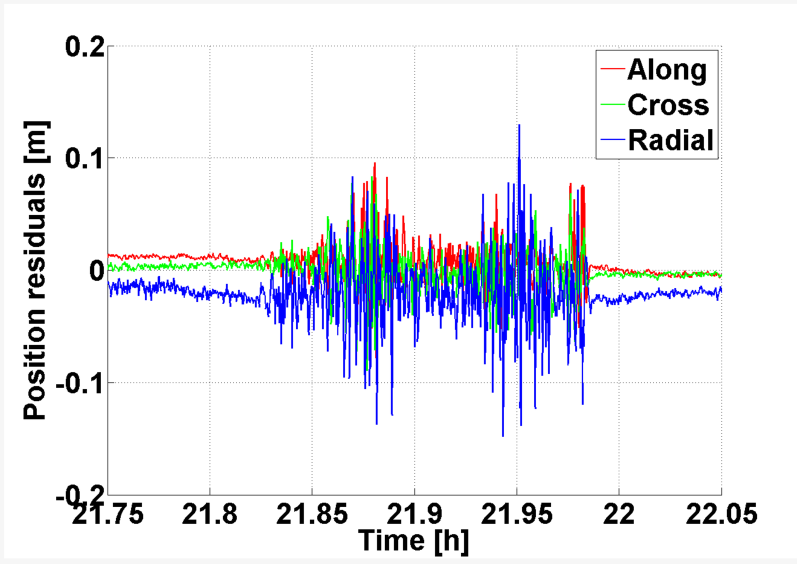
Introduction

- Ionospheric scintillations impact GPS ionosphere-free linear observations from SWARM satellites and subsequently the derived orbits and gravity field solution.
- Different patterns of noise exist when flying above the equator or pole



(a) L3 carrier phase noise (from 2nd difference of successive phase observations, after removing the geometric distances) when flying above equatorial areas, DOY333 of year 2015.



(b) Propagation of the noise in the kinematic orbit of SWARM satellites, kinematic orbit residuals w.r.t. ESA reduced-dynamic orbits.

Fig. 1: Disturbances by ionospheric scintillations

Strategies to mitigate the impact of scintillation in observation time series

1) Simple elimination of noisy parts impacts:
   - Strength of the positioning reduced
   - Ambiguity estimation more difficult
   - Low degrees of gravity field solutions affected (Jäggi, 2016)

2) Boxcar averaging:
   - Smoothing of the observations
   - Possible elimination of more than the ionospheric noise

3) **Here:** Physically based mitigation of the impact of scintillation based on spectral content (Rino 1979):

$$S_w(\omega) = \frac{F}{(\omega^2 + \alpha^2)^{P/2}} \tag{1}$$

with ω angular frequency of carrier phase fluctuations, α is related to the length of the ionospheric disturbances, P is the smoothness parameter and factor F is the spectral strength of the carrier phase noise at 1Hz when $\alpha = 0$.

Summary of applied methodology

Step1
- Preprocessing step
- Substraction of the mean and polynomial fitting of the observations

Step2
- Noise detection in the preprocessed observations
- Rate of change with $\left|\frac{d\varphi}{dt}\right|$ ionosphere-free linear combination of carrier phase observations
- Empirical threshold 3σ 0.012 ms^{-1}

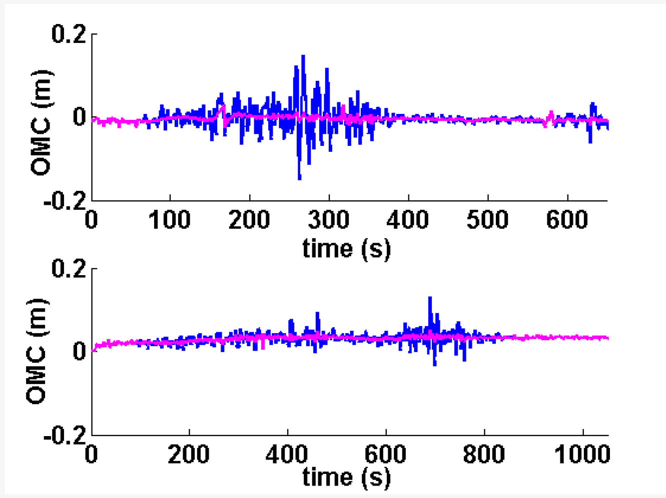
Step3
- Extraction of the iono-TS: minimal length 250 s
- filtering with adequate VCM

Step4
- Reconstruction of the observations

Fig. 2: Summary of the methodology used to detect, filter and reconstruct the contaminated time series of observations.

Filtering with Mátern covariance matrix

- An adequate covariance matrix **W** (Kermarrec and Schön 2017) is built based on the knowledge of the ionospheric spectral density: $\mathbf{W}(\tau) = (\alpha\tau)^{\nu} K_{\nu}(\alpha\tau)$.
  Smoothness ν depends on the ionospheric strength (weak: 0.1-0.5, moderate: 0.5-1.2, strong: 1.2-1.7).
- The noise corresponding to ionospheric scintillations is extracted from the identified time series $\mathbf{y}' = \gamma\hat{\mathbf{y}}$,
  with $\hat{\mathbf{y}} = \mathbf{W}^{-\frac{1}{2}}\mathbf{y}$, $\gamma = \frac{\sigma_{\phi,ref}}{\sigma_{\hat{y}}}$ with $\sigma_{\phi,ref} = 3mm$.



(a) Original (blue line) and filtered (magenta line) carrier phase OMC of PRN20 for 2 different starting times, with $\alpha = 1.5$ and $\nu = 1$.

	Slope case study
Reference slope	-1.1 (+/-0.1)
Non filtered full-TS	-2.9 (+/-0.2)
Filtered full-TS $[\alpha,\nu]=[1.5,1]$	**-1.3 (+/-0.2)**
Filtered full-TS $[\alpha,\nu]=[5,1]$	-2.8 (+/-0.2)
Filtered full-TS $[\alpha,\nu]=[0.1,1]$	-0.2 (+/-0.2)
Filtered full-TS $[\alpha,\nu]=[1.5,3]$	-0.5 (+/-0.2)
Filtered full-TS $[\alpha,\nu]=[1.5,\frac{1}{3}]$	-2.4 (+/-0.2)

(b) Influence of the parameter sets α and ν on the slopes of the PSD at frequencies between 0.1 Hz (12,5 s) and 0.5 Hz (2 s), for PRN 20.

Fig. 3: Filtering with Mátern covariance matrix

Improved kinematic orbit determination

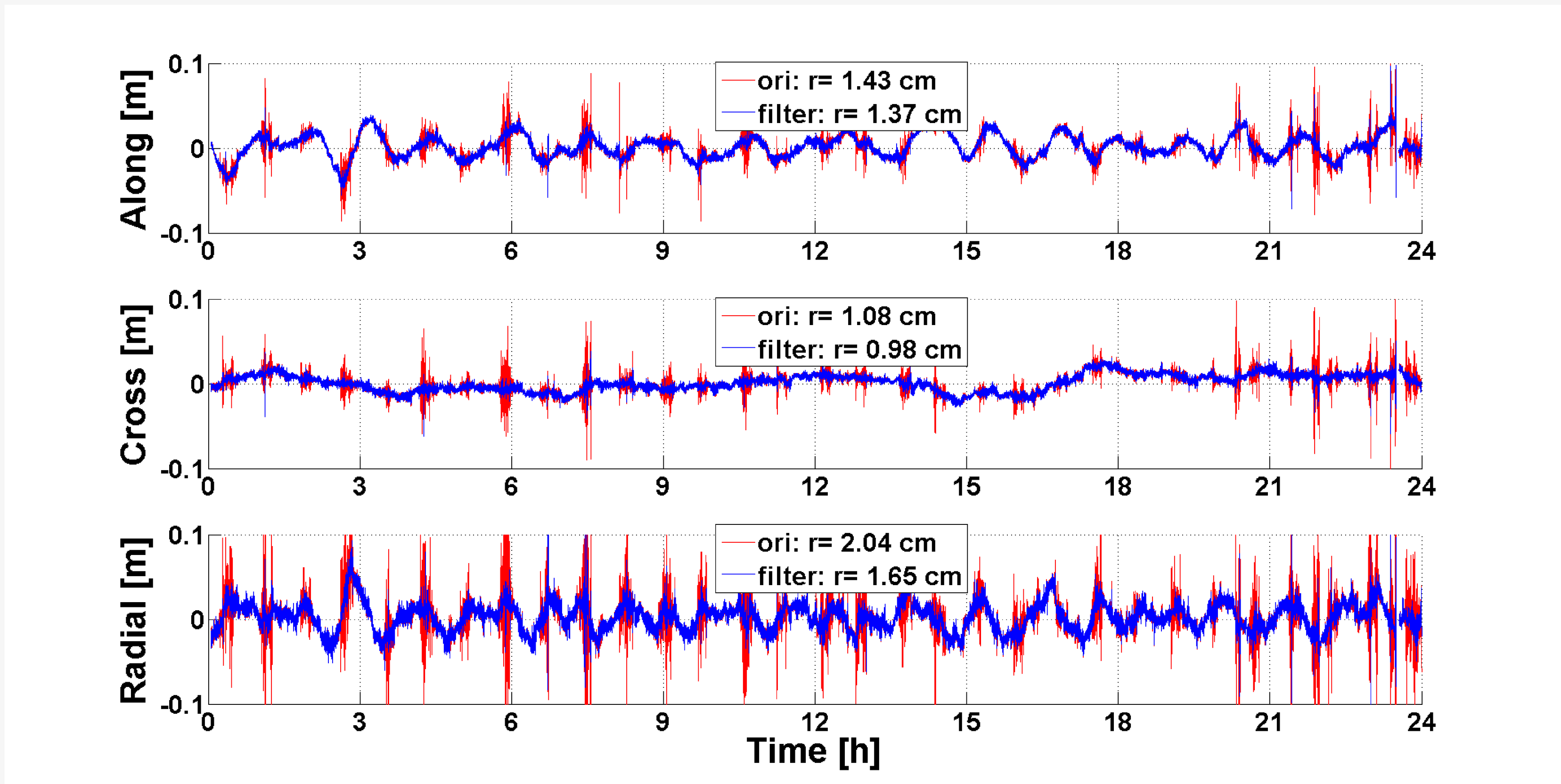


Fig. 4: Position residuals in the along, cross and radial components of the Swarm A orbit solution computed with (blue) and without (red) filtering, w.r.t. reduced-dynamic orbits from ESA, on DoY 333, 2015.

Model	Description
GPS tracking data (30 hours)	undifferenced ionosphere-free code and phase
GPS Orbits	CODE final GPS orbits and 5s clocks
GPS phase model	igs08.atx (week 1888)
Swarm attitude	quaternion from star camera (Level 1b)
Swarm phase model	phase center offset (Level 1b) phase center variations map (provided by TU Delft)
stochastic model	$sin(Elev)/(\sigma_c)^2$ or $sin^2(Elev)/(\sigma_c)^2$, $1/(\sigma_p)^2$
a priori coordinates	Medium Accurate Orbit Determination MOD (Level 1b)
elevation cut-off angle	2°
ionospheric delay	ionosphere-free linear combination
phase wind-up	model (Wu, 1993)
relativistic corrections	model (IS-GPS-200H, 2014) Shapiro effect (Hofmann-Wellenhof, 2008)

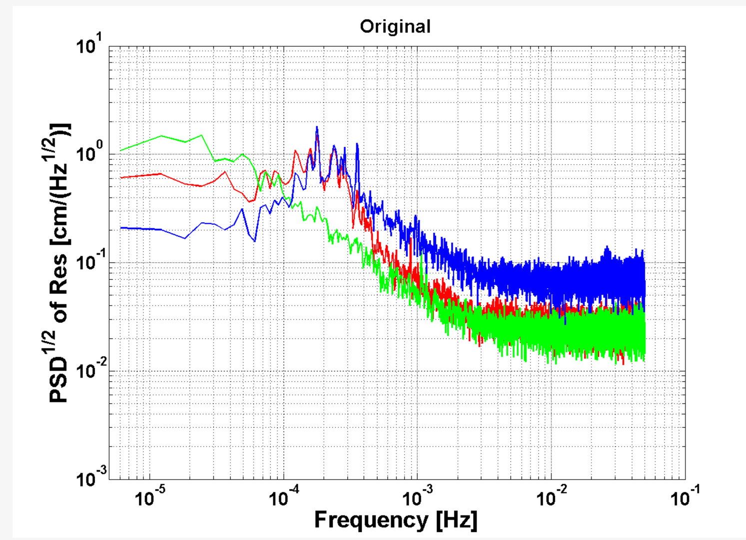
Tab. 1: Summary of the measurement and corrections models used for Swarm kinematic orbit determination of IfE.

Monthly solution

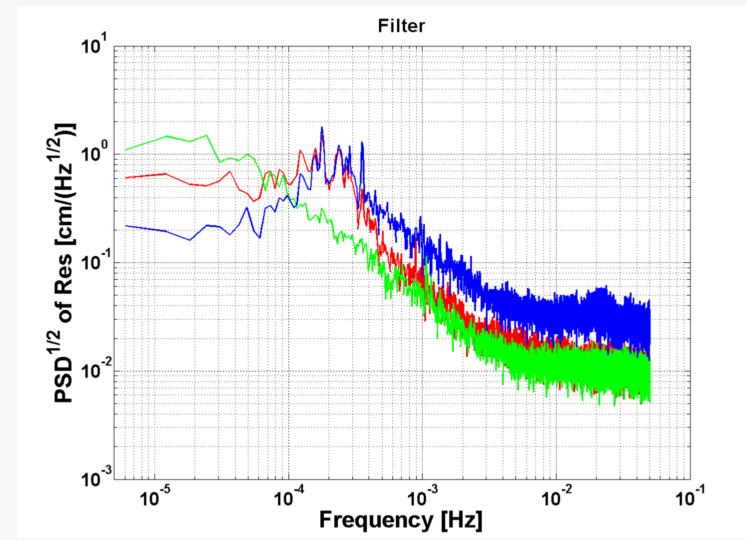
WEEKLY DOY 328-334	RMS Along/Cross/ Radial [cm] %	Mean Along/Cross/ Radial [cm]	MONTHLY DOY 305-334	RMS Along/Cross /Radial [cm] %	Mean Along/Cross/ Radial [cm]
Non filtered OMC	1.48 1.21 2.07	0.24 0.12 0.21	Non filtered OMC	1.56 1.20 2.21	0.10 0.10 0.14
filtered OMC	1.38 6.8% 1.09 10.0% 1.65 20.2%	0.24 0.12 0.21	filtered OMC	1.46 6.4% 1.08 10.0% 1.72 22.2%	0.10 0.10 0.14

Fig. 5: RMS and mean of the along, cross and radial components of the orbit solution computed with $\alpha = 1.5$ and $\nu = 1$.

- The position residuals contain less high frequency noise.



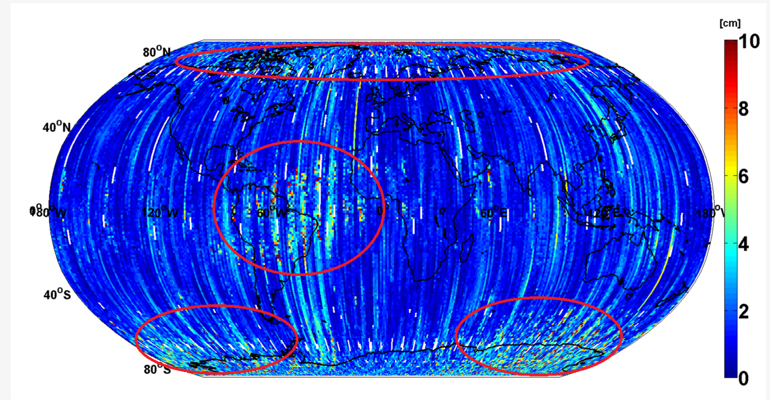
(a) Without filtering



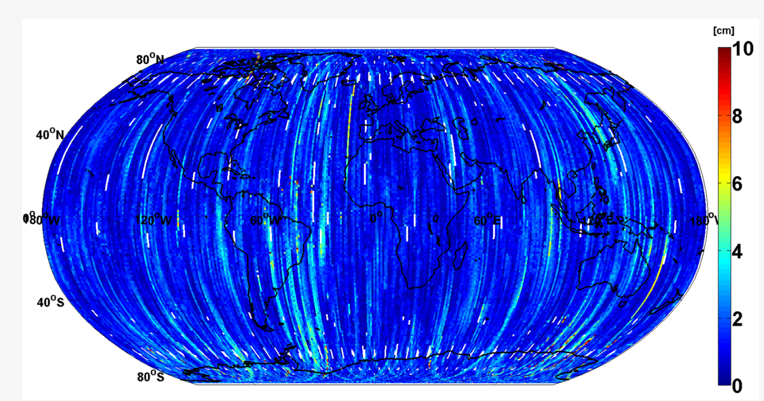
(b) With filtering

Fig. 6: Spectral analysis of position residuals with/without filter in November 2015 for Swarm A

- Global distribution of the residuals in radial direction with/without filtering shows that the noise in polar and equatorial regions is strongly eliminated.



(a) Without filter



(b) With filter

Fig. 7: Radial residuals with/without filter in November 2015, showing the improvement at polar and equatorial areas.

Conclusions

- Mátern covariance matrices with $\alpha = 1.5$ and $\nu = 1$ are used to mitigate the impact of noise increase due to ionospheric scintillations and these homogenize the observation noise.
- The spectral decomposition -slope of the psd at high frequency- of the filtered OMC is similar to the one that would be obtained without noisy observations.
- The noise caused by ionospheric scintillation is strongly eliminated using Mátern covariance matrix, with 6%, 10% and 20% in the along-, cross-track and radial direction, respectively .

References/Acknowledgement

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