Mitigation of ionospheric effects on Swarm GPS observations and kinematic orbits

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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

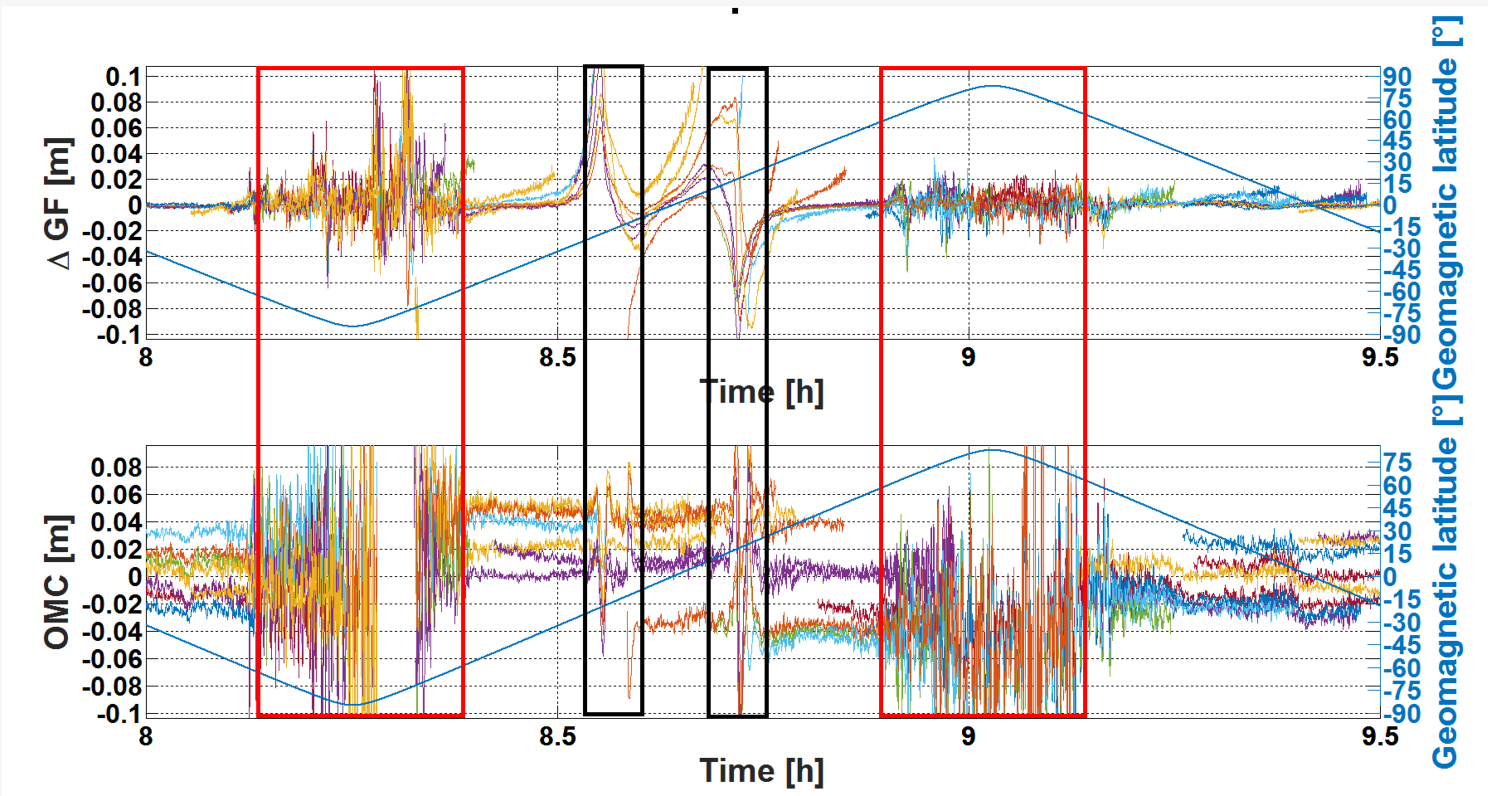


Fig. 1: Time differences of geometry-free linie combination (upper) and Observed-minus-Computed (OMC) of ionosphere-free linear combination for Swarm A on DoY 135, 2015.

- Large high frequency noise at polar areas and some equatorial areas (red box)
- Systematic errors at equatorial areas (black box)

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):

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

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

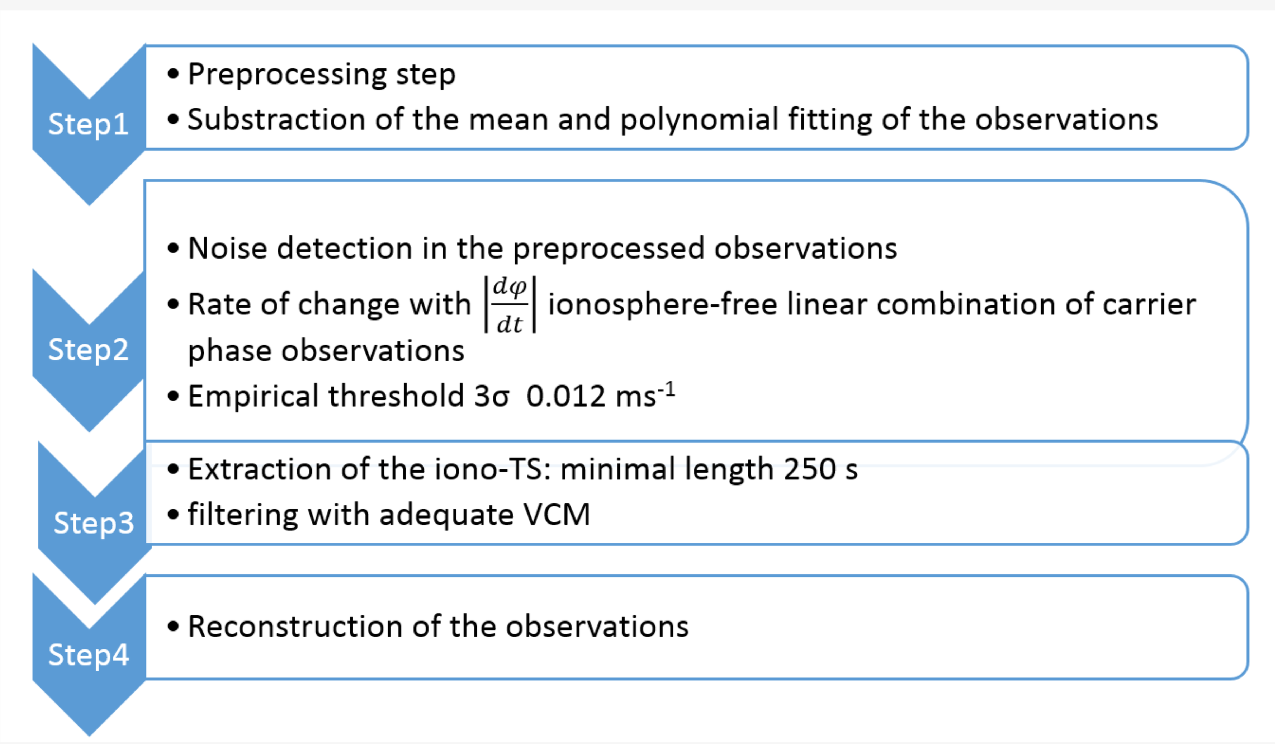


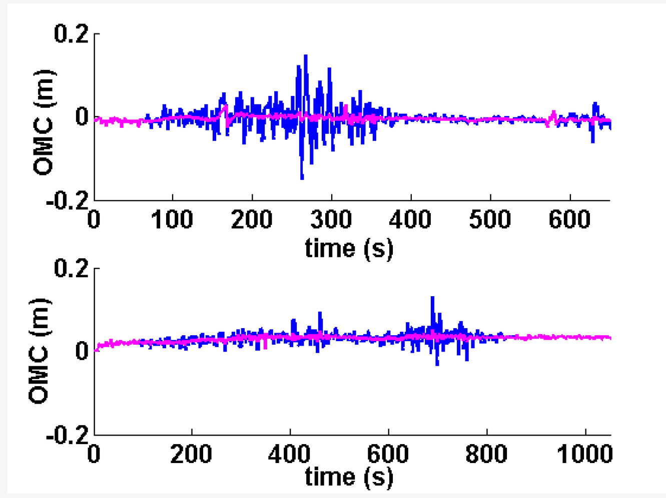
Fig. 2: Summary of the methodology used to detect, filter and reconstruct the contaminated time series of observations.

Filtering high-frequency noise with Mátern covariance matrix

- An adequate covariance matrix $\mathbf{W}$ (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 $\sigma_{\phi,ref} = 3mm$.



	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)

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

(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

- Daily RMSE in radial direction can be reduced by around 20%.

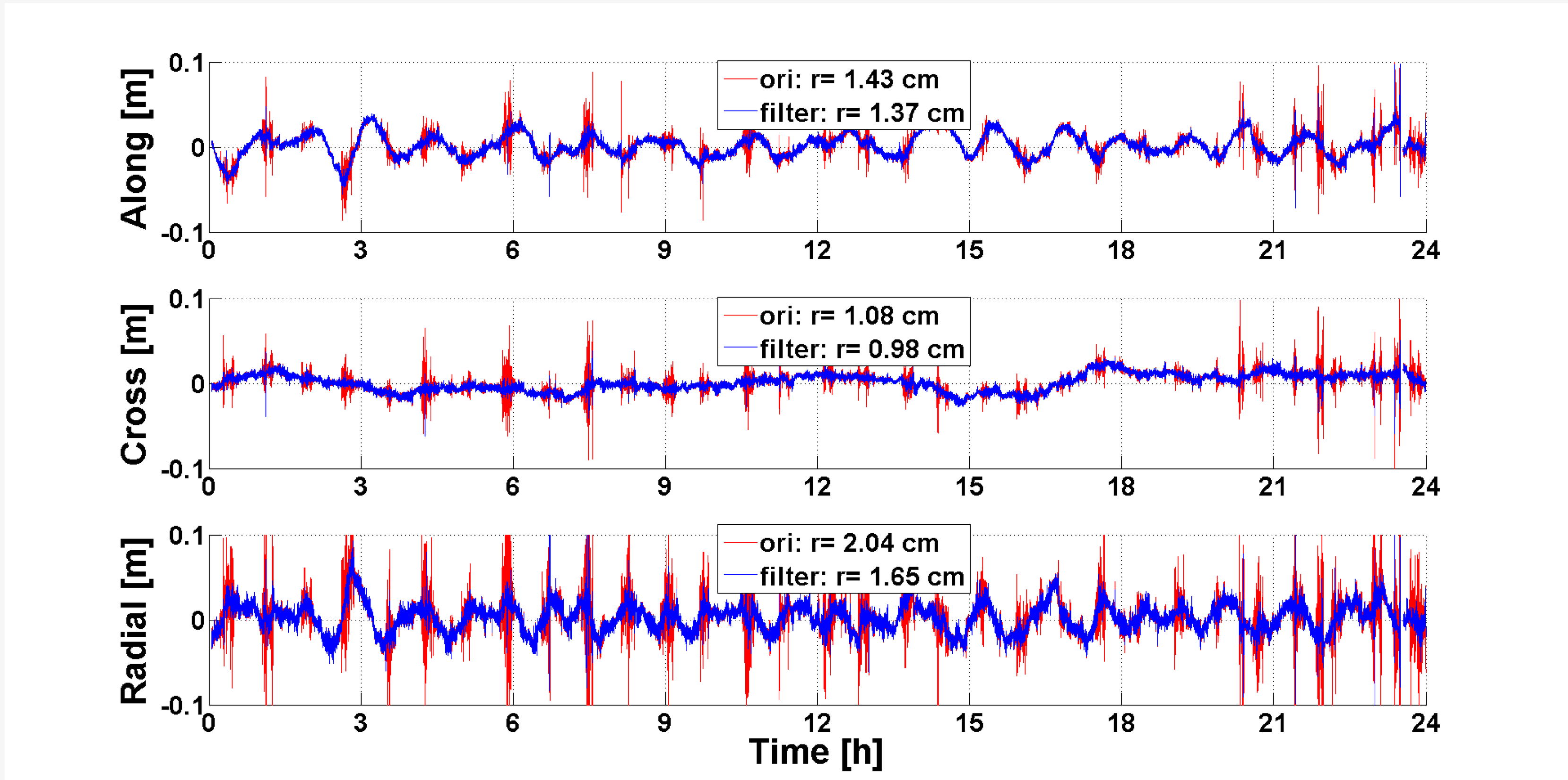
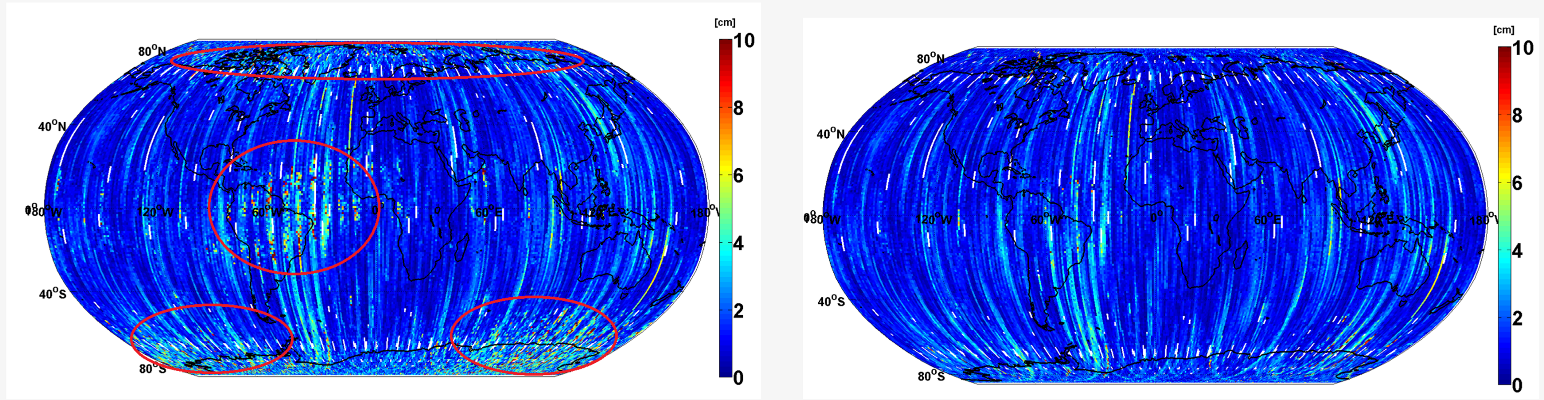


Fig. 4: Position residuals in the along, cross and radial components of the Swarm A orbit solution computed with (blue) and without (red) filtering, w.r.t. reduced-dynamic orbits from ESA, on DoY 333, 2015.

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

Impact of systematic errors at equatorial areas

- Phase OMC is the ionosphere-free linear combination of phase observations minus the geometry distance based on reduced-dynamic orbits, receiver clock errors and ambiguities.
- Large systematic errors (red) are caused by rapid change of electron density for Swarm A
- The corrected OMC (black) is polynomial curve fitting of undisturbed OMC (blue) plus white noise at the same level.
- The systematic errors are much smaller for Swarm C (violet) after the update of phase tracking loop (time series is 5 cm shifted).

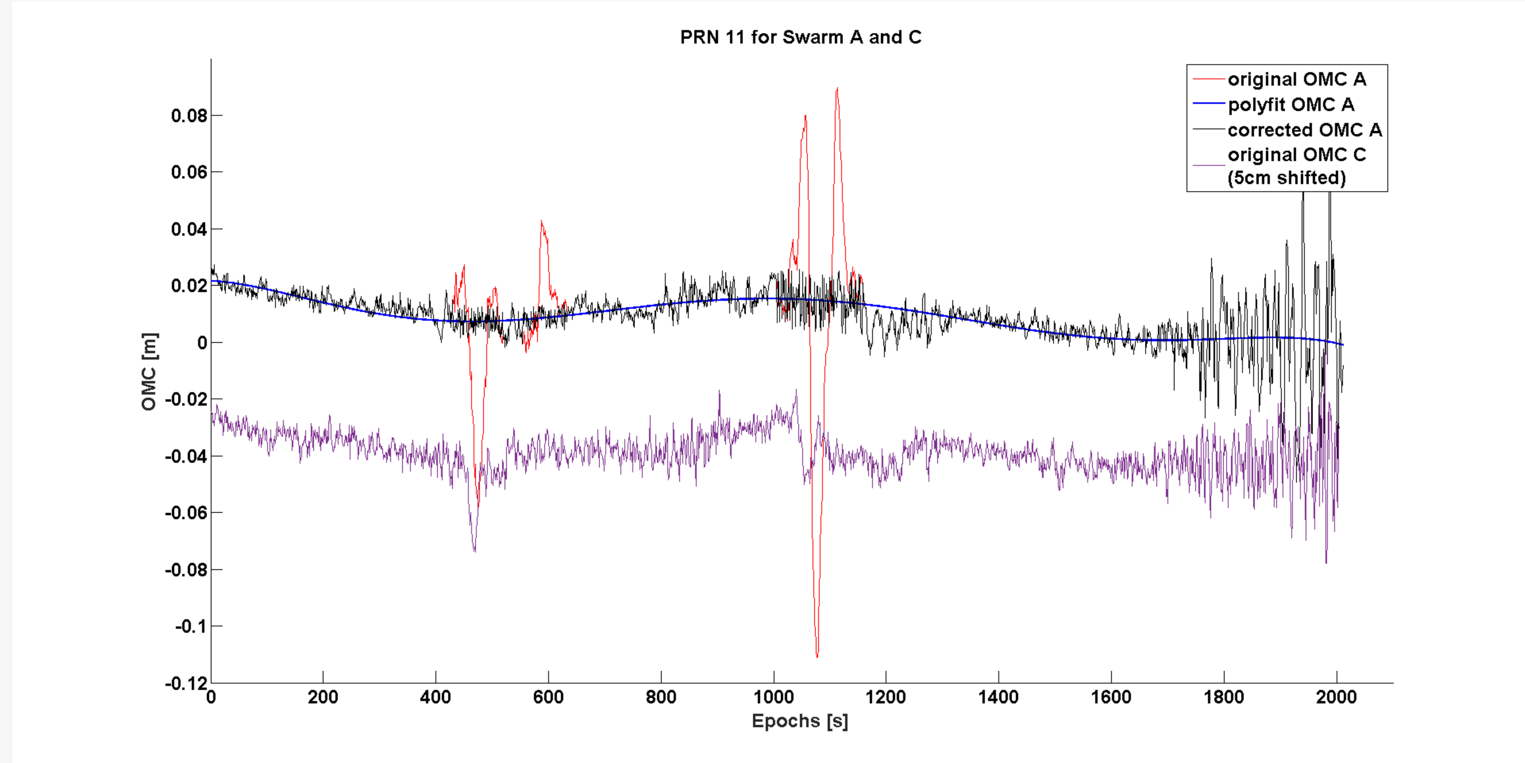


Fig. 6: Impact of systematic errors of PRN 11 for Swarm A and C, on DoY 135, 2015 from 30326 s to 32337 s.

- Severe systematic errors along geomagnetic equator are significantly eliminated after correcting the disturbed observations.

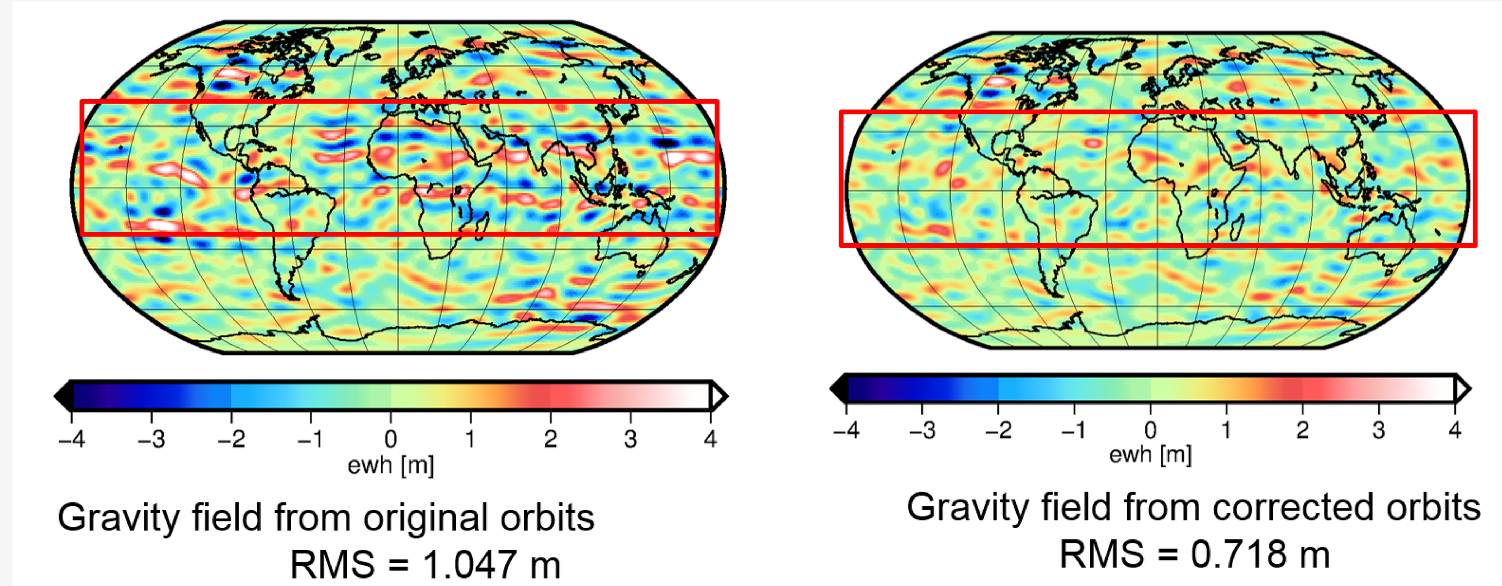


Fig. 7: Differences between the gravity field derived from the Swarm kinematic orbits and from GRACE KBR, Swarm A, Mai, 2015.

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.
- Systematic errors at equatorial areas can be eliminated using the polynomial curve fitting of undisturbed OMC, in order to reduce the errors in the gravity field.

References/Acknowledgement

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