Relative kinematic orbit determination for Swarm satellites

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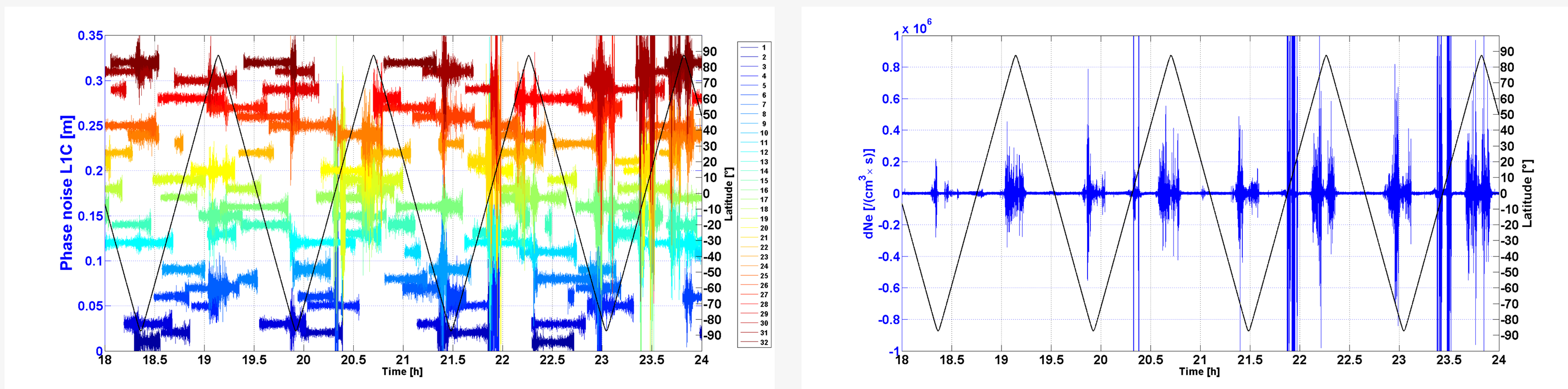
Introduction

The Swarm mission is ESA's first constellation of satellites to study the dynamics of the Earth's magnetic field and its interaction with the Earth system. In this contribution, we will determine the relative kinematic orbits using the GPS double-difference method and compare the orbits with the absolute kinematic orbits. First results show that although the noise in the relative orbits are enlarged, the typical systematic oscillations in the absolute orbits can be removed. Our investigations revealed that carrier phase observations from the Swarm satellites can contain half cycle ambiguities.

Fig. 1: Swarm constellation: Swarm A and C fly almost side-by-side at an initial altitude of 460 km, Swarm B in a higher orbit of about 530 km.

Receiver performance



(a) L1C phase noise (The time series are offset by PRN × 1 cm)

(b) Rate of ionospheric electron density

Fig. 2: L1C phase noise and rate of ionospheric electron density at Swarm altitude for Swarm A from 18-24 h on day 333 of 2015

- Carrier phase noise: 2-times differentiations of successive phase observations from RINEX file after removing geometric distance, (qualitative rather than quantitative evaluation).
- Electron density: derived from the current measured at the Electric Field Instrument (EFI) on Swarm satellite.
- Phase observations are strongly disturbed under ionospheric scintillations and the increase of noise corresponds to rate of ionospheric electron density.

Relative kinematic orbit determination

- The Swarm satellite A and C fly side by side, which makes the relative positioning between A and C possible. The observation and error modeling used for the relative kinematic orbit determination are listed in Table 1.

Table 1. Summary of the measurement and error models used for Swarm kinematic relative orbit determination

Model	Description
GPS tracking data (30 hours)	double-differenced ionosphere-free linear phase combination
GPS Orbits	CODE final GPS orbits and 5s clocks
GPS phase model	igs08.atx (week 1888)
Swarm attitude	quaternion from star camera
Swarm phase model	Swarm PCV map (provided by TU Delft)
stochastic model	equal weights
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-200D, 2004)+ Shapiro effect
reference station	reduced-dynamic orbits of Swarm A
reference GPS satellite	elevation higher than 35°

- The positions of Swarm A are kept fixed to the reduced-dynamic orbits and the kinematic orbits of Swarm C are estimated using the double-differences (DD) ionosphere-free combination.
- The observations from Swarm A and C at the same epoch can be directly used to form the DD-observations without interpolation to a common epoch.

References

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Ambiguity resolution

- The observation equation for ionosphere-free DD is:

$$DD = \nabla\Delta\rho + \lambda_c \nabla\Delta b_1 + \frac{cf_2}{f_1^2 - f_2^2}\nabla\Delta b_w$$

- In order to resolve the ambiguities to their integer values, the wide-lane ambiguities $\nabla\Delta b_w$ are first resolved with the Melbourne-Wübbena linear combination and introduced to the equation as known.
- Then the float narrow-lane ambiguities $\nabla\Delta b_1$ are estimated together with the baseline and resolved with the integer rounding method.
- The carrier phase observations of Swarm receiver contain half cycles. A histogram for the fractional part of the float narrow-lane ambiguities to their nearest integer for DoY 50, 2016 is shown in Fig. 3. The fractional part of around 50% ambiguities are smaller than 0.1 narrow-lane cycle, which can be fixed to an integer and around 35% are larger than 0.4 cycle, which can be fixed to half integer. Around 15% between 0.1 and 0.4 cycle are considered as unfixable.
- The rates of full cycle, half cycle and unfixed ambiguity from January to March, 2016 are shown in Fig. 4 .

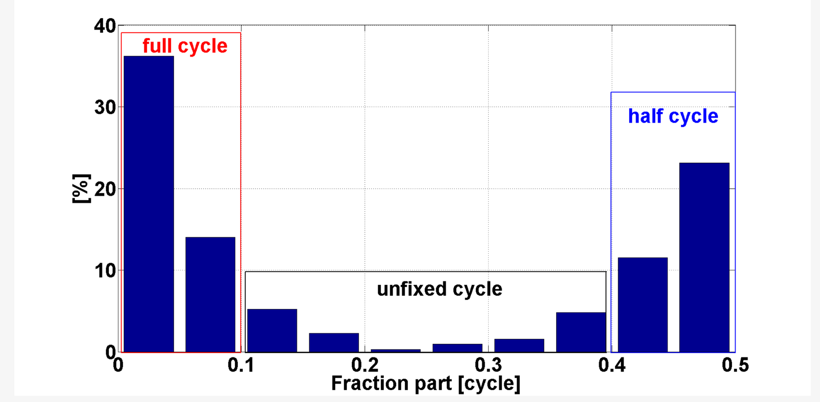


Fig. 3: Histogram for the fractional part of narrow-lane ambiguities on DoY 50, 2016

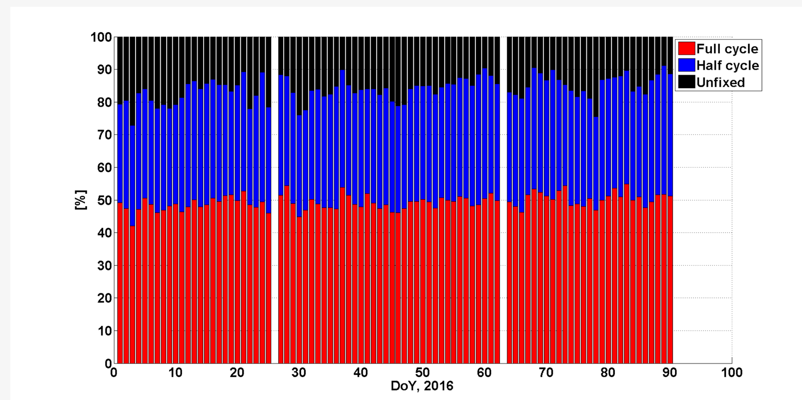
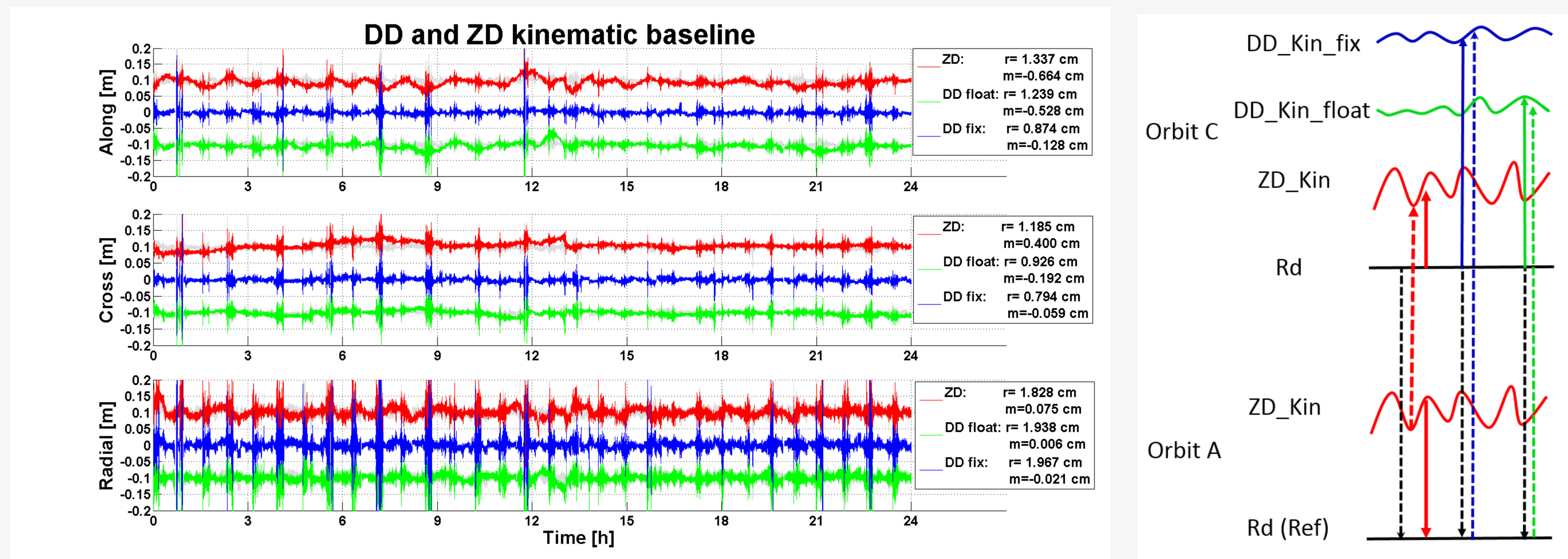


Fig. 4: Rates of full cycle, half cycle and unfixed cycle of narrow-lane ambiguities

Comparison of absolute and relative kinematic baseline

- The kinematic baseline estimated using DD with float and fixed solution and zero-difference (ZD) w.r.t. its reduced-dynamic baseline on DoY 10, 2016 are shown in Fig. 5 as an example.



(a)

(b)

Fig. 5: DD and ZD kinematic baseline w.r.t. reduced-dynamic baseline for Swarm C (10 cm offset) (a) and its schema (b)

- The RMS errors in along, cross and radial track are around 1, 1 and 2 cm for ZD and DD, respectively.
- The large phase noise caused by the ionospheric scintillation degrades the position and is mainly absorbed in radial track. Improved observation weighting is under investigation.
- The systematic oscillations in ZD are significantly eliminated using DD and are further removed using the fixed ambiguity.

Acknowledgement

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- The systematic oscillations in ZD-baseline are caused by the different tracked GPS satellites for Swarm A and C. Although they fly near to each other, the tracked satellites are not always the same, shown in Fig. 6. Subsequently, the different GPS constellations lead to the different ZD position residuals (Fig. 6 top) and then the oscillations in baseline (Fig. 5 red).

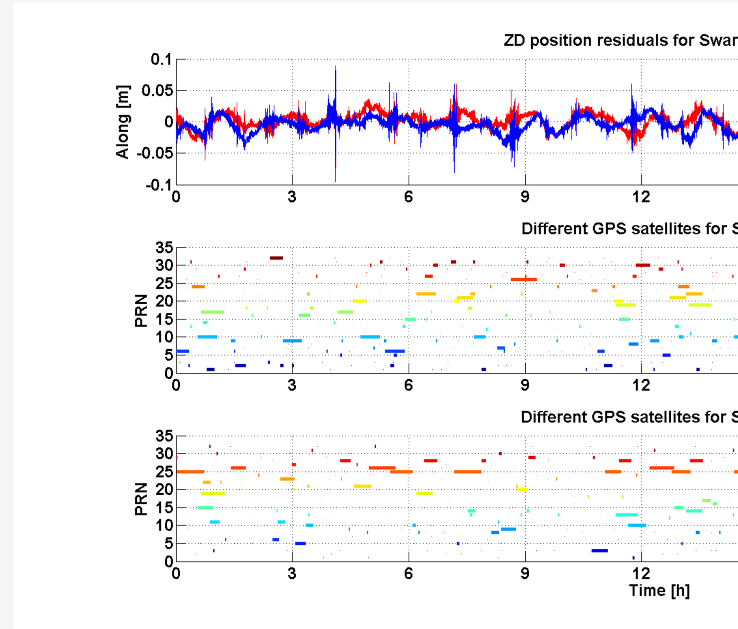
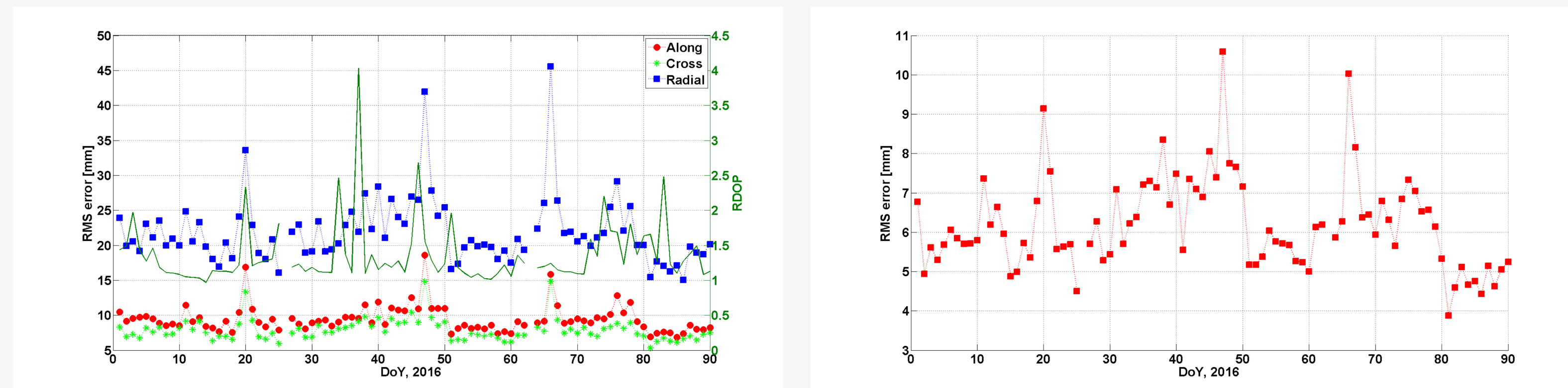


Fig. 6: ZD position residuals w.r.t. reduced-dynamic orbits (top) and different tracked GPS satellites for Swarm A (middle) and C (bottom)

Daily solution of kinematic relative baseline

- The daily RMS errors of position residuals with fixed ambiguities w.r.t. reduced-dynamic orbits in along, cross and radial track and carrier phase residuals from January to March, 2016 are shown in Fig. 7.

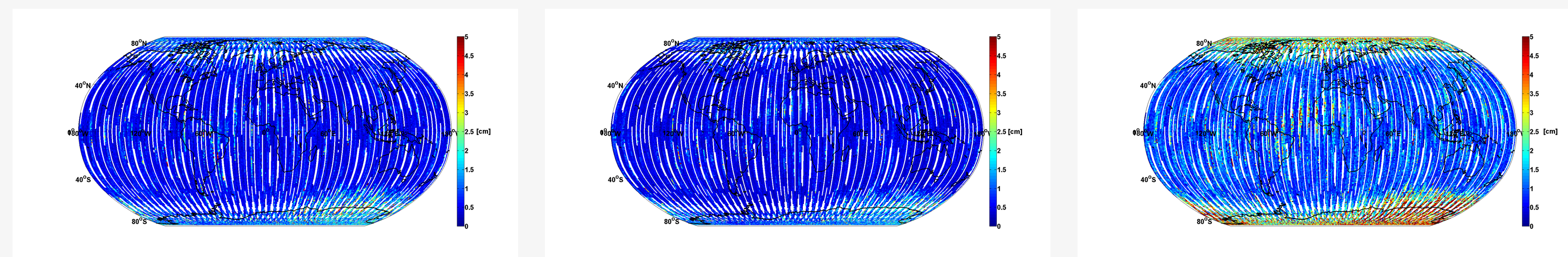


(a) Daily RMS errors of the difference between relative kinematic and absolute reduced-dynamic orbits, as well as RDOP

(b) Daily RMS errors of carrier phase residuals

Fig. 7: Daily RMS errors. Their magnitude depends on both the satellite geometry (RDOP) and the observation quality (phase residuals).

- The daily RMS errors of position residuals are around 1, 1 and 2 cm, respectively.
- The daily RMS errors of DD phase residuals are at the mm level.
- The bin-wise global distribution of RMS errors of position residuals are shown in Fig. 8. The quality of the kinematic orbits is highly affected in polar areas and some equatorial areas due to ionospheric scintillations, especially in the radial track.



(a) Along

(b) Cross

(c) Radial

Fig. 8: Global distribution of RMS errors of position residuals

Conclusion

- The carrier phase observations of Swarm contain half cycle ambiguities. Per day around 50% of the ambiguities can be fixed to integer and 35% can be fixed to half cycle.
- The rms errors of relative orbits with fixed ambiguity in along, cross and radial track are about 1 cm, 1 cm and 2 cm, respectively. The position quality in polar areas and some equatorial areas is degraded due to ionospheric scintillations.
- The systematic errors in ZD-baseline are significantly removed using fixed DD.

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