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Swarm absolute and relative orbit determination

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Introduction

Swarm is the fifth mission of ESA's (European Space Agency) living planet programme. Consisting of three identical satellites, Swarm was launched on 22 November 2013 to unscramble the Earth's geomagnetic field and its temporal variation.

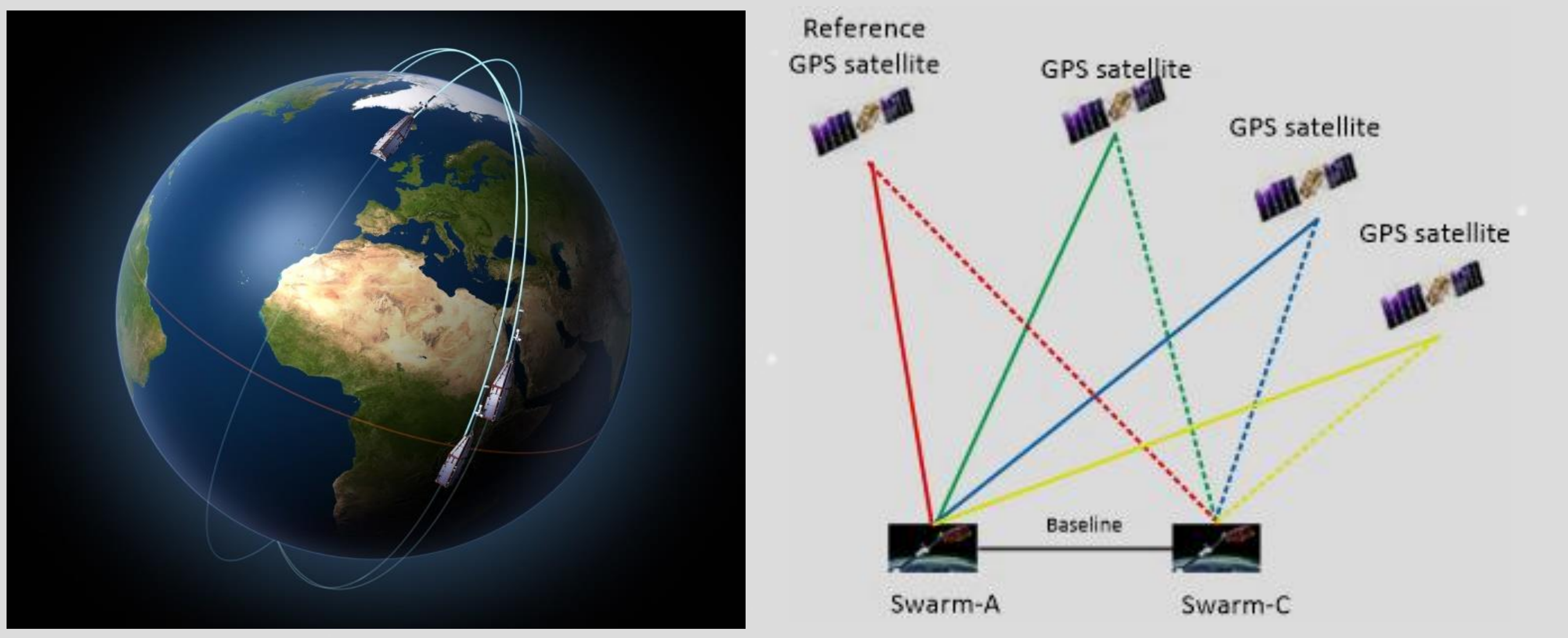

Figure 1: Artist's view of Swarm constellation (left, ©ESA/ATG Media lab): Two satellites are flying in pendulum formation at near-polar orbits with an initial altitude of 460 km, the third flying in a higher 530 km orbit. Absolute and relative orbit determination can be done using the onboard GPS system (right).

Swarm satellites are equipped with on-board high precision 8-channels dual-frequency Global Positioning System (GPS) receivers, which provide prime observations for precise absolute and relative orbit determination of low Earth orbiters (LEO). These orbit determination methods are implemented in the GHOST (GPS High Precision Orbit Determination Software Tools) software (Wermuth et al, 2010) developed by DLR (German Space Operations Centre) and TU Delft. In this research, one of the GHOST precise orbit determination tools using Kalman filtering approach was extended to make use of frequency-dependent antenna patterns and iterative integer ambiguities fixing. Preliminary computation was done for the pendulum formation flying Swarm-A and Swarm-C satellites in the period 2014/219 - 2014/235 (day of year), detailed information can be found in Table.1.

Table 1: Methods and models used in absolute and relative orbit determination

Item	Absolute orbit determination	Relative orbit determination
GPS observations	Un-differenced frequency dependent observations	Double-differenced frequency dependent observations
GPS data processing	Clock synchronization, data editing, phase wind-up	
GPS products	CODE 5s GPS orbits and clocks, transmitter antenna phase center offsets and variations, Ionospheric maps	
Antenna patterns	Frequency dependent phase center variations from absolute orbit determination	
Gravitational forces	GOCO03S gravity field, FES2004 ocean tides, third body accelerations	
Non-gravitational forces	Cannon ball model, Jacchia 71 air density model, conical Earth shadow, empirical acceleration in radial/along-track/cross-track at 10 mins interval	
Ambiguities	Float ambiguities	Half cycle ambiguities
Kalman filter	1 iteration	Continue till convergence

Phase Center Variation

The Phase Center Variation (PCV) map has been realized as a fundamental way to improve precise absolute orbit determination (Jäggi, et al. 2009), which was usually based on the Ionospheric-Free (IF) combination. This study implemented a Kalman filter approach dealing with frequency dependent patterns, the IF combination of these two maps looks similar to the IF pattern in (van den IJssel, et al. 2015).

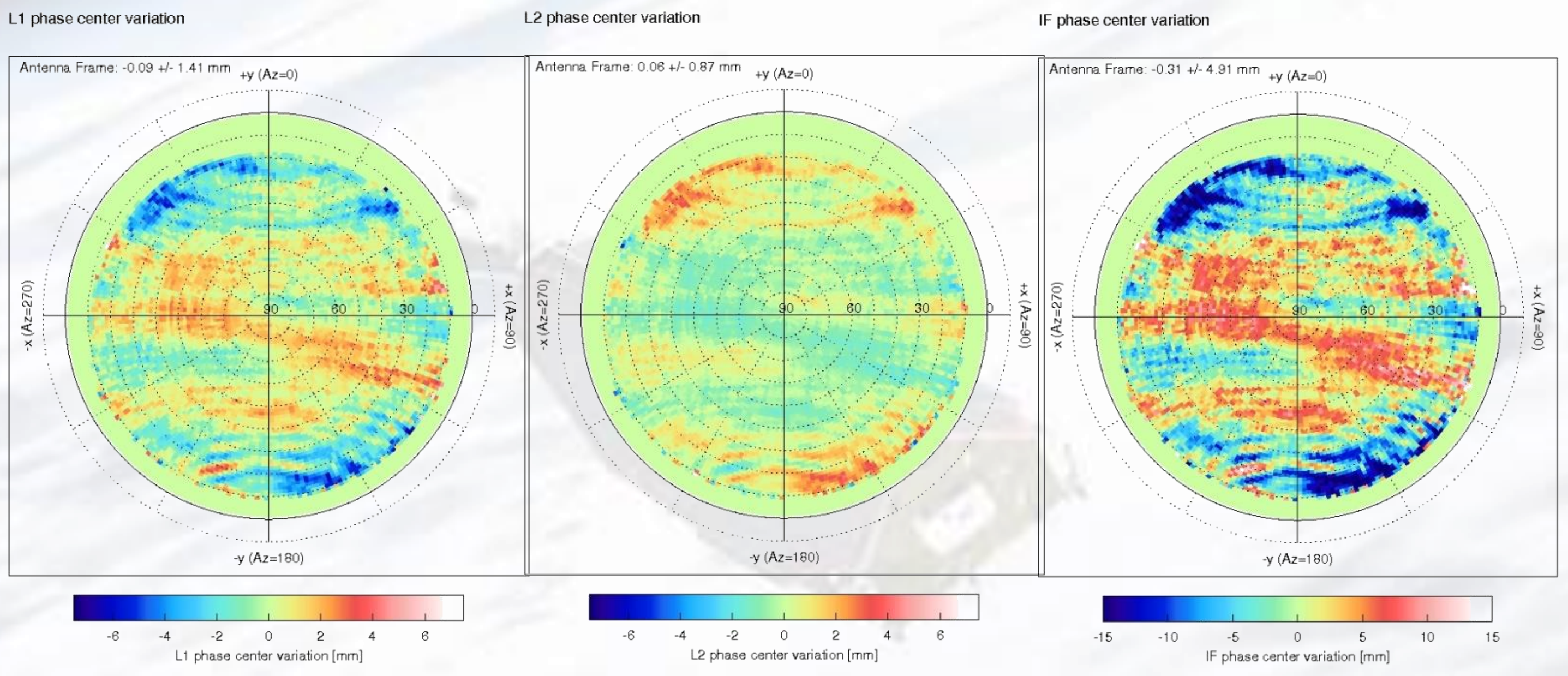

Figure 2: PCV map of Swarm-A on the first(left)/second(middle) frequency and the ionospheric free combination (right). All Swarm satellites experienced similar patterns, and on two frequencies showed nearly flipped distribution with absolute ratio close to f_1^2/f_2^2, in which f denotes to frequency. It emphasized that PCV is highly determined by the frequency of signal.

Absolute orbit determination results

Phase residuals on each frequency are obviously reduced by the PCV maps, thus improve coherence to the external Satellite Laser Ranging (SLR) validation system. During the orbit determination process, so called empirical accelerations are estimated to compensate the mis-modelling of satellite dynamics, their change indicate that PCV maps are able to shift and improve orbit (especially in radial and cross-track direction).

Table 2: Swarm-A and Swarm-C absolute orbit determination using frequency dependent PCV maps.

Satellite		Phase [mm]		Empirical acceleration [nm/s^2]			SLR [cm]
		f_1	f_2	radial	Along track	Cross track	
Swarm-A	w/o PCV	1.91	1.25	5.1+/-1.9	5.1+/-12.5	1.9+/-12.2	-0.4+/-2.4
	w PCV	1.59	1.07	0.6+/-1.5	5.0+/-10.0	0.2+/-10.9	-0.5+/-2.2
Swarm-C	w/o PCV	1.92	1.24	5.1+/-1.9	5.2+/-12.4	2.0+/-12.2	-0.1+/-2.0
	w PCV	1.64	1.08	0.6+/-1.5	5.0+/-10.0	0.2+/-10.9	-0.2+/-1.8

Relative orbit determination results

The Least squares AMBiguity Decorrelation Adjustment (LAMBDA) is used to fix double-differenced ambiguities. In the Kalman filter, fixed ambiguities from previous iteration are set as known input in next iteration, thus the fixing success rate is being continuously improved until convergence. For Swarm mission whose receivers suffering from half cycle ambiguity, the wavelength on each GPS signal frequency has to be adjusted to half. PCV maps hardly make improvement to the ambiguities fixing, reasoning that PCV maps are nearly identical for two satellites thus when double-differenced these effects are mostly canceled.

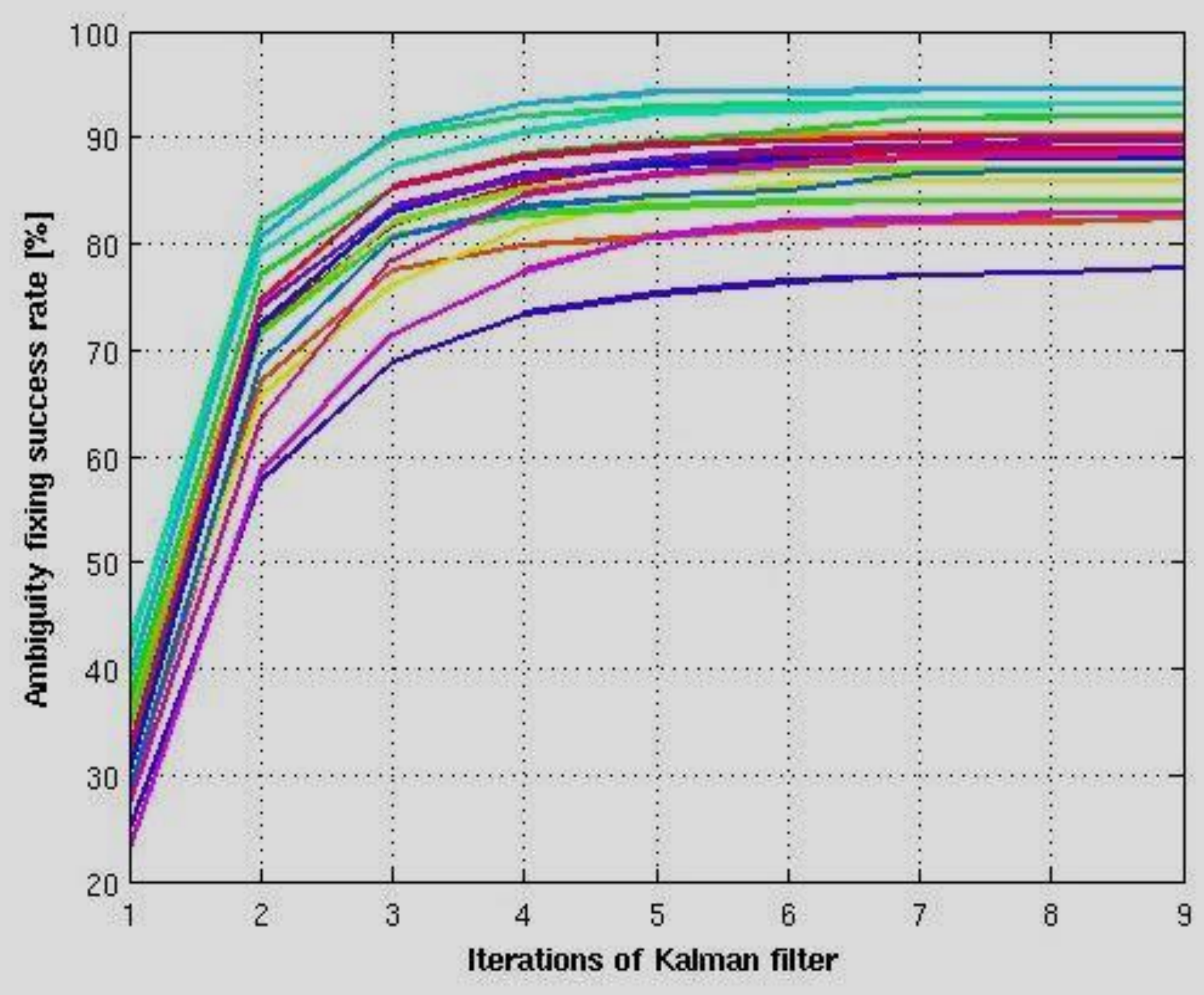

Figure 3: Double-differenced half cycle ambiguity fixing success rate in iterative Kalman filter, all 17 days were plotted in different colors. The success rate became higher as fixed ambiguities from previous iteration significantly facilitate the next iteration. In general it converged after 5 iterations, average success rate was 88%.

For relative orbit determination validation, a reasonable way is analyzing the consistency between kinematic and reduced-dynamic baselines (Allende-Alba, et al. 2016). Both approaches are based on ambiguity-fixed GPS observations, but the kinematic one solely exploiting GPS observations in a batch least squares filter, while the other using Kalman filter which relies on the reduced-dynamic models of satellites.

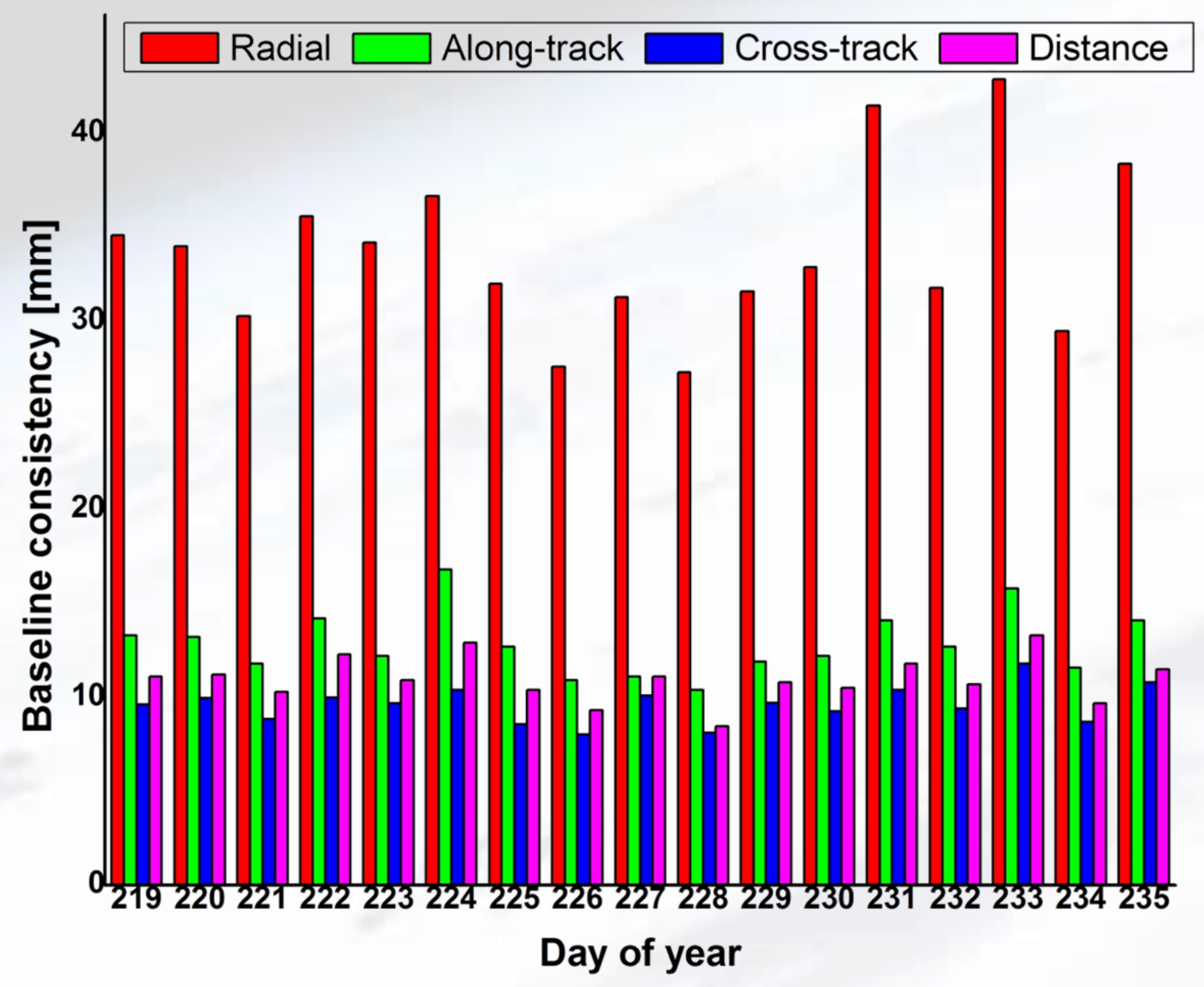

Figure 4: Consistency between kinematic and reduced-dynamic baselines. The radial baseline consistency was larger because the component of Geometric Dilution Of Precision in this direction has significant impact. The 1 dimensional distance statistics was 11 mm, comparable to the research in (Allende-Alba, et al. 2016).

Ionospheric influence on baseline determination

Swarm GPS receivers suffer from ionospheric scintillation, especially during polar and equatorial passes (van den Ijssel, et al. 2015), which can be observed on the daily phase residual variations. The ionospheric influence at these areas repeated every orbital period. A shorter orbital arc computation excluding Earth polar areas was done and the 1 dimensional baseline consistency became much better, from 11 mm to 5 mm level. The ambiguities fixing success rate also reached to 96.9%, compared to the average 88% of 24 hours orbital arc.

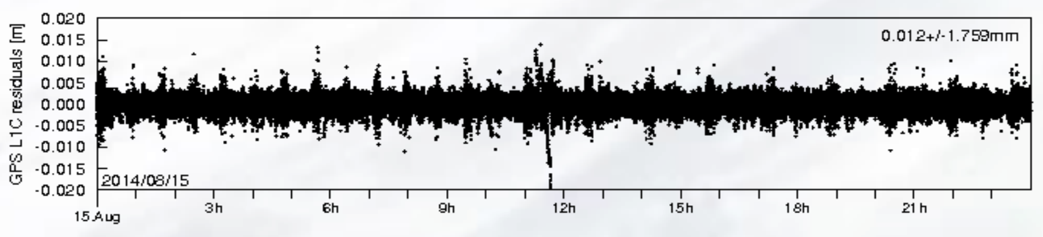

Figure 5: Swarm-C phase residual varying trend for day 14/227 (22-Aug-2014). Note the peaks are always at polar and equatorial areas.

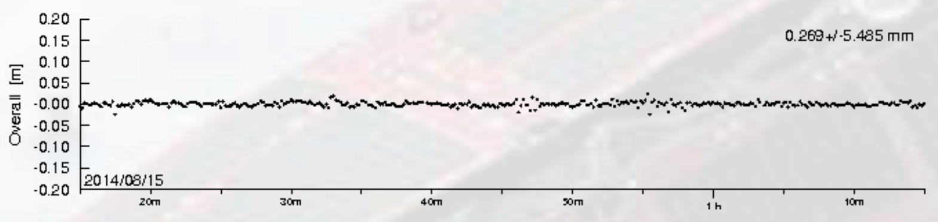

Figure 6: Consistency between kinematic and reduced-dynamic baselines, when polar area was excluded. Day: 14/227 (22-Aug-2014).

Summary and discussion

A preliminary analysis of Swarm absolute and relative orbit determination was done in this research.

- Frequency dependent PCV maps improve absolute orbits, mostly in radial and cross-track direction.
- The iterative Kalman filter for relative orbit determination is able to fix 88% half cycle ambiguities in 5 iterations, reach to 11 mm consistency between kinematic and reduced-dynamic baseline.
- Excluding polar areas affected by ionospheric scintillation improve the integer ambiguity fixing rate to 96.9%, leading the consistency between kinematic and reduced-dynamic baselines to 5mm.
- Future work can be done with antenna code patterns, and receiver tracking loop settings which also impact on receiver performance in more active ionospheric scintillation area.

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