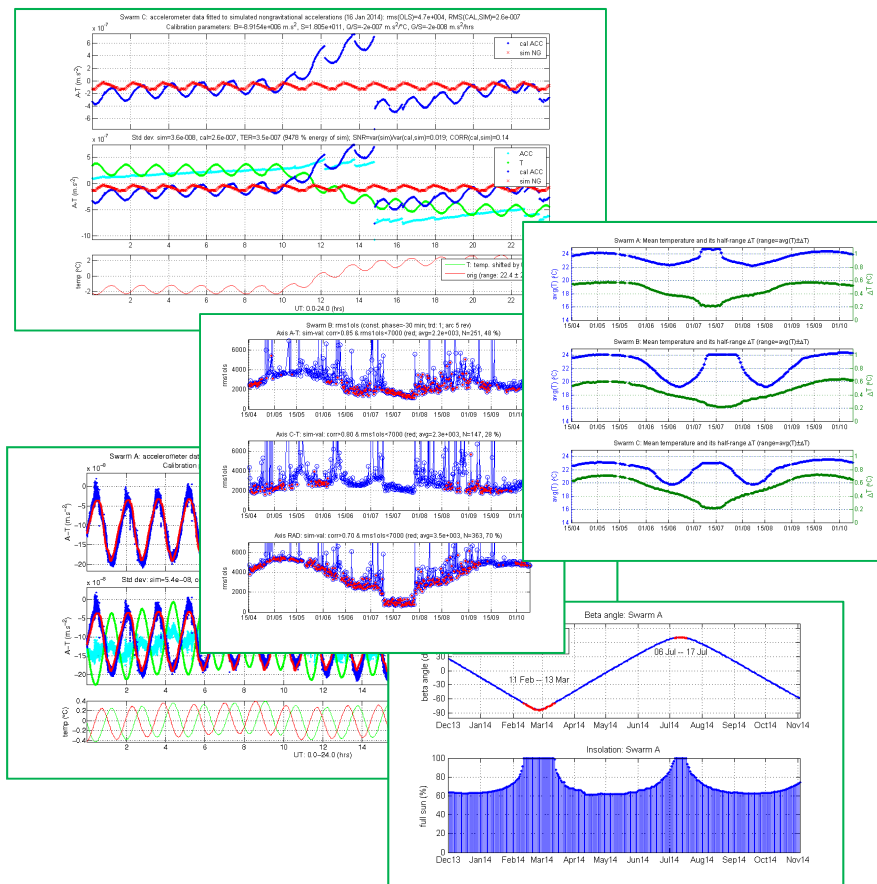


Swarm ACC data: physical signal and temperature dependence



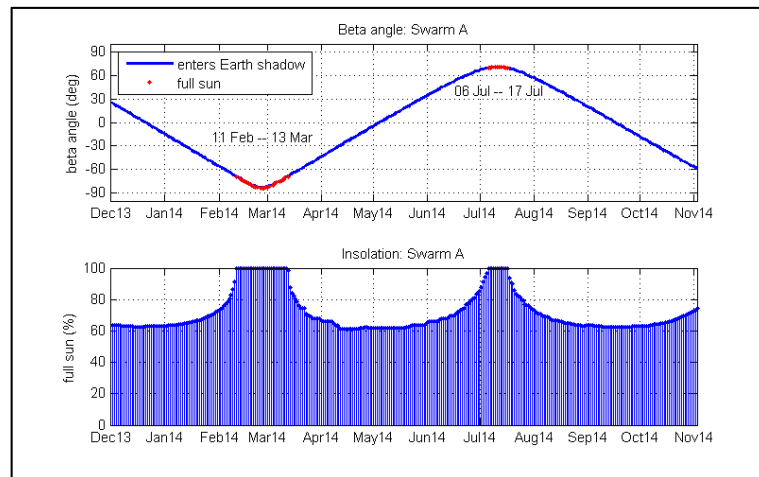
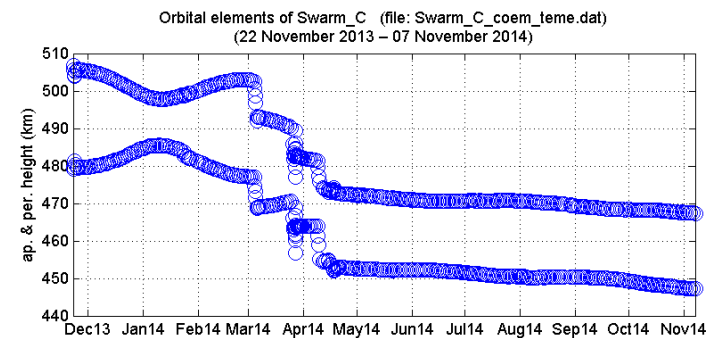
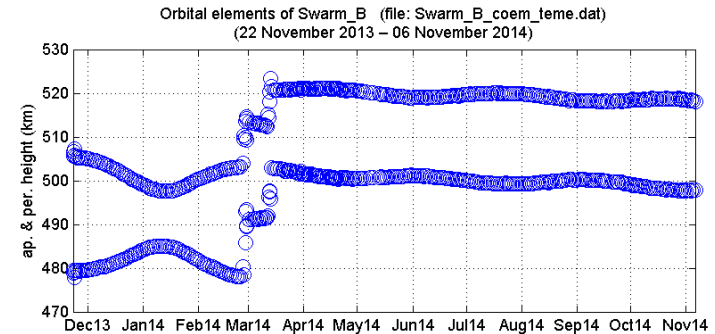
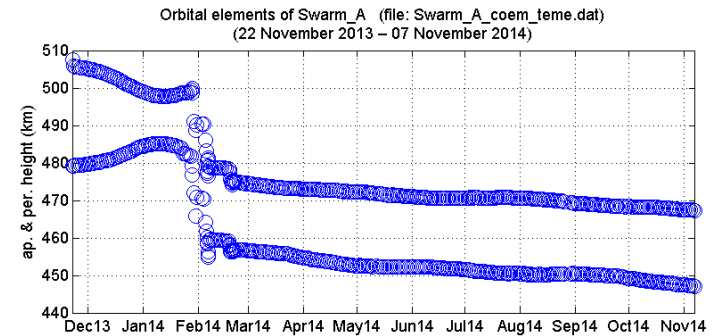
Aleš Bezděk
Josef Sebera
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Astronomical Institute,
Academy of Sciences of the
Czech Republic

Swarm 4th DATA QUALITY
WORKSHOP, GFZ Potsdam,
2–5 December 2014

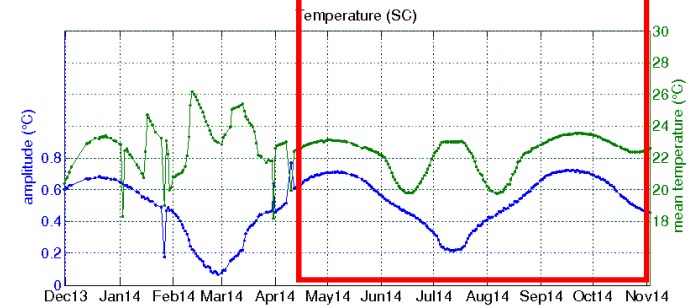
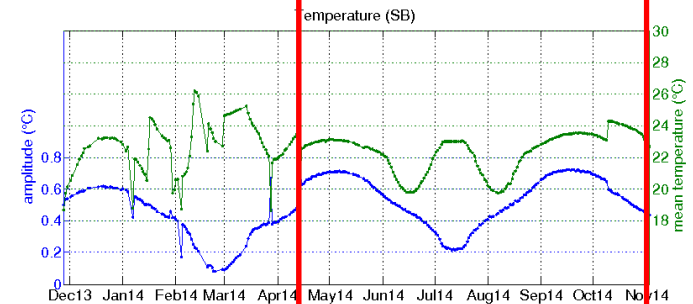
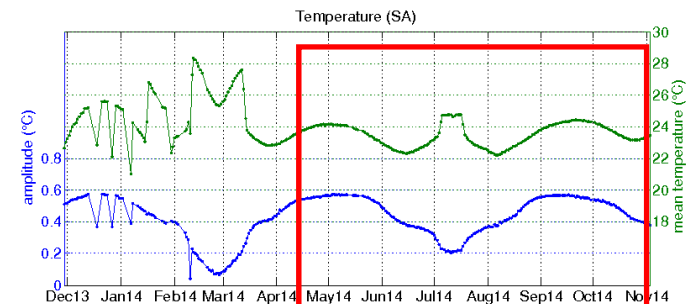
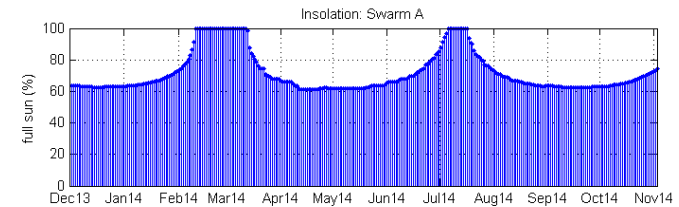
Swarm satellites: orbit & insolation

- Orbital manoeuvres before mid-April 2014
 - mean altitude of Swarm A/C ≈ 460 km
 - mean altitude of Swarm B ≈ 510 km
- Full-sun conditions: March, July 2014
- We have a macromodel $\rightarrow$ better modelled nongravitational forces



Swarm satellites: temperature

- Long-term temperature behaviour more stable since mid-April 2014
- We have new GPS kinematic orbits
 - time step 10 sec: 25 Nov – 14 Jul
 - time step 1 sec: 15 Jul – 9 Oct
- We selected a **study period** with a stable mean temperature behaviour & GPS data available:
 - **15 Apr – 9 Oct 2014**
 - we estimated new gravity field models
 - we studied temperature & ACC data



Gravity field models from new GPS orbits

- Swarm A/C: inc=87.35°, mean alt=460 km
- Swarm B: inc=87.75°, mean alt=510 km
- Grace A, Jan 2003: inc=89°, mean alt=480 km
 - Grace A: time step 30 sec

Upper figure: previous monthly solutions of Swarm A/B/C

- monthly solutions Feb/Mar 2014
- for more details, see our Copenhagen presentation

Middle figure: new solutions for 10-sec Swarm orbits

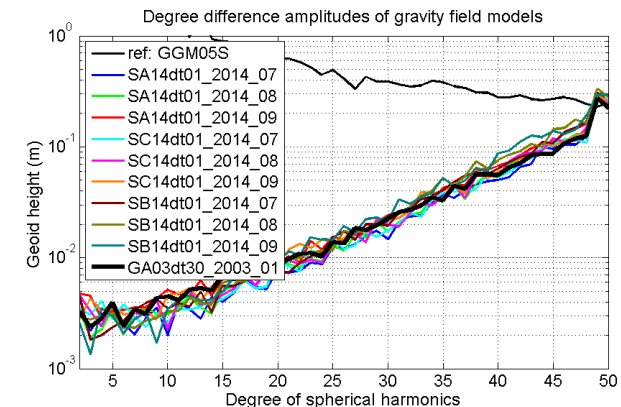
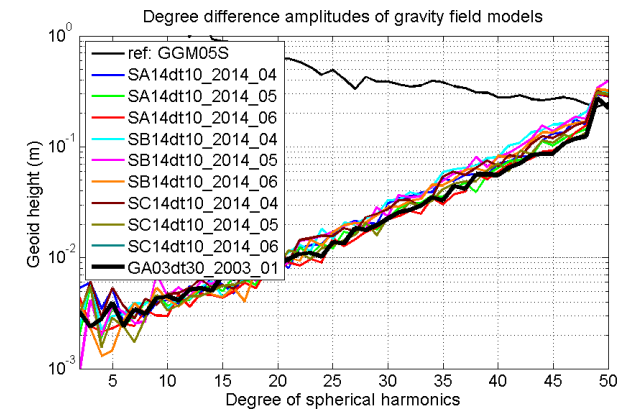
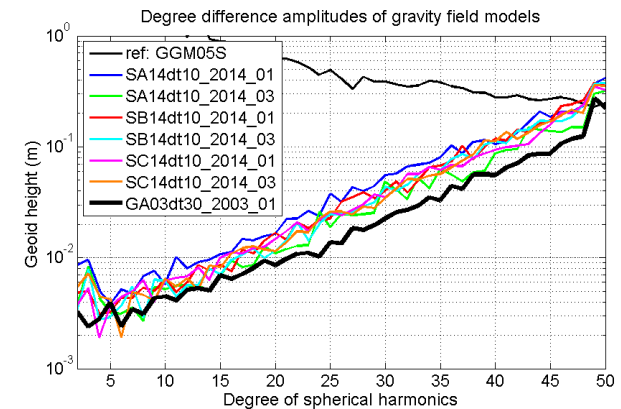
- monthly solutions Apr/May/Jun 2014
- clearly there is an [improvement wrt previous solutions](#)

Bottom figure: new solutions for 1-sec orbits

- monthly solutions Jul/Sep/Oct 2014
- even slightly better compared to new 10-sec solutions

Better Swarm solutions are favourable both for:

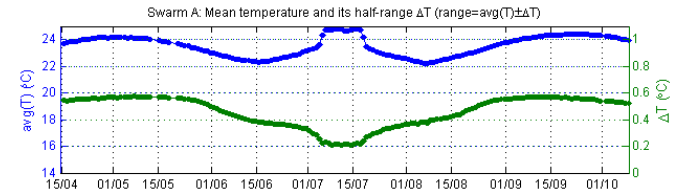
- gravity field solutions derived from Swarm GPS orbits
- GPS-based calibration of Swarm ACC data



Swarm satellites: nongravitational signal (NG)

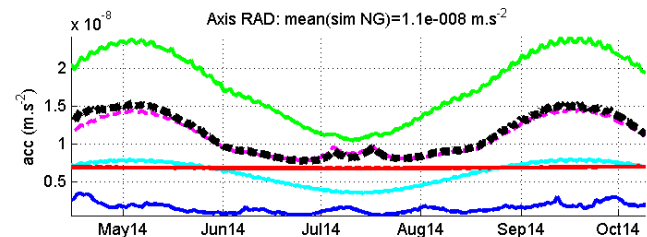
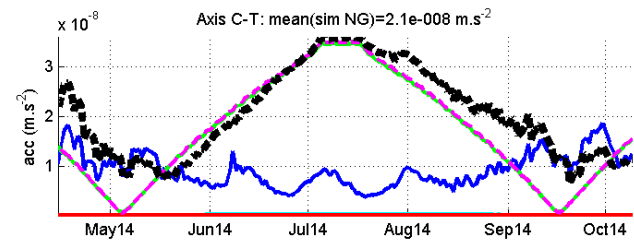
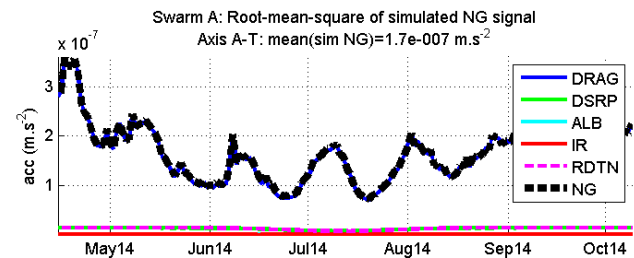
Upper figure shows the temperature on Swarm A:

- left axis: **mean temperature** (22—24 °C)
- right axis: **amplitude of temperature variation** around the mean (std dev) (0.2–0.5 °C)
- Orbit in the full sun: around 15 July



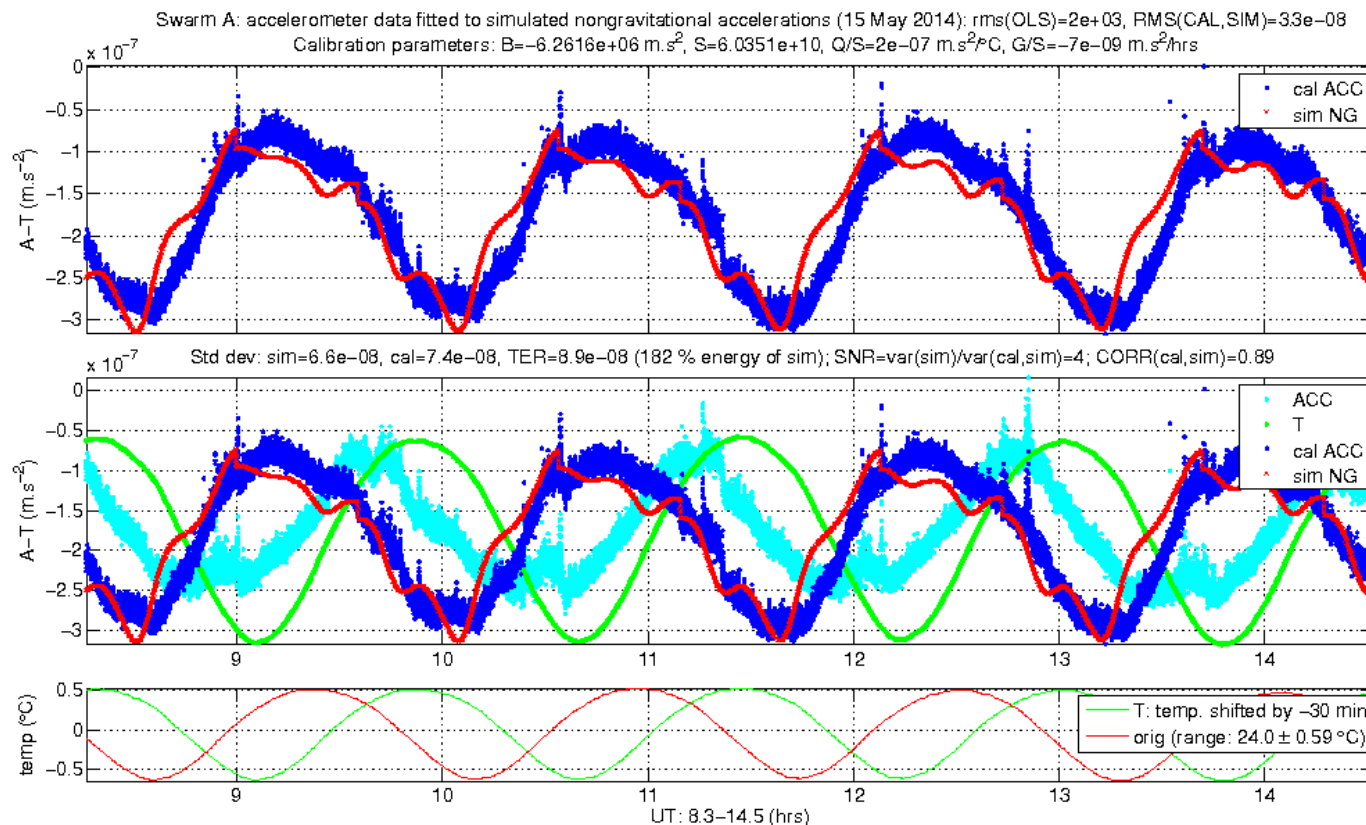
Bottom figure: magnitude of NG accelerations:

- Physical NG signal **in along-track (A-T) direction** is approx. **ten times stronger** compared to those in cross-track (C-T) and radial (RAD) directions
- Similar behaviour for Swarm B, Swarm C
- NG signal in A-T direction dominated by atmospheric drag
- Measured physical signal for ACC ten times stronger in A-T direction compared to other directions



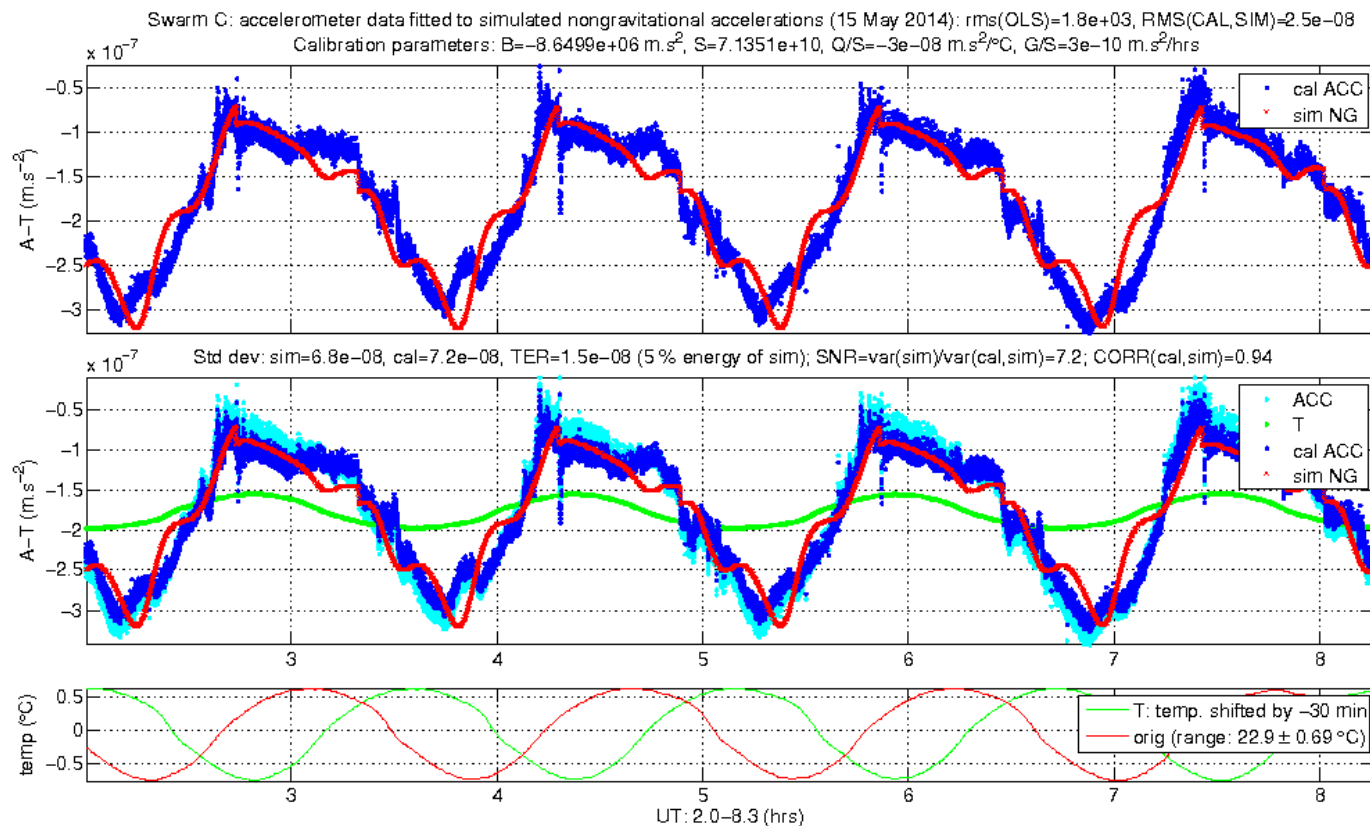
Recall: Temperature dependence of ACC data: Swarm A/B

- Example: Swarm A, 15 May 2014
- Large temperature dependence of ACC readouts
 - the same applies to ACC data of Swarm B
- Shown is an arc of 4 revolutions
- Orbital arc = specified part of satellite trajectory (e.g. $\frac{1}{2}$ revolution, multiple revolutions, 1 day)



Recall: Temperature dependence of ACC data: Swarm C

- Example: Swarm C, 15 May 2014
- Generally much smaller temperature dependence compared to Swarm B/C
- Here, temperature on ACC oscillates around mean 22.9 ± 0.7 °C (red curve in bottom panel)



Validation of ACC data by means of simulated NG signal

$$\begin{aligned}\text{UNCAL} &= \mathbf{B} + \mathbf{S} \times \text{SIM} + \mathbf{Q} \times \mathbf{T}(\mathbf{t} + \mathbf{F}) + \mathbf{G} \times (\mathbf{t} - \mathbf{t}_0) + \varepsilon \\ \text{CAL} &= [\text{UNCAL} - \mathbf{B} - \mathbf{Q} \times \mathbf{T}(\mathbf{t} + \mathbf{F}) - \mathbf{G} \times (\mathbf{t} - \mathbf{t}_0)] / \mathbf{S}\end{aligned}$$

- **UNCAL**..uncalibrated ACC data; **B**..bias; **S**..scale factor; **SIM**..modelled NG signal;
- **Q**..temperature factor; **T(t+F)**..temperature with phase shift **F**; **t**..time; **G**×(t−t₀)..trend; ε..noise
- **CAL**..calibrated ACC signal
 - this pair of equations is defined for each linear ACC channel
 - local reference frame (LRF) is used: along-track (A-T); cross-track (C-T); radial (RAD)

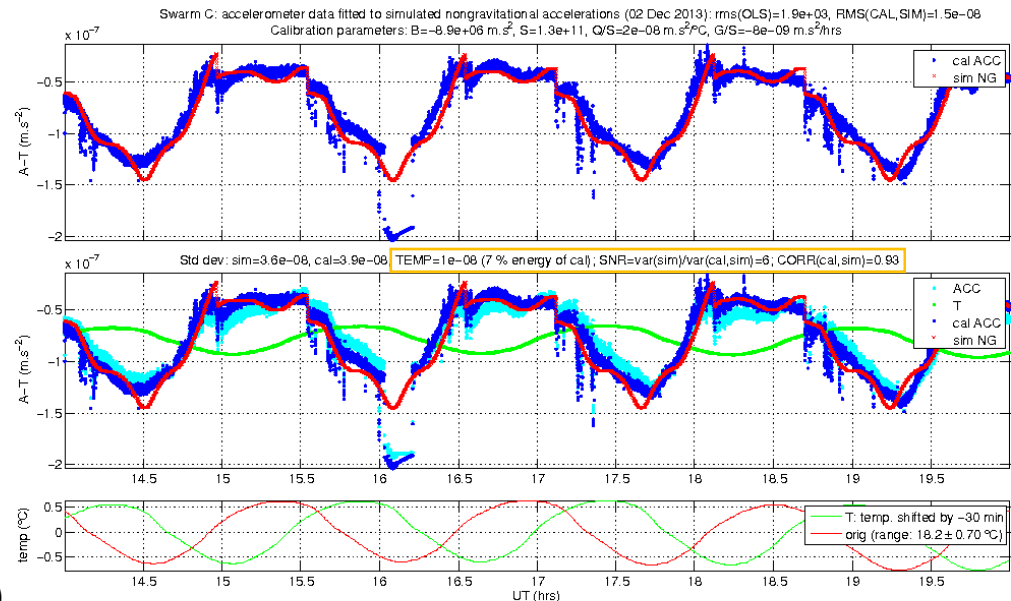
Swarm C (2 Dec 2013)

- **T(t+F)**: **F**=-30 min
- **CORR**=0.93 (match **CAL**&**SIM**)
- **TER**=7%
(temperature-energy-ratio=
energy in **T** divided by
energy in **SIM**)

If CORR is “high” & RMS “low”:

→ waveform of **CAL**
validated by **SIM** (**SIM-validated**)

→ for SIM-validated arcs TER quantifies the contribution of temperature **T**



Testing of temperature correction by SIM-validation

- ACC waveform is compared with simulated physical NG signal
- To the comparison, optionally the temperature variation signal can be added
- Linear temperature correction (LTC):
 - temperature variation signal $Q.T(t+F)$ is subtracted from observed ACC data readouts
 - one needs to know the amplitude Q and phase F
 - so far, the phase F appears to be constant

SIM-validated arcs are defined:

- good agreement of (un)corrected ACC waveform with physical nongravitational signal
- quantitatively: orbital arcs having high CORR(CAL,NG) and low RMS (std. error of the fit)

Two basic reasons for an arc **not** to be SIM-validated:

- (1) arcs with substantial ACC anomalies (steps, jumps, spikes, ...)
- (2) arcs with important temperature dependence (Swarm A/B, Swarm C less)

When applying a temperature correction (LTC or VZLU) to ACC signal:

- An increase in the number of SIM-validated arcs is expected:
 - because reason (2) should be removed by correction;
 - however, reason (1) is still present even for temperature-corrected ACC signal.

Increase in #SIM-validated arcs by temperature correction

Tables show percentage of SIM-validated arcs

Systematic results for all satellites:

- ACC data with no temperature correction do not correspond well to physical NG signal
- Correlation of **temperature corrected ACC data** with NG is improved substantially

Especially important for A-T direction, where atmospheric density signal is present at most

This test is easy to perform for any temperature correction (LTC, VZLU01, VZLU02, ...)

Specific choice of **SIM-validated criteria** is essential for specific results.

Along-track	Swarm A	Swarm B	Swarm C
temperature not corrected	7 %	6 %	54 %
temperature corrected	59 %	48 %	85 %

Cross-track	Swarm A	Swarm B	Swarm C
temperature not corrected	6 %	8 %	8 %
temperature corrected	41 %	28 %	49 %

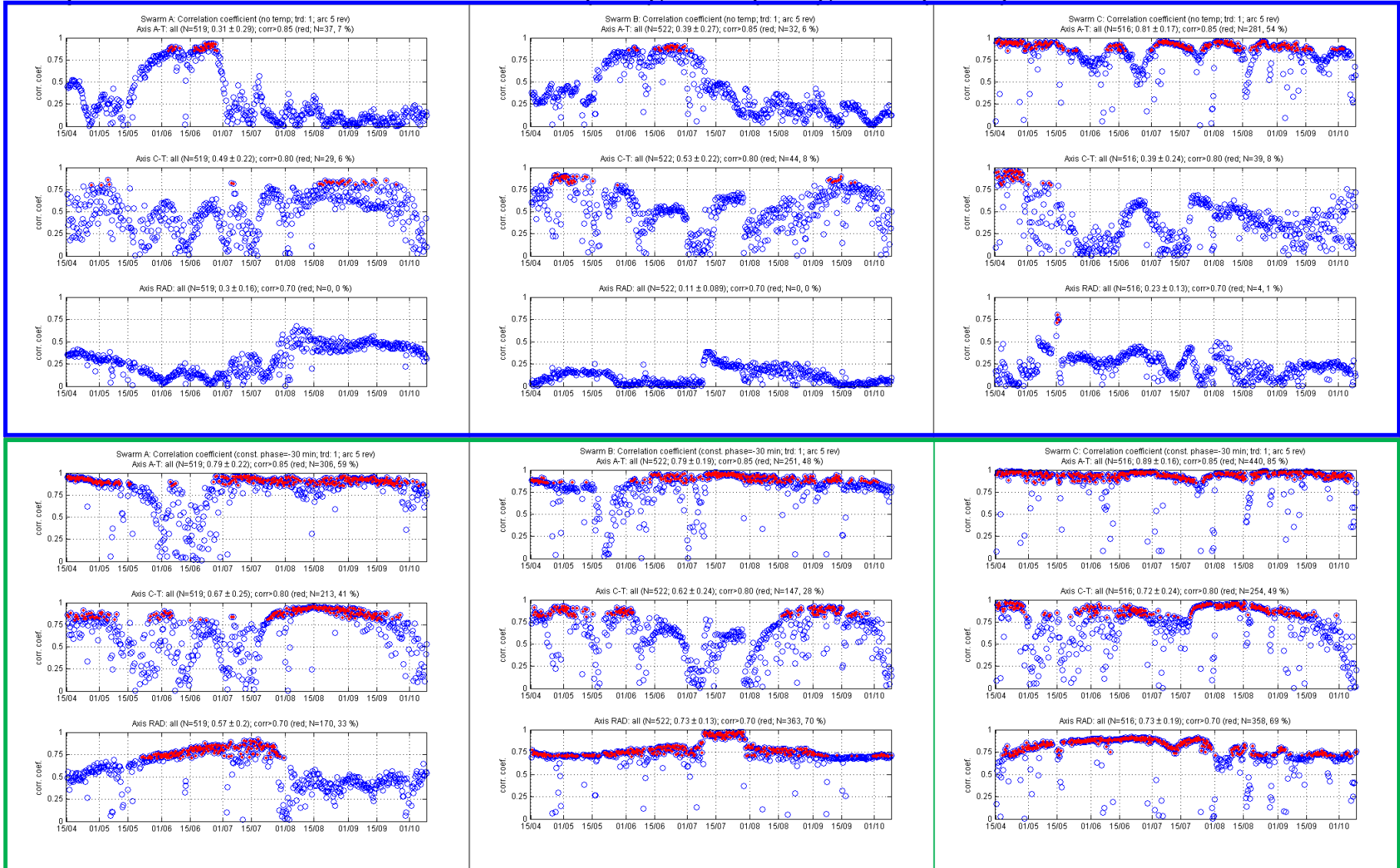
Radial	Swarm A	Swarm B	Swarm C
temperature not corrected	0 %	0 %	1 %
temperature corrected	33 %	70 %	69 %

SIM-val criteria	along-track	cross-track	radial
correlation coefficient	>0.85	>0.8	>0.7
RMS (std error of fit)	7000	7000	7000

Increase in #SIM-validated arcs by temperature correction

Correlation of ACC and NG signals (upper figs: no temp correction; lower figs: temp corrected)

Red points: correlation coefficient >0.85 (A-T), >0.8 (C-T), >0.7 (RAD)



Noise levels in ACC components of Swarm satellites

RMS (std error of the fit): measure of correspondence between temp-corrected ACC and NG

Red points: SIM-validated arcs

Swarm A: medium performance

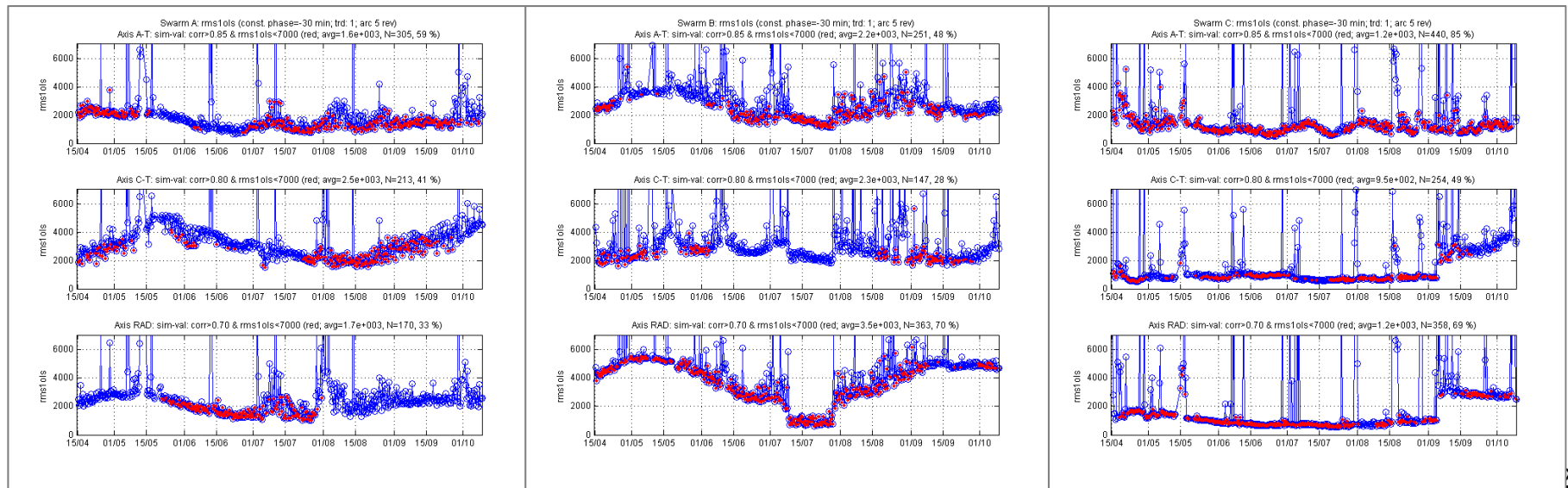
Swarm B: worst performance

- but weaker A-T signal due to higher altitude

Swarm C: best performance (lowest noise)

Mean RMS of SIM-val arcs	Swarm A	Swarm B	Swarm C
Along-track	1.6e3	2.2e3	1.2e3
Cross-track	2.5e3	2.3e3	9.5e2
Radial	1.7e3	3.5e3	1.2e3

Swarm C: Sharp increase of RMS in C-T and RAD components after 5 Sep 2014



Systematic variations in RMS, fit of phase for each arc

Swarm B: Systematic variations in RMS following the temperature variation ΔT

Systematic variations in residuals $\rightarrow$ not optimal OLS model

Temperature correction $Q.T(t+F)$:

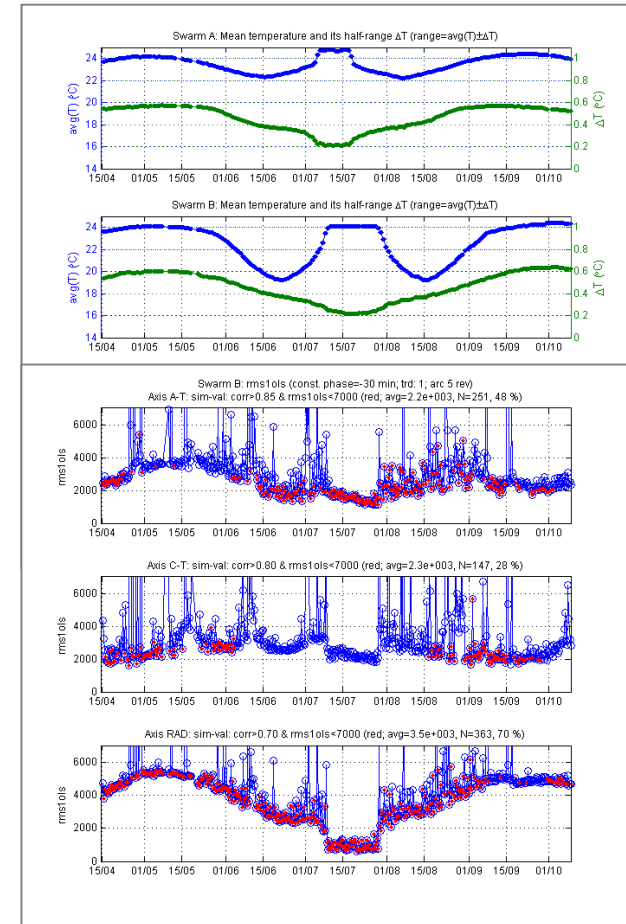
- maybe *constant* phase $F = -30$ min is wrong

Fit of phase F for each arc (as with Q)

- Systematic RMS pattern disappeared and RMS decreased
- but correlation of ACC and NG was substantially reduced
- Similar results for all Swarm satellites and all components

Conclusion

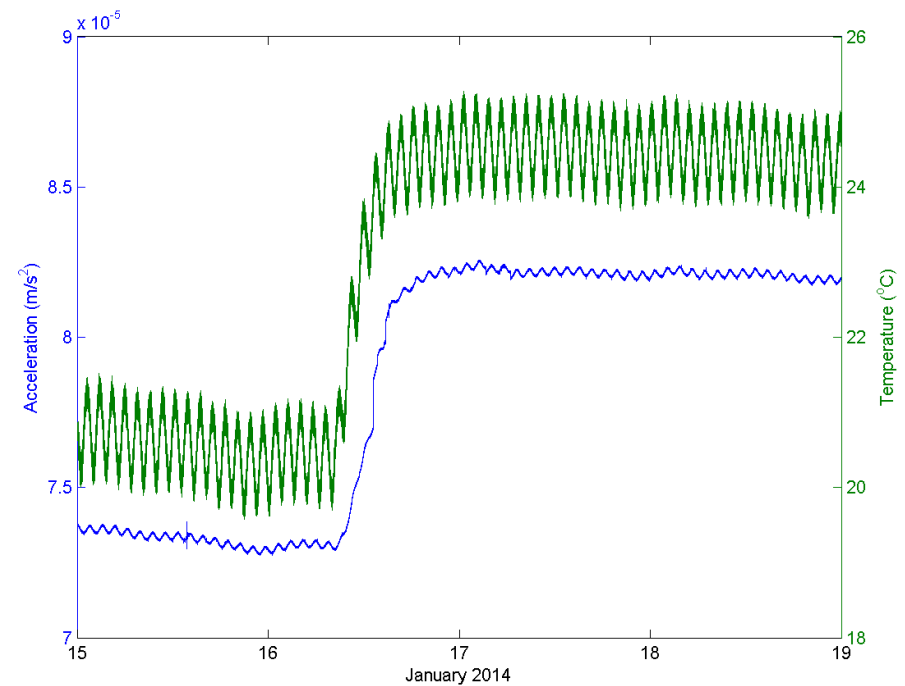
- (Nearly) constant phase $F \approx -30$ min is appropriate for linear temperature correction more than the phase fitted for each arc separately.



Heater action used to estimate the phase

ESL report, p. 20, fig. 2.6 (Swarm B, A-T)

- Perhaps the start of heater action on 16 Jan 2014 on board of all Swarm satellites could be used to find out the delay in reaction of ACC data to temperature change.
- This delay is the phase we look for.
- We investigated such a possibility as well.



Heater action used to estimate the phase

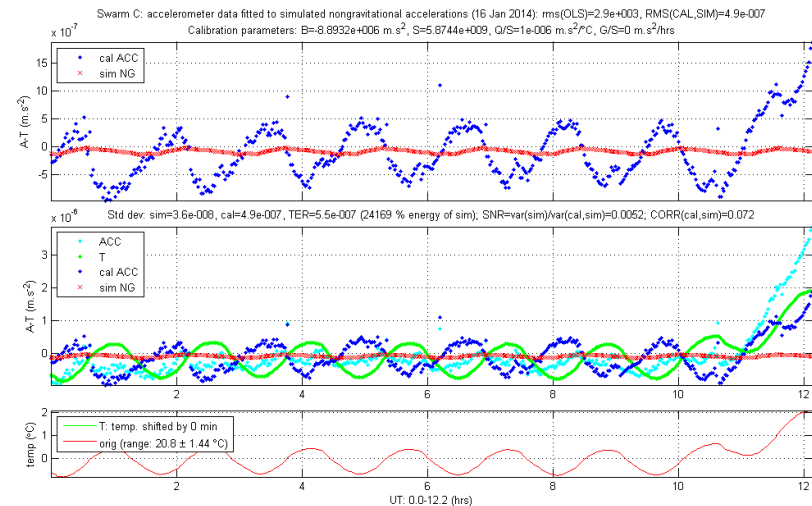
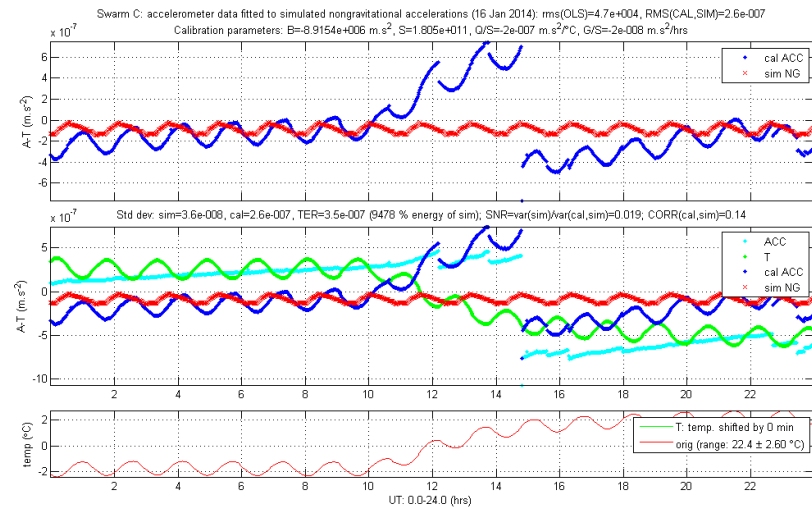
Swarm C, 16 Jan 2014, A-T component

Upper fig: Fit for the whole day

- Apparent ruptures in ACC signal due to thermo-mechanical stress

Lower fig: Fit over arc of 0-12 hrs UT

- Arc limited to portion without ruptures
- Shown is a bad OLS fit for temperature with lag=0 (correlation 0.072)



Heater action used to estimate the phase

Swarm C, 16 Jan 2014, A-T component

We cycle over lags in temperature
with objective: obtain the best fit

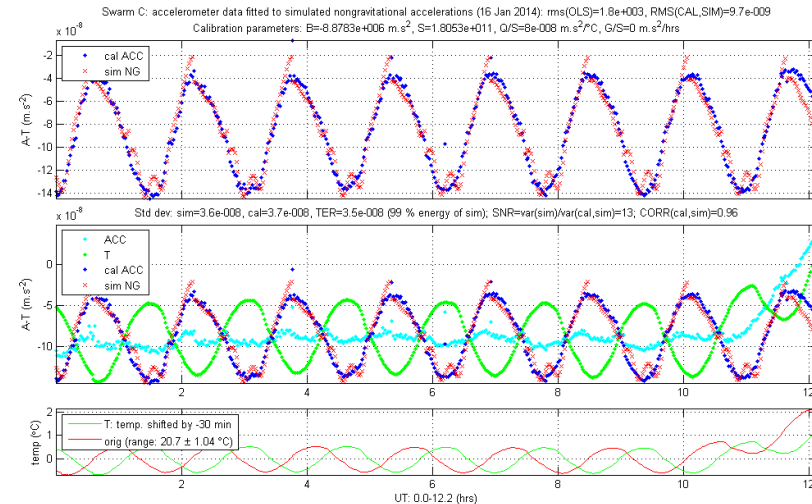
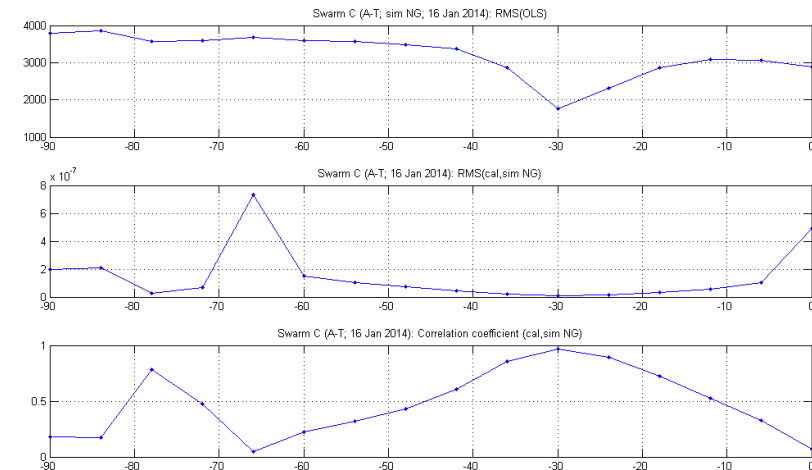
Upper fig: Best fit for lag of –30 min

- Criteria: RMS(ols), RMS(cal,ng),
coefficient of correlation

Lower fig: Fit with $F = -30$ min

- Temperature influence is important
- Temperature-energy-ratio: TER=99%

Delay in reaction of ACC readouts to sharp temperature change appears to be close to –30 min in accordance with other tests.



Number of SIM-validated arc of whole-day length

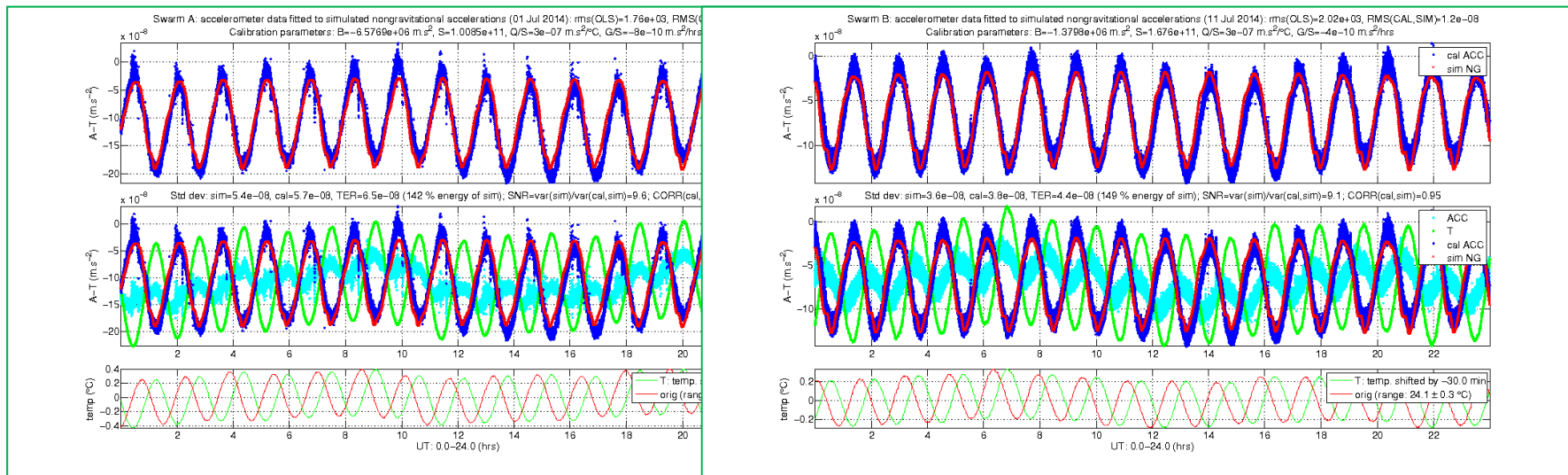
Number of whole-day arcs is relatively high

- due to quiet orbital & temperature conditions

GPS-based calibration

- We obtained first results using 10-sec GPS positions of Swarm C with small temperature dependence
- Change of biases in accordance with SIM-val biases
- Main objective of our Cal/Val activities:
 - Calibration parameters and calibrated ACC signal without influence of NG models
 - Uncertainty of calibrated ACC signal depends on quality of GPS satellite positions

Number of SIM-val arcs in A-T direction	Swarm A	Swarm B	Swarm C
Number	52	42	112
Percent	30 %	24 %	65 %



Conclusions

Study period with stable temperature on all Swarm satellites: 15 Apr – 9 Oct 2014

- Monthly gravity field models of improved quality were obtained → thanks to better GPS orbits.
- Application of linear temperature correction substantially improves correlation of corrected ACC data with physical nongravitational accelerations.
- Comparison of ACC data with physical nongravitational accelerations shows that:
 - ACC on Swarm C has the best performance (lowest noise)
 - ACC on Swarm B has the worst performance
- Constant phase $F \approx -30$ min is appropriate for linear temperature correction more than the phase fitted for each arc separately.
- Presented activities serve as preparation for GPS-based calibration, which should provide calibrated ACC measurements accompanied by an estimate of their uncertainty:
 - GPS-calibrated ACC measurements are not influenced by NG models
 - First results obtained, work under way

Thank you for your attention