An inter-agency comparison of non-gravitational force modeling for Sentinel-3A

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Introduction

Sentinel-3:

- Sentinel-3A (launched on February 16, 2016) and -3B (expected launch in April 2018), Sun-synchronous, near polar orbits at around 815 km altitude
- Measure sea surface topography in the frame of the Copernicus ocean and land observation services, synthetic aperture radar (SAR) altimeter → **precise and accurate orbit information crucial**
- Precise Orbit Determination (POD) with GPS and DORIS instrument. Sophisticated modelling of non-gravitational forces desired to avoid degradation of orbit solutions due to empirical parameters
- Copernicus POD Quality Working Group (QWG): Different institutions deliver orbit solutions for cross-comparison and validation purposes

Goal:

- Compare modeled non-gravitational accelerations from 6 different members of the POD QWG:

Agency	POD Software	
Astronomical Institute, University of Bern	AIUB	Bernese GNSS S/W
Centre National d'Etudes Spatiales	CNES	Zoom
Copernicus POD Service	CPOD	NAPEOS
German Space Operations Center	DLR	GHOST
EUMETSAT	EUM	NAPEOS
Technical University of Munich	TUM	Bernese GNSS S/W

- Check impact of differences on orbit solutions

Methods:

- Each member used their POD software to compute the following non-gravitational accelerations along a fixed Sentinel-3 orbit for three days in 2016 in the inertial and satellite-fixed coordinate frames:
  - Aerodynamic acceleration
  - Direct Solar Radiation Pressure (SRP)
  - Emitted and reflected Planetary Radiation Pressure (PRP)
- Direct comparison of accelerations:
  1. Transform delivered accelerations into the radial (R), tangential (T), normal (N) orbit frame realized by one reduced-dynamic orbit
  2. Fit accelerations with linear splines to overcome different and non-uniform sampling of accelerations
  3. Compare interpolated accelerations at a sampling of 10 s
- Compute orbit differences, perform Satellite Laser Ranging (SLR) validation and estimate orbit offsets from SLR residuals

Satellite macro model

- Satellite shape and surface properties: 8-plate macro model, two plates (front and back of solar panel) are movable
- No self-shadowing
- Satellite mass: mass history file (1129.6 kg at start, 1122.3 kg at end of 2017)
- CNES and DLR model thermal re-emission
- Drag and, if applied, lift coefficients are modeled. CNES employs Cook theory, the other groups Sentman theory.

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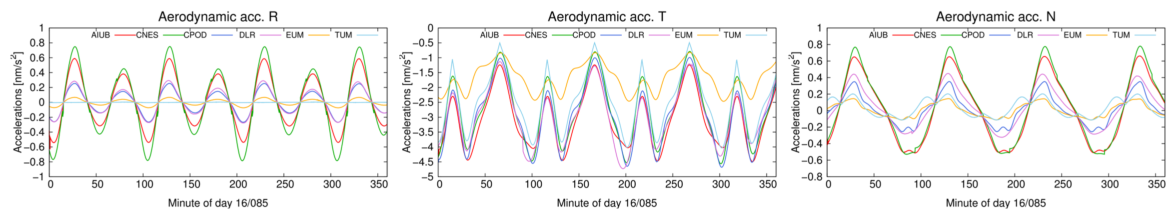
Aerodynamic accelerations

	Density model	Horizontal wind model
AIUB	DTM2013 (Bruinsma et al., 2003)	HWM14 (Hedin et al., 1996)
CNES	MSIS-86 (Picone et al., 2002)	None
CPOD	MSISE-90	HWM93
DLR	NRLMSISE-00	None
EUM	MSISE-90	HWM93
TUM	MSISE-90	None

Table 1: Modeling details of the different QWG members w.r.t. aerodynamic accelerations. All groups except EUM and TUM model aerodynamic lift accelerations.



		CNES	CPOD	DLR	EUM	TUM
AIUB	R	$+0.011\pm0.088$	$+0.019\pm0.184$	$+0.014\pm0.176$	$+0.021\pm0.290$	$+0.022\pm0.328$
	T	-0.408 ± 0.281	-0.140 ± 0.235	-0.330 ± 0.269	-1.378 ± 0.571	-0.624 ± 0.207
	N	-0.029 ± 0.047	$+0.000\pm0.243$	-0.024 ± 0.194	-0.001 ± 0.337	-0.027 ± 0.354
CNES	R		$+0.007\pm0.267$	$+0.003\pm0.259$	$+0.010\pm0.372$	$+0.011\pm0.411$
	T		$+0.268\pm0.220$	$+0.079\pm0.294$	-0.970 ± 0.716	-0.215 ± 0.197
	N		$+0.029\pm0.254$	$+0.005\pm0.206$	$+0.028\pm0.351$	$+0.002\pm0.365$
CPOD	R			-0.004 ± 0.012	$+0.003\pm0.106$	$+0.004\pm0.144$
	T			-0.189 ± 0.262	-1.238 ± 0.620	-0.483 ± 0.149
	N			-0.024 ± 0.055	-0.001 ± 0.104	-0.027 ± 0.114
DLR	R				$+0.007\pm0.114$	$+0.008\pm0.152$
	T				-1.049 ± 0.522	-0.294 ± 0.259
	N				$+0.023\pm0.148$	-0.004 ± 0.162
EUM	R					$+0.001\pm0.038$
	T					$+0.755\pm0.596$
	N					-0.026 ± 0.041

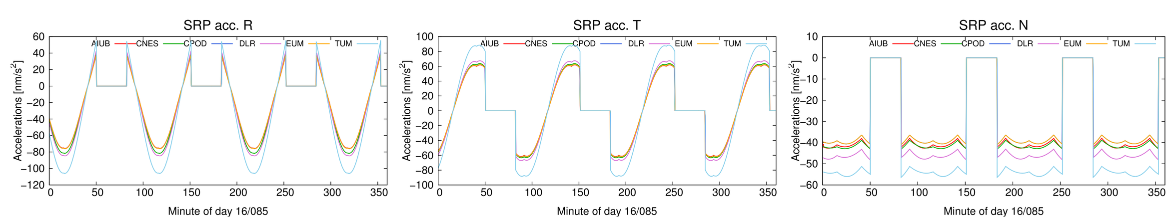
Table 2: Aerodynamic acceleration differences in R, T, N for day 16/085. For each direction the smallest and largest absolute mean differences and standard deviations are indicated in green and red, respectively. Values in nm/s^2.

- EUM and TUM do not model lift, hence their smaller accelerations in R and N.
- EUM acceleration in T rather different than for other groups.

Solar Radiation Pressure

	Earth model	Shadow model	Atm. refr.	Atm. abs.
AIUB	Oblated	Conical	No	No
CNES	Oblated	Conical	Yes	No
CPOD	Spherical	Conical	No	Yes
DLR	Spherical	Conical	No	No
EUM	Spherical	Conical	No	No
TUM	Spherical	Cylindrical	No	No

Table 3: Modeling details of the different QWG members regarding SRP accelerations



		CNES	CPOD	DLR	EUM	TUM
AIUB	R	$+1.567\pm2.441$	$+0.185\pm1.370$	$+2.457\pm4.285$	-0.010 ± 1.296	$+8.385\pm13.738$
	T	-0.035 ± 1.474	-0.010 ± 2.105	$+0.036\pm3.914$	-0.052 ± 1.969	$+0.013\pm17.313$
	N	$+0.347\pm0.939$	-1.292 ± 1.768	$+3.484\pm2.621$	-1.081 ± 1.693	$+8.984\pm6.137$
CNES	R		-1.381 ± 2.507	$+0.891\pm2.184$	-1.576 ± 2.621	$+6.819\pm11.485$
	T		$+0.024\pm1.673$	$+0.070\pm3.102$	-0.017 ± 2.492	$+0.047\pm16.448$
	N		-1.638 ± 1.520	$+3.138\pm2.409$	-1.427 ± 2.095	$+8.637\pm5.944$
CPOD	R			$+2.272\pm4.294$	-0.195 ± 1.881	$+8.200\pm13.845$
	T			$+0.046\pm3.844$	-0.042 ± 2.876	$+0.023\pm17.404$
	N			$+4.776\pm3.378$	$+0.211\pm2.036$	$+10.275\pm7.157$
DLR	R				-2.467 ± 4.046	$+5.925\pm9.712$
	T				-0.087 ± 3.639	-0.019 ± 13.940
	N				-4.565 ± 3.429	$+5.498\pm4.170$
EUM	R					$+8.392\pm13.545$
	T					$+0.068\pm17.099$
	N					$+10.063\pm7.108$

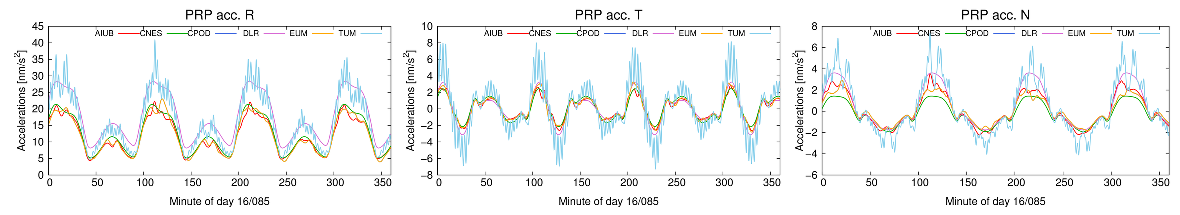
Table 4: SRP acceleration differences in R, T, N for day 16/085. For each direction the smallest and largest absolute mean differences and standard deviations are indicated in green and red, respectively. Values in nm/s^2.

- The TUM accelerations show the largest amplitudes. They are markedly scaled w.r.t. the accelerations of the other groups.

Planetary Radiation Pressure

	Earth model	Radiation model
AIUB	Grid 2.5° × 2.5°	CERES (Wielicki et al., 1996)
CNES	Ring segments	(Knocke et al., 1988)
CPOD	Grid 5° × 5°	CERES
DLR	Ring segments	CERES, approx.
EUM	Grid 5° × 5°	CERES
TUM	Grid 10° × 10°	CERES

Table 5: Modeling details of the different QWG members regarding PRP accelerations. "Ring segments" stands for concentric rings with sectors around satellite foot point (3 rings with 4, 8, and 12 sectors for DLR and 15 rings with 15 sectors for CNES). "CERES, approx." means that a 2nd order polynomial in latitude and a periodic function in time is used to approximate the CERES grid values.



		CNES	CPOD	DLR	EUM	TUM
AIUB	R	-0.756 ± 0.860	-0.066 ± 1.140	-5.683 ± 1.997	-0.066 ± 1.140	-4.514 ± 3.346
	T	$+0.001\pm0.327$	-0.013 ± 0.315	$+0.019\pm0.414$	-0.013 ± 0.315	-0.061 ± 1.776
	N	$+0.366\pm0.500$	$+0.058\pm0.431$	-0.294 ± 0.449	$+0.058\pm0.431$	-0.264 ± 1.147
CNES	R		$+0.690\pm0.859$	-4.926 ± 1.578	$+0.690\pm0.859$	-3.758 ± 3.269
	T		-0.013 ± 0.335	$+0.018\pm0.489$	-0.013 ± 0.335	-0.062 ± 1.842
	N		-0.307 ± 0.235	-0.659 ± 0.789	-0.307 ± 0.235	-0.630 ± 1.540
CPOD	R			-5.617 ± 1.753	$+0.000\pm0.002$	-4.448 ± 3.336
	T			$+0.032\pm0.371$	$+0.000\pm0.001$	-0.049 ± 1.731
	N			-0.352 ± 0.686	$+0.000\pm0.001$	-0.322 ± 1.440
DLR	R				$+5.617\pm1.753$	$+1.169\pm2.403$
	T				-0.032 ± 0.371	-0.081 ± 1.612
	N				$+0.352\pm0.686$	$+0.030\pm0.977$
EUM	R					-4.448 ± 3.337
	T					-0.049 ± 1.731
	N					-0.322 ± 1.441

Table 6: PRP acceleration differences in R, T, N for day 16/085. For each direction the smallest and largest absolute mean differences and standard deviations are indicated in green and red, respectively. Values in nm/s^2.

- CPOD and EUM seem to have identical PRP modeling.
- TUM accelerations show the largest amplitudes, the accelerations seem "noisy".
- The radial DLR and TUM accelerations are larger than for the other groups.

Orbit differences

Some agencies have changed their non-gravitational modeling details since they computed the 2016 Sentinel-3A orbits. To compare orbits that have been produced based on the models and settings of Tables 1, 3 and 5, an inter-agency comparison of December 2017 orbits was performed (similar beta angles and orbital altitudes as for the 2016 period):

		CNES	CPOD	DLR	EUM	TUM
AIUB	R	-1.22 ± 8.23	-0.10 ± 8.93	$+5.48\pm4.49$	$+1.25\pm11.66$	$+0.74\pm5.65$
	T	$+5.27\pm16.39$	$+0.30\pm14.82$	-0.11 ± 9.29	$+6.16\pm23.11$	$+4.52\pm6.13$
	N	$+2.86\pm7.48$	-0.53 ± 9.51	$+7.53\pm6.16$	-3.07 ± 14.15	$+6.27\pm3.92$
CNES	R		$+1.12\pm6.78$	$+6.70\pm9.37$	$+2.47\pm11.86$	$+1.96\pm8.20$
	T		-4.97 ± 15.20	-5.38 ± 17.93	$+0.89\pm24.22$	-0.75 ± 15.85
	N		-3.39 ± 9.22	$+4.67\pm9.85$	-5.94 ± 16.06	$+3.41\pm7.76$
CPOD	R			$+5.58\pm9.31$	$+1.35\pm11.19$	$+0.84\pm9.58$
	T			-0.41 ± 14.00	$+5.85\pm22.55$	$+4.22\pm14.61$
	N			$+8.05\pm11.05$	-2.55 ± 15.60	$+6.79\pm10.06$
DLR	R				-4.23 ± 12.04	-4.74 ± 7.12
	T				$+6.26\pm23.75$	$+4.63\pm10.48$
	N				-10.60 ± 15.67	-1.26 ± 7.64
EUM	R					-0.51 ± 13.96
	T					-1.63 ± 23.86
	N					$+9.34\pm14.64$

Table 7: Orbit differences in R, T, N for December 2017. For each direction the smallest and largest absolute mean differences and standard deviations are indicated in green and red, respectively. Values in mm.

- The DLR orbits show a radial offset w.r.t. the other solutions. This might partly be related to the offset in the modeled radial PRP accelerations, but it has to be noted that, for the POD, the modeled non-gravitational accelerations are rescaled by estimated scaling factors and that all groups also estimate empirical accelerations on top.
- No other clear correlations can be observed.

SLR validation

The same December 2017 Sentinel-3A orbits of all agencies were validated by SLR. 2922 SLR observations of 10 high-performing stations of the International Laser Ranging Service network were used to compute SLR residuals, i.e., differences between measured and modeled ranges. Station coordinates were introduced according to SLRF2014.

	Mean value	Std. dev.
AIUB	-0.33	10.97
CNES	$+1.02$	13.57
CPOD	-0.03	12.70
DLR	-3.65	10.91
EUM	-2.05	19.04
TUM	-1.22	11.39

Table 8: SLR residual statistics for December 2017. Values in mm.

In addition, RTN orbit offsets were estimated from the SLR residuals (Arnold et al., 2017):

	ΔR	ΔT	ΔN	Mean value	Std. dev.
AIUB	-0.4 ± 0.6	$+3.8\pm0.7$	$+5.4\pm0.7$	-0.04	10.43
CNES	$+1.9\pm0.6$	-7.9 ± 0.7	$+2.9\pm0.7$	$+0.33$	12.82
CPOD	$+0.1\pm0.6$	-1.3 ± 0.7	$+5.5\pm0.7$	$+0.19$	12.32
DLR	-6.2 ± 0.6	$+3.1\pm0.7$	-1.7 ± 0.7	$+0.16$	10.66
EUM	-1.0 ± 0.6	-17.2 ± 0.7	$+10.4\pm0.7$	-0.04	15.77
TUM	-2.3 ± 0.6	$+1.4\pm0.7$	-2.0 ± 0.7	$+0.10$	11.30

Table 9: Orbit offsets and formal errors estimated from SLR residuals of 10 SLR stations in December 2017, as well as residual statistics after adjustment. Values in mm.

- Again, no clear correlation between acceleration differences and SLR residuals or orbit offsets can be observed. Possible exception: Radial offset of DLR and TUM orbits.

Conclusions

- There is a large variation of employed models and details for non-gravitational accelerations between the different QWG members.
- The most obvious differences between different QWG members concern aerodynamic accelerations in R for EUM and TUM (no lift), the aerodynamic acceleration in T for EUM (considerably smaller), the SRP accelerations for TUM (largest amplitudes), the PRP accelerations of TUM (large amplitudes and scatter), and the (largest) PRP accelerations of DLR in R direction.

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