Recent POD-related activities at DGFI-TUM

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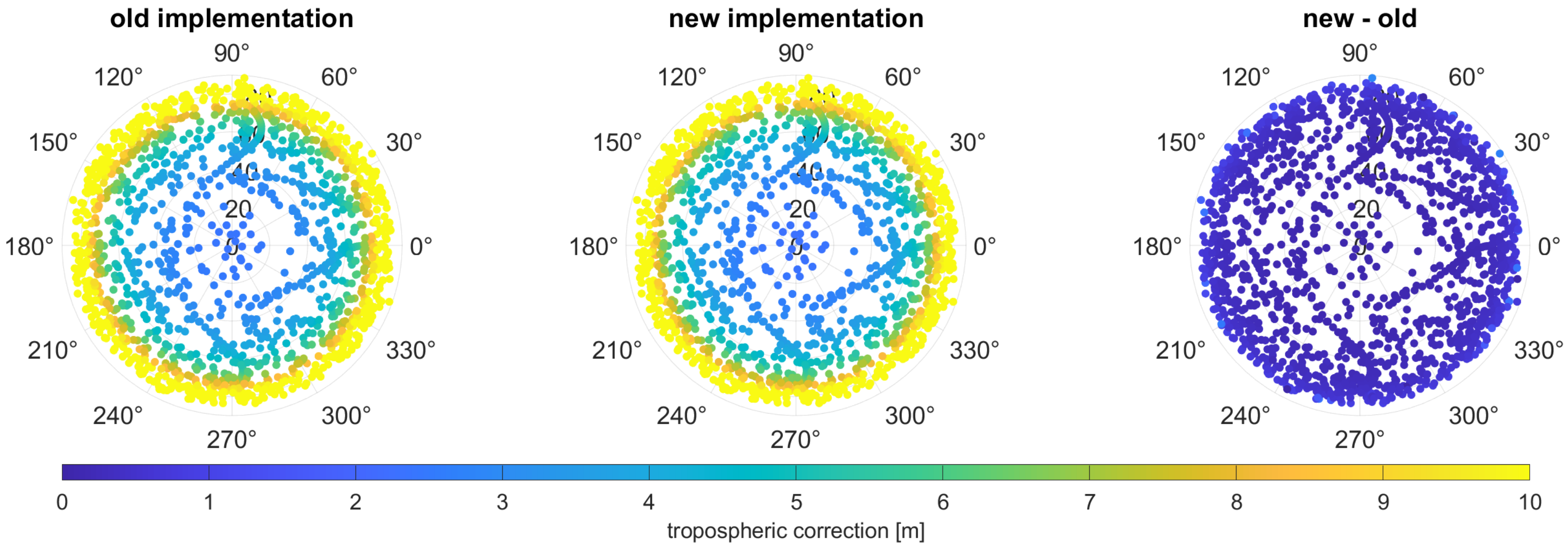
- Recent software developments
- TOPEX/Poseidon attitude comparison
- Interpolation of altimetry satellite orbits
- Tests of Earth’s gravity field models

Recent software developments

- Refinement of tropospheric modelling ongoing in DOGS-OC
- “Old modelling”:
  - Zenith delay according to averaged global mean model by Collins (1999),
  - Mapping functions (dry, wet) by Niell.
- “New modelling”:
  - A priori zenith wet delay (dry) according to Saastamoinen, (dry, wet) VMF3-based mapping functions,
  - A priori gradients in NS and EW direction equal to zero, (dry, wet) mapping functions based on Chen-Herring,
  - Tropospheric corrections are estimable; iterative improvement of parameters.
- Example: Jason-3 arc, tropospheric corrections of Toulouse (TLSB)



Recent software developments

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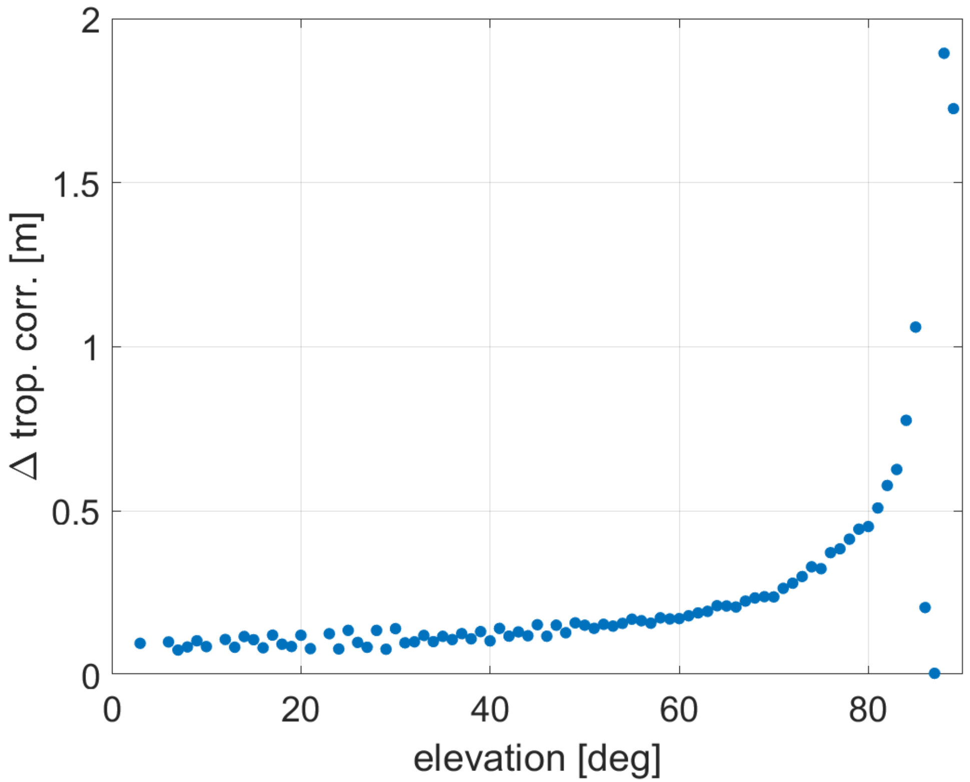
  - Tropospheric corrections are estimable; iterative improvement of parameters.
- Example: Jason-3 arc, tropospheric corrections of Toulouse (TLSB)
  - Elevation cut-off of 10 degrees applied
  - Mean of differences between “old” and “new” modelling: ~ 17 cm
  - Further improvement expected when parameters corrected!



TOPEX/Poseidon attitude

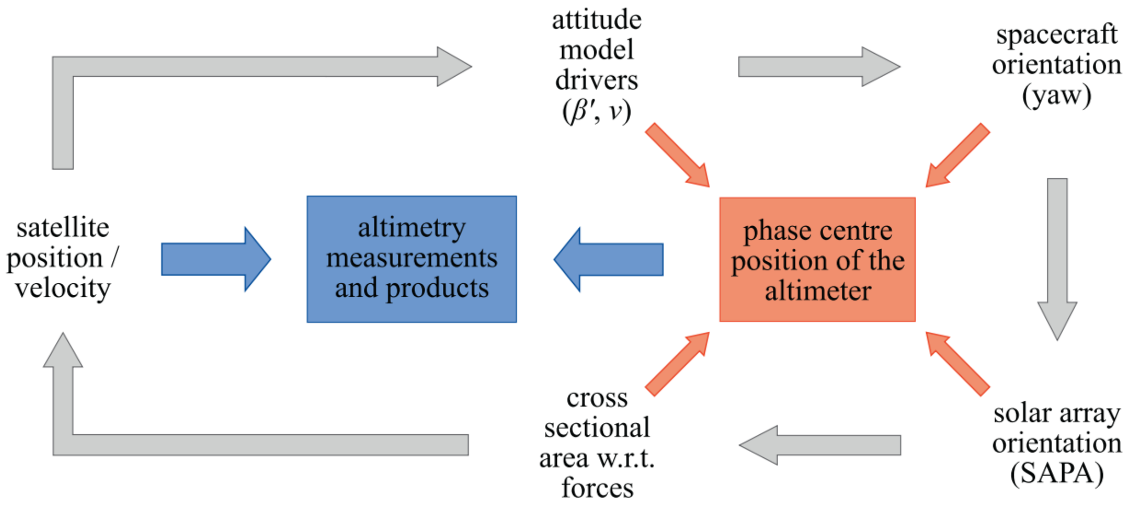
- Accurate attitude realisation for the precise orbit determination (POD) of TOPEX/Poseidon (T/P) is quite challenging
- Two algorithms were developed by Perrygo (1987), one for the orientation of the spacecraft bus and one for the orientation of the solar array
- Overview of the formulae for the determination of the nominal yaw angle (Zeitlhöfler et al., 2024a):

Table 1
Sequence of modes and events in the yaw steering strategy of the T/P spacecraft. The sinusoidal and fixed yaw modes are connected by yaw ramp transition events, and the fixed yaw mode is interrupted by a yaw flip event. β'_0 is approximately 15° in the first mission years and 30° in later years. The exact values are listed in the T/P nominal attitude file. All values in the table are in degrees. The model is based on Casotto et al. (1994) except fixed yaw in regions of $|\beta'| > 80°$ (cf. Section 4).

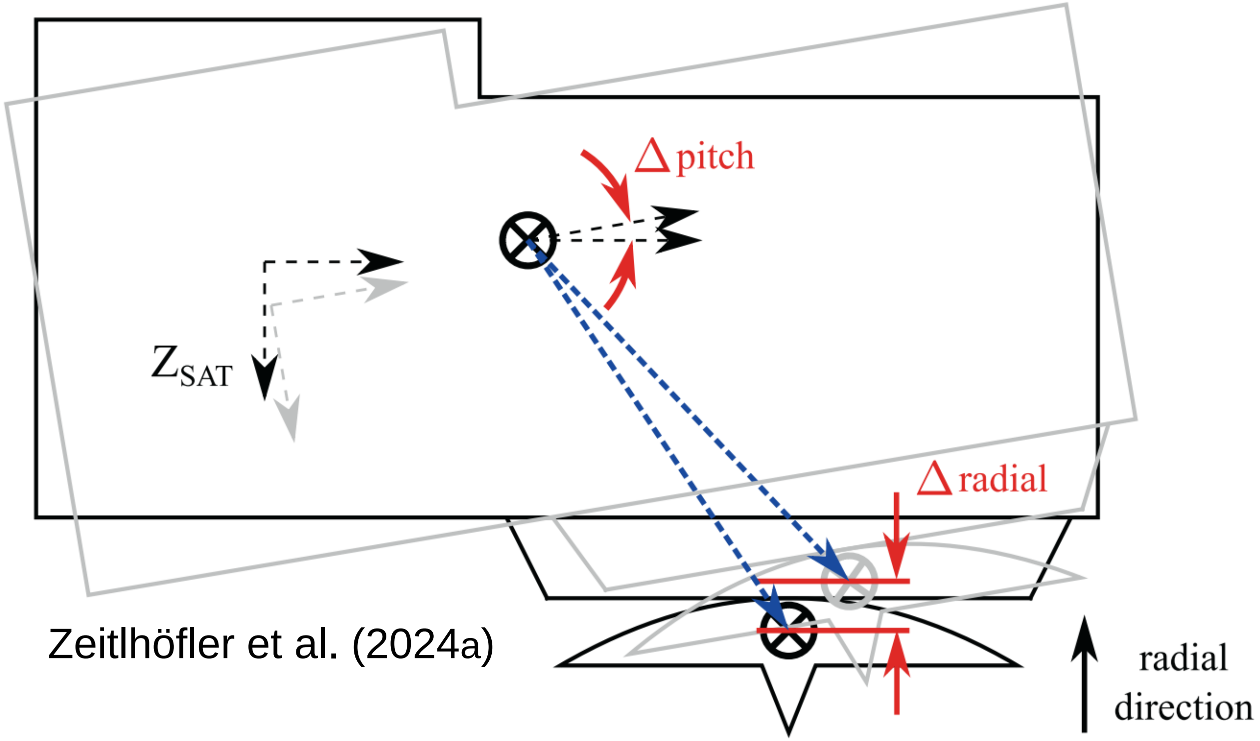
Description	Nominal yaw ψ_N	β' region			v region
		Active	Start	Condition	
Fixed yaw (flying forward)	0	$0 < \beta' < +\beta'_0$			
Yaw ramp up	$+\beta' \sin^2 v$		$\beta' \approx +\beta'_0$	$\dot{\beta}' > 0$	$0 \leqslant v \leqslant 90$
Sinusoidal yaw	$+90 - (90 - \beta') \sin v$	$+\beta'_0 < \beta'$			
Yaw ramp down	$+\beta' \sin^2 v$		$\beta' \approx +\beta'_0$	$\dot{\beta}' < 0$	$90 \leqslant v \leqslant 180$
Fixed yaw (flying forward)	0	$0 < \beta' < +\beta'_0$			
Yaw flip	$-90(1 + \sin v)$		$\beta' \approx 0$	$\dot{\beta}' < 0$	$90 \leqslant v \leqslant 270$
Fixed yaw (flying backward)	-180	$-\beta'_0 < \beta' < 0$			
Yaw ramp up	$-\beta' \sin^2 v - 180$		$\beta' \approx -\beta'_0$	$\dot{\beta}' < 0$	$180 \leqslant v \leqslant 270$
Sinusoidal yaw	$-90 + (90 + \beta') \sin v$	$\beta' < -\beta'_0$			
Yaw ramp down	$-\beta' \sin^2 v - 180$		$\beta' \approx -\beta'_0$	$\dot{\beta}' > 0$	$270 \leqslant v \leqslant 360$
Fixed yaw (flying backward)	-180	$-\beta'_0 < \beta' < 0$			
Yaw flip	$-90(1 - \sin v)$		$\beta' \approx 0$	$\dot{\beta}' > 0$	$90 \leqslant v \leqslant 270$
Fixed yaw (flying forward)	0	$0 < \beta' < +\beta'_0$			

TOPEX/Poseidon attitude

- No continuous supply of attitude quaternions for the T/P mission
- Attitude quaternions at some periods of so-called off-nominal attitude behaviour are available (Zelensky et al., 2024)
  => Allows the validation and quality assessment of the nominal model
- Accurate attitude is prerequisite for high-quality altimetry products



Zeitlhöfler et al. (2024a)



Zeitlhöfler et al. (2024a)

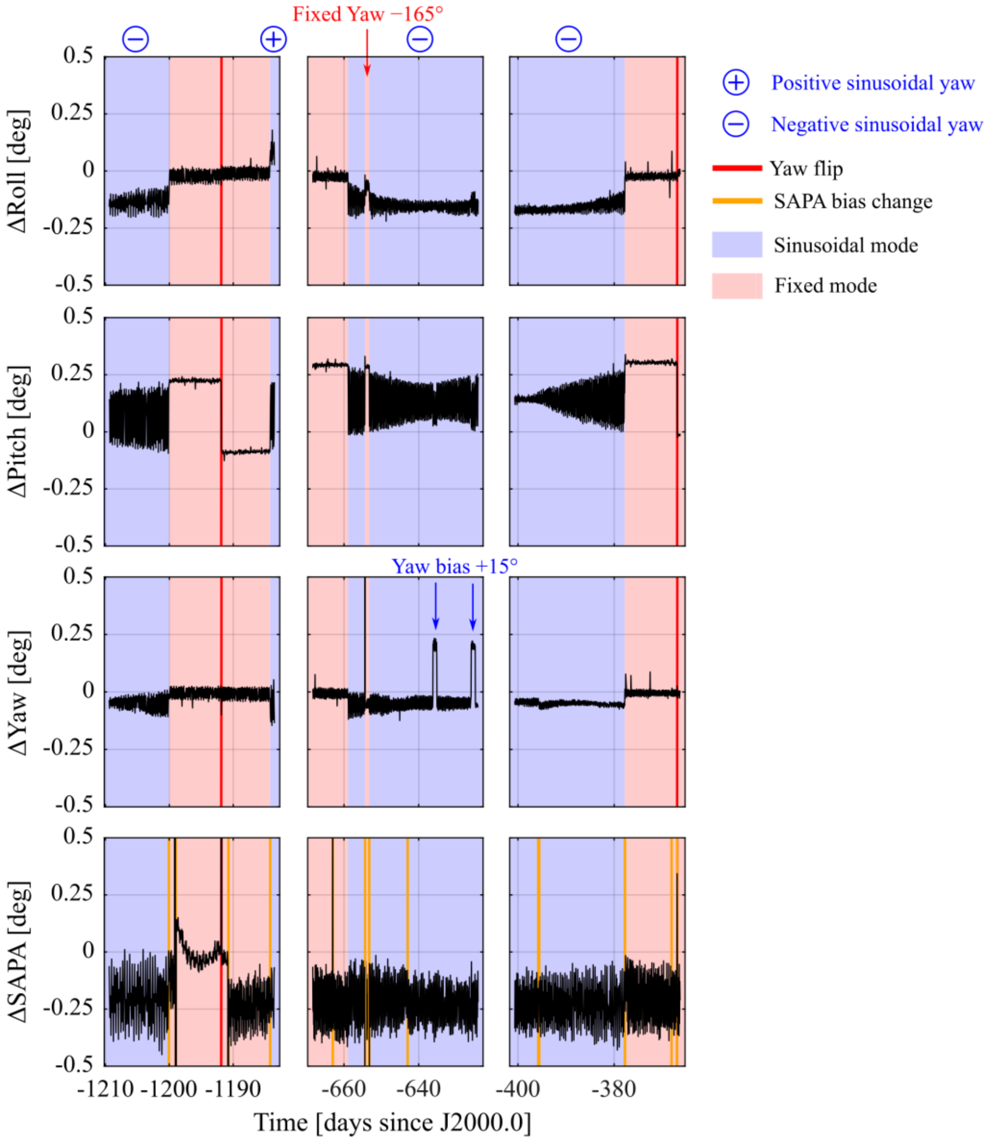
TOPEX/Poseidon attitude

- Comparison of attitude angles at nine intervals
  - Spacecraft roll, pitch, and yaw angles
  - Solar array pitch angle (SAPA)

- Angular differences depending on the mode
  - Roll: largest differences in sinusoidal mode (up to 0.17°)
  - Pitch: largest differences in fixed mode (up to 0.31°)
  - Yaw: differences up to 0.05° on average
  - SAPA: constant offset (approx. -0.19°)

- In general, good agreement between the nominal attitude model and the quaternion data.

- Mis-modelling of the pitch orientation by 0.31° introduces an positional changes of the altimeter phase centre of 7 mm in the radial direction.



Zeitlhöfler et al. (2024a)

Orbit interpolation

- Orbit comparisons with internal and external orbit solutions are very important for orbit validation and quality assessment
- However, the orbits to be compared might be provided in different time systems (e.g., UTC, TAI, GPS) and at different time instants
  => Interpolation of one orbit solution is required

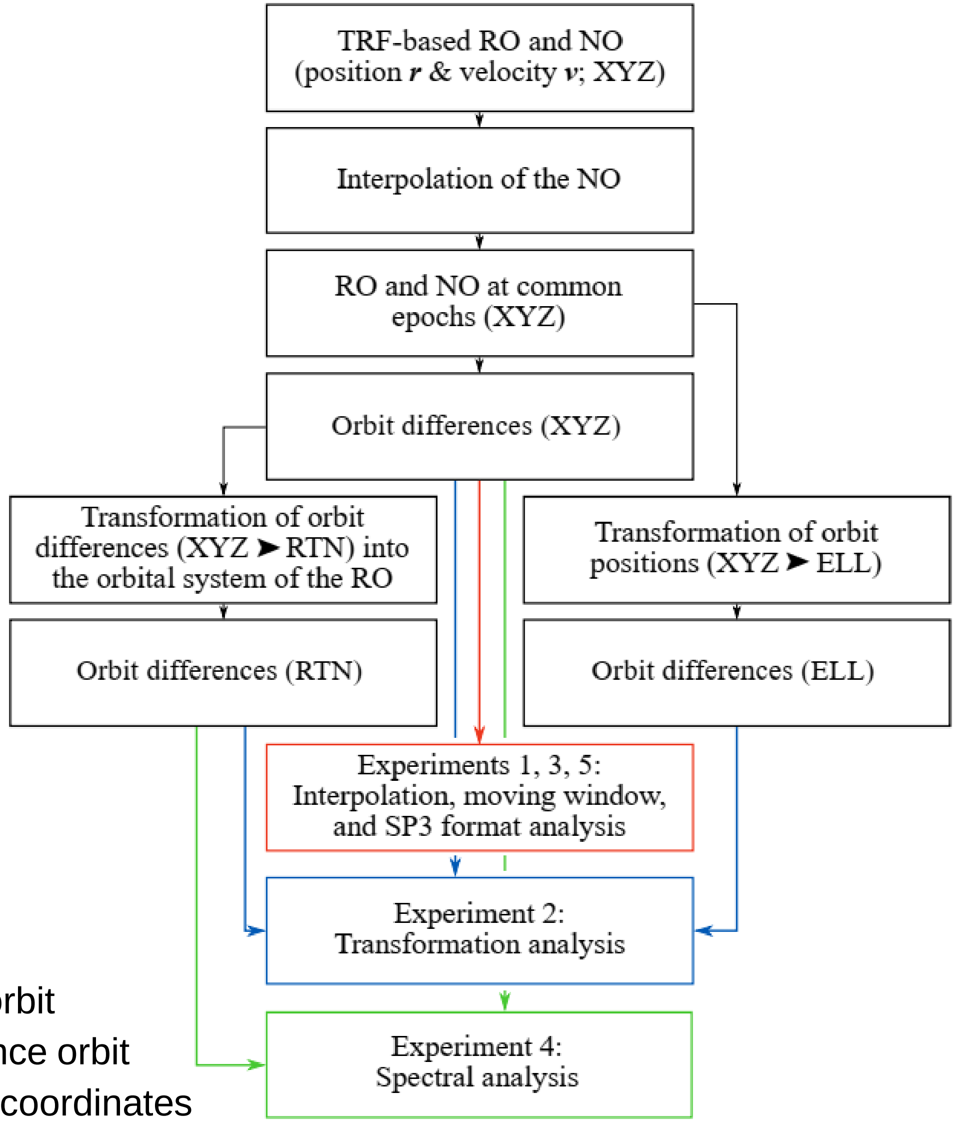
- Most orbit solutions of altimetry satellites are exchanged via the SP3 format (Hilla, 2016) in the terrestrial reference frame (TRF)
- However, the comparison of satellite positions is conducted in the orbital system (radial, transverse, normal, RTN)
  => Coordinate transformation is required

- We performed several experiments to assess the accuracy of different polynomial interpolation methods (Lagrange, Newton, Hermite) (Zeitlhöfler et al., 2024b)

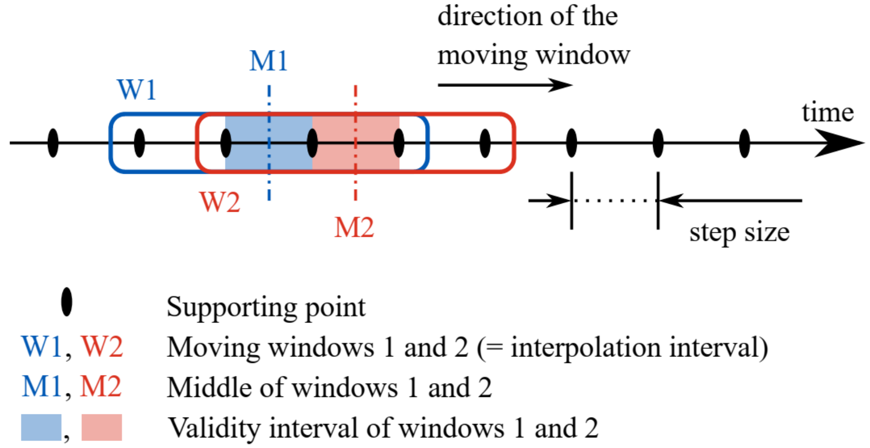
Target: well below millimetre interpolation accuracy

Orbit interpolation

Experiment
- #1: Interpolation accuracy using TRF coordinates
- #2: Transformation accuracy from TRF to RTN
- #3: Interpolation accuracy inside the moving window
- #4: Spectral analysis of transformation error
- #5: Suggestion for improved SP3 format



Moving window approach:



RO: reference orbit
NO: non-reference orbit
ELL: ellipsoidal coordinates

Orbit interpolation

Interpolation accuracy:

- Best results for the Hermite interpolation method
- Increasing the interpolation degree benefits the interpolation accuracy
- Minimum interpolation error of 0.5 mm in all cases (average value)

Statistical values (average (avg) and standard deviation (std)) of the interpolation error [mm]:

	Degree	Temporal step size of the reference and non-reference solutions					
		≤ 30 sec		60 sec		120 sec	
		avg	std	avg	std	avg	std
Newton	5	0.61	0.23	**1.18**	**0.36**	**66.62**	**3.66**
	6	0.62	0.24	0.62	0.23	**3.88**	**0.96**
	7	0.62	0.24	0.61	0.23	**0.83**	0.40
	8	0.63	0.24	0.62	0.23	0.76	0.35
	9+	0.62	0.24	0.62	0.23	0.72	0.31
Hermite	5	0.57	0.21	0.57	0.21	**2.72**	**0.39**
	7+	0.56	0.21	0.56	0.20	0.57	0.21
	7+[a]	0.06	0.02	0.06	0.02	0.07	0.03
	7+[b]	0.01	0.01	0.03	0.01	0.05	0.02

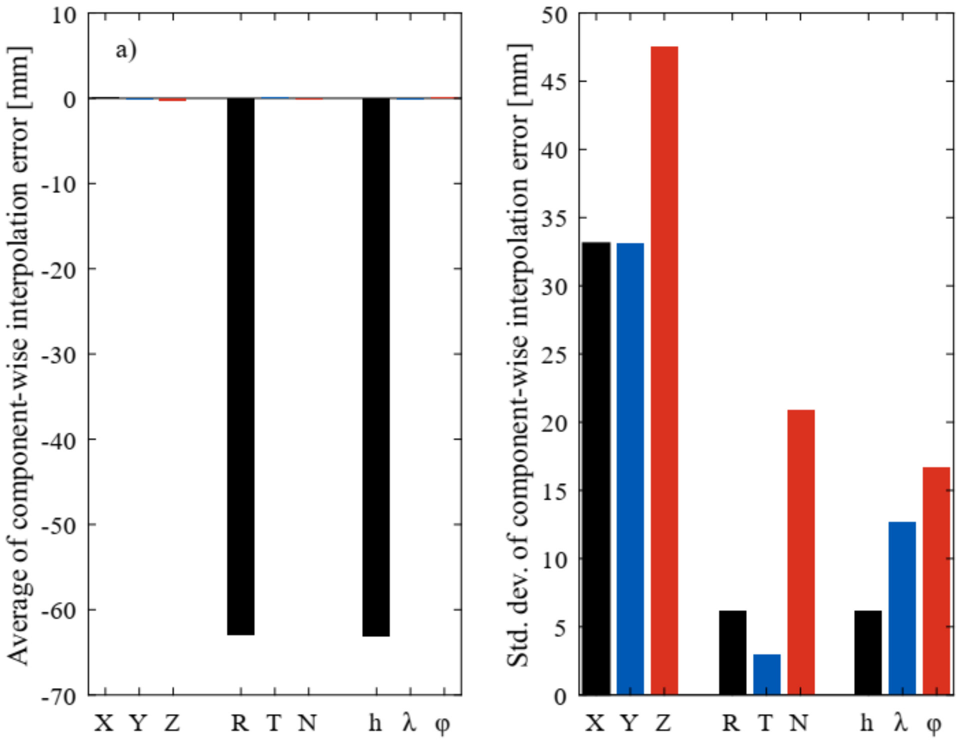
[a]Seven instead of six (default) decimal digits in the SP3 file; [b]Eight instead of six (default) decimal digits in the SP3 file

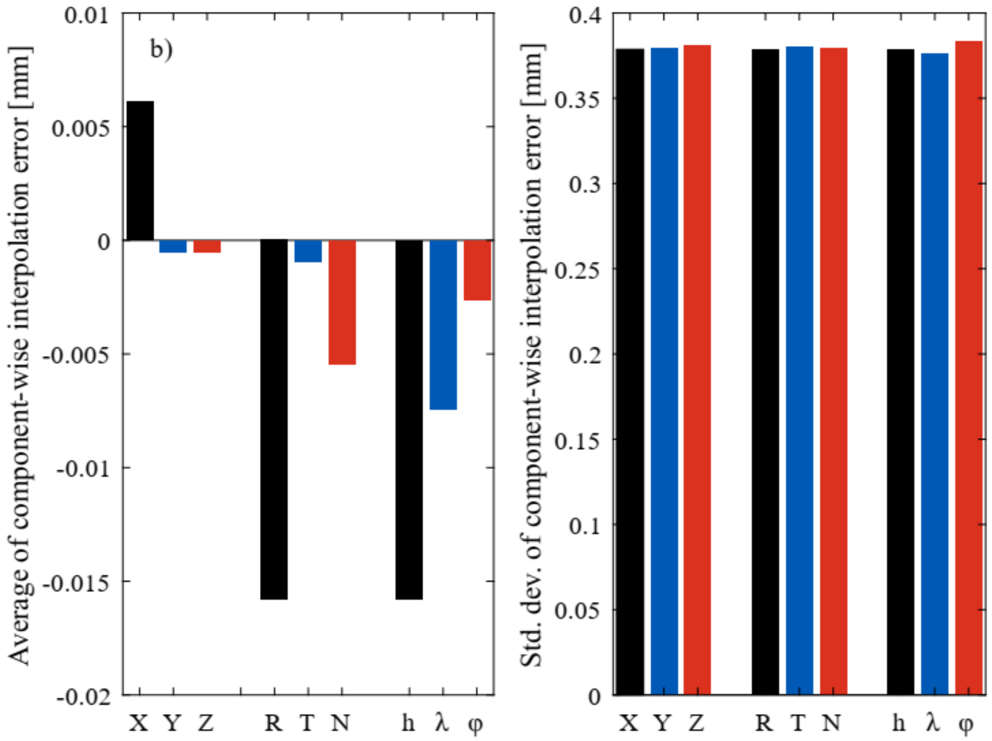
Orbit interpolation

Transformation effects:

- Redistribution of orbit error into certain components at transformation
- The choice of sufficient interpolation settings prevents this effect

Newton interpolation, degree 5, step size 120 seconds (left) and 30 seconds (right):





Tests of some recent Earth's time-variable gravity field models for POD of Jason-3 (2016-2023): a test setup

Seven Earth's time-variable gravity field models are used.

Observation type used: Satellite Laser Ranging (SLR).

Dynamical models are according to Rudenko et al. (2023) for the DGFI-TUM DSO1 orbits.

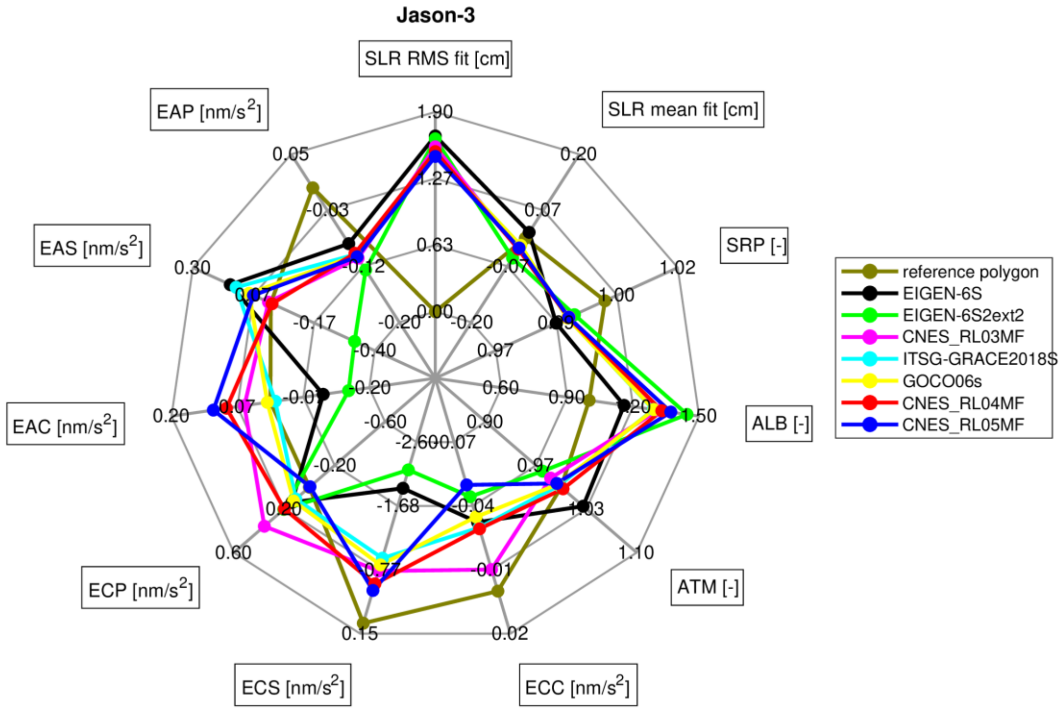
Terrestrial Reference Frame realization used: SLRF2020

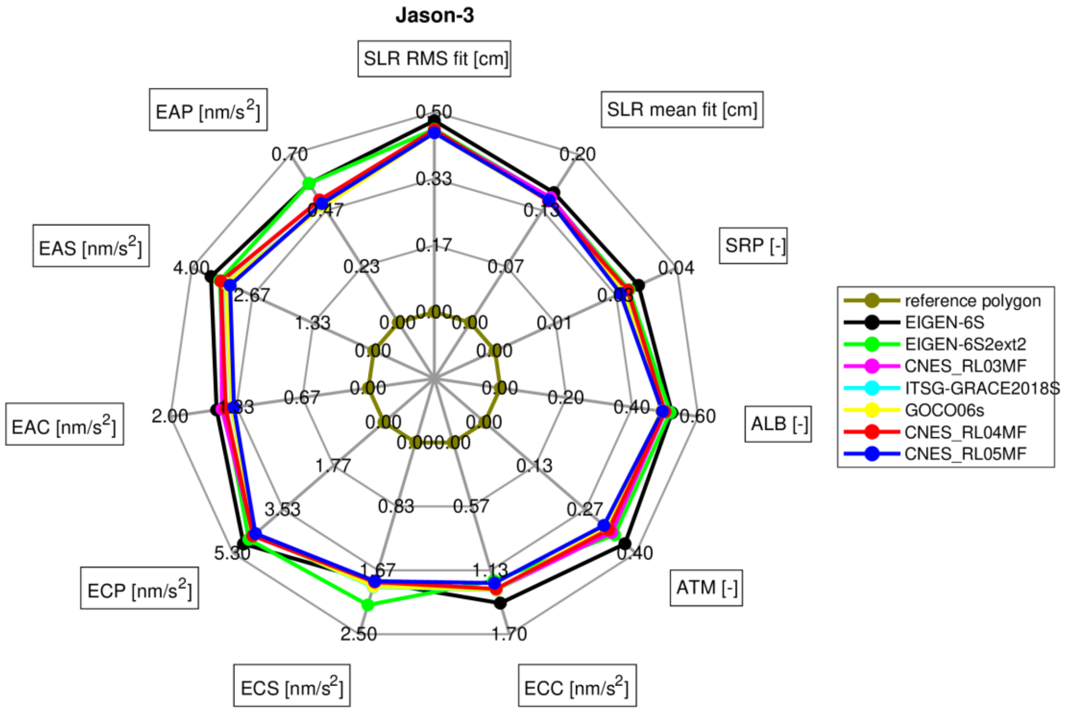
Impact on the following orbital parameters is investigated:

- RMS and mean values of SLR observations residuals,
- scale factors of the solar radiation pressure, Earth's albedo and infrared radiation and atmospheric drag,
- empirical accelerations in the along-track and cross-track directions.

Model name	Model name abbreviation	Data time span	Max time-variable degree
EIGEN-6S (Foerste et al., 2011)	EIGEN-6S	1985-2009	50
EIGEN-6S2.extended.v2 (Rudenko et al., 2014)	EIGEN-6S2ext2	1985-2014	50
EIGEN-GRGS.RL03-v2.MEAN-FIELD.mean_slope_extrapolation (Lemoine et al., 2014)	CNES_RL03MF	1985-2014	80
ITSG-GRACE2018S (Mayer-Gürr et al., 2018)	ITSG-GRACE2018S	2002-2017	200
GOCO6S (Kvas et al., 2021)	GOCO6S	2002-2017	200
EIGEN-GRGS.RL04.MEAN-FIELD (Lemoine et al., 2019)	CNES_RL04MF	1985-2016.5	90
CNES_GRGS.RL05MF_combined_GRACE_SLR_DORIS (Lemoine et al., 2023)	CNES_RL05MF	1985-2022	90

Tests of some recent Earth's time-variable gravity field models for POD of Jason-3 (2016-2023): mean (left) and standard deviation (right) of orbital parameters





The **CNES_GRGS.RL05MF_combined_GRACE_SLR_DORIS** model **performs best** among the models tested, since the time-variable terms of this model were determined over the longest time span (1985 – 2022) among the models used.

More results will be given in Rudenko et al. (in preparation).

Conclusions

- Attitude realisation of TOPEX/Poseidon for POD primarily by the use of the nominal attitude model
- Very limited quaternion data (spacecraft body and solar array) allows the validation of the nominal model
- Both approaches are similar with angular differences up to approximately 0.31°
- Interpolation is a necessary tool for orbit comparisons (of mainly external solutions)
- The Hermite interpolation method of degrees 7-11 provides best results and smallest interpolation errors
- The current SP3 format limits the interpolation accuracy to ~0.6 mm => recommendation for an update of the format by providing additional decimal digits for the satellite position and velocity
- The CNES_GRGS.RL05MF_combined_GRACE_SLR_DORIS time-variable gravity model performs best for POD of Jason-3 since it is based on input data between 1985 and 2022

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