

Estimation of station-dependent LRA correction parameters for the TOPEX/Poseidon mission

Julian Zeitlhöfler, Mathis Bloßfeld, Sergei Rudenko, and Florian Seitz

Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM)

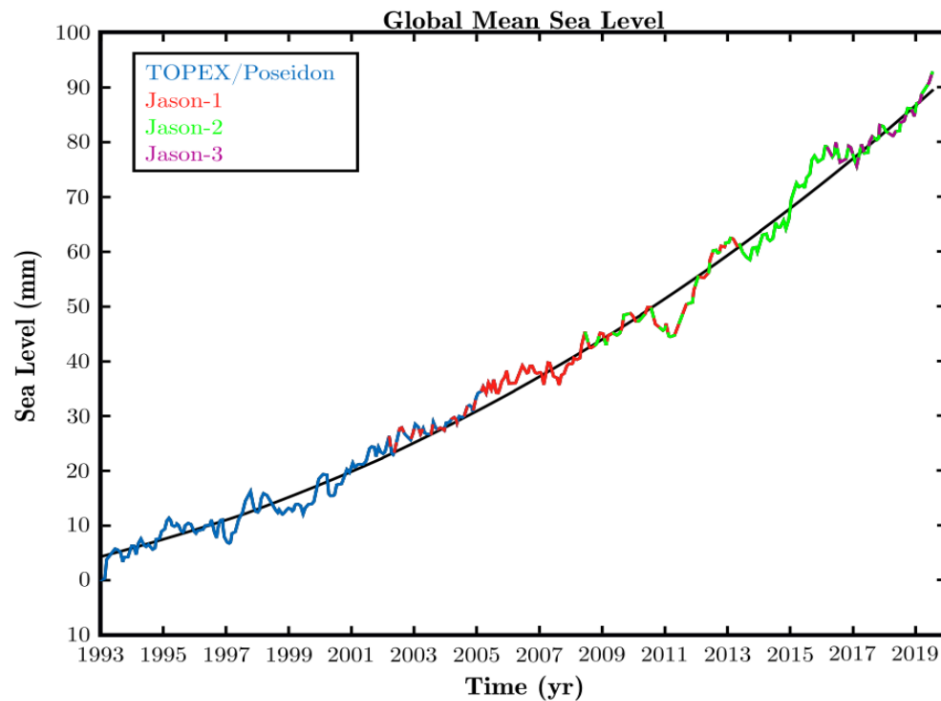
EGU General Assembly, 27.04.2021

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Overview of the TOPEX/Poseidon mission

- One of the first major altimetry missions
- Mission duration: August 1992 – January 2006
- Predecessor of Jason series and Sentinel-6
- Important mission for a continues sea level monitoring since 1992



Source: Cazenave et al., 2019

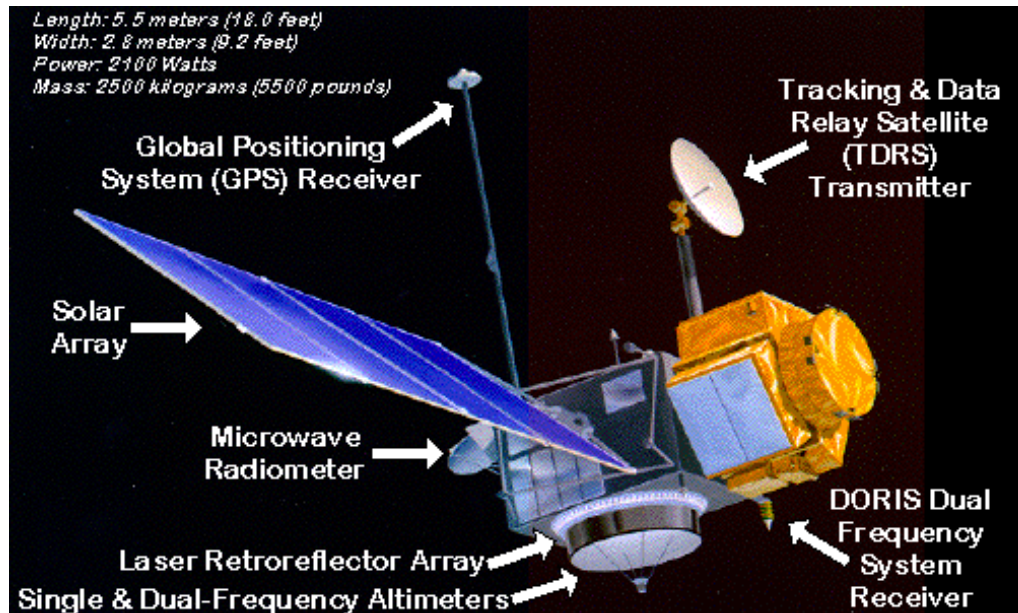


Source: aviso.altimetry.fr

Overview of the TOPEX/Poseidon mission

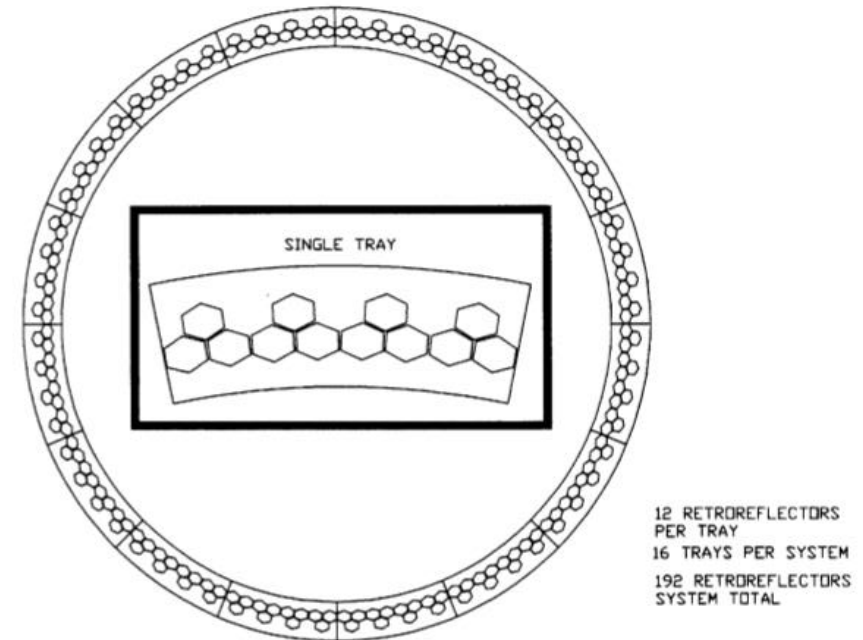
Tracking payload of TOPEX/Poseidon

- GPS receiver
- DORIS receiver
- Laser Retroreflector Array (LRA) for SLR range measurements
 - Not ideally designed
 - Diameter ca. 88 cm (Varghese, 1993)
 - Dimensions cause large phase centre variations



Source: ilrs.gsfc.nasa.gov

TOPEX/Poseidon LRA



Source: Varghese, 1993

Attitude modelling of TOPEX/Poseidon

Attitude

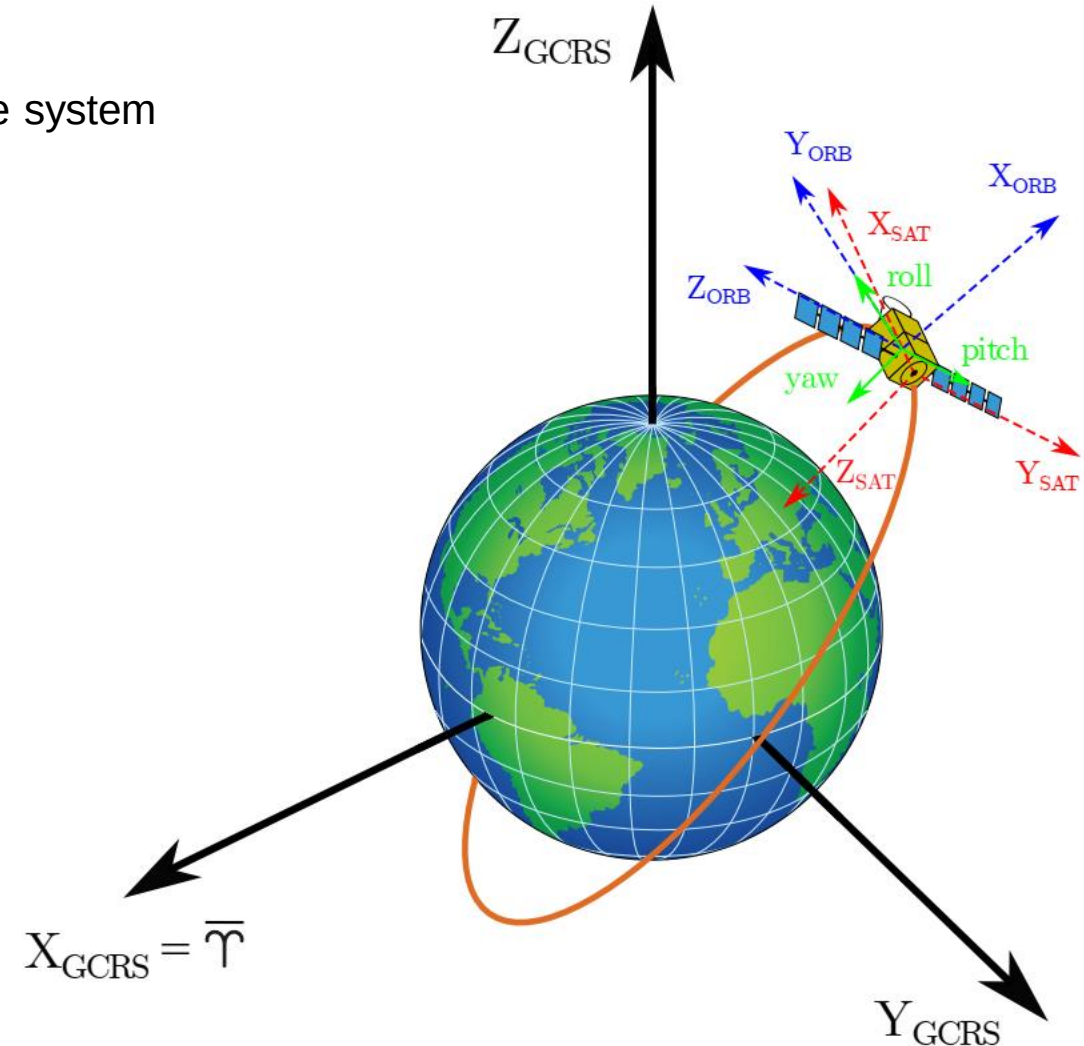
Orientation of the satellite coordinate system within a reference system

$$\begin{aligned}
 \mathbf{X}_{SAT} &= \mathbf{R}_{GCRS}^{SAT} \mathbf{X}_{GCRS} \\
 &= \mathbf{R}_{ORB}^{SAT} \mathbf{R}_{GCRS}^{ORB} \mathbf{X}_{GCRS} \\
 &= \mathbf{R}_{RPY}^{SAT} \mathbf{R}_{ORB}^{RPY} \mathbf{R}_{GCRS}^{ORB} \mathbf{X}_{GCRS}
 \end{aligned}$$

$\mathbf{X}_K$ position vector in the coordinate system K
 $\mathbf{R}_K^L$ rotation matrices from system K to system L

Occurring coordinate systems:

- Geo-centric references System (GCRS)
- Satellite reference system (SAT)
- Orbital coordinate system (ORB)
= Radial-transversal-normal direction
- Roll-Pitch-Yaw direction (RPY)



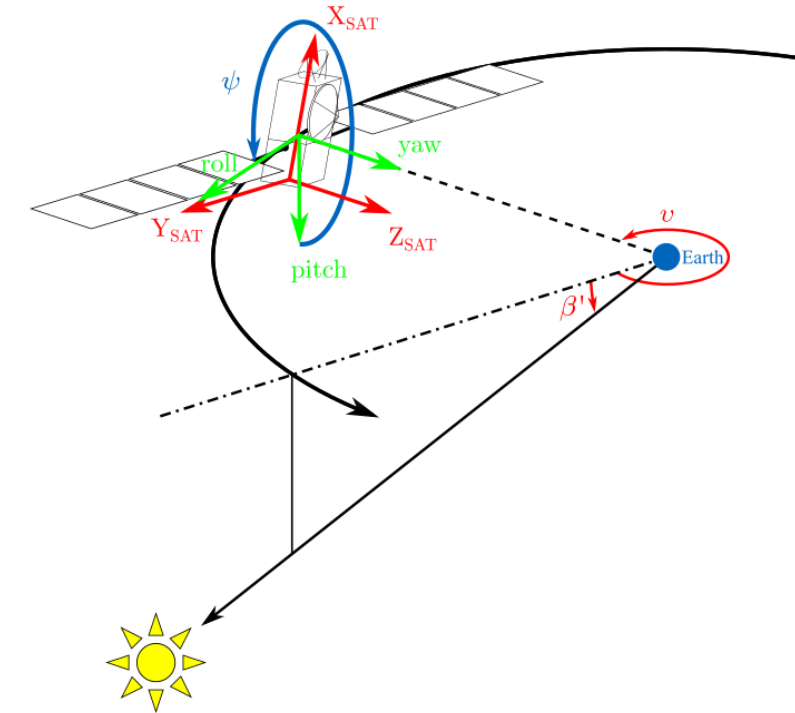
Attitude modelling of TOPEX/Poseidon

Attitude

Important parameters for the attitude modelling of TOPEX/Poseidon and the Jason satellites:

- β' angle between the orbital plane and the earth-sun vector
- ν vector of the satellite in the orbital plane

The yaw steering of the spacecraft and the rotation of the solar array is based on β' and ν .



Source: Cerri, 2010

Attitude modelling of TOPEX/Poseidon

Nominal yaw steering model

1) Spacecraft attitude (Perrygo, 1987; Casotto et al., 1994)

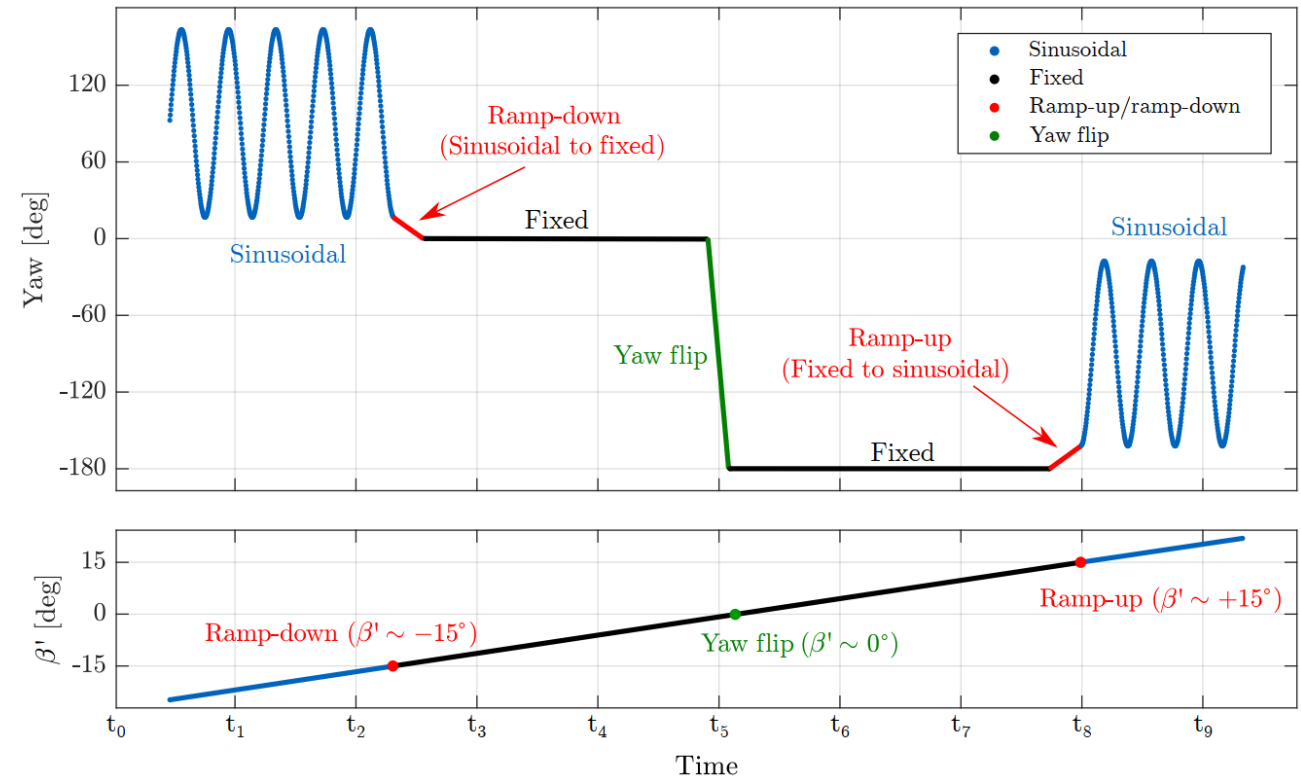
Yaw regime	Occurrence	Description
Sinusoidal	$ \beta' > 15^\circ$	Yaw sinusoidal law
Fixed	$ \beta' < 15^\circ$	Yaw = 0° if $\beta' > 0^\circ$ Yaw = 180° if $\beta' < 0^\circ$
Ramp-up	$ \beta' \geq 15^\circ$	Yaw fixed to sinusoidal
Ramp-down	$ \beta' \leq 15^\circ$	Yaw sinusoidal to fixed
Yaw flip	$ \beta' \approx 0^\circ$	Yaw = 0° if $\beta' > 0^\circ$ Yaw = 180° if $\beta' < 0^\circ$

$$yaw_{nominal} = \psi_{nominal} = \begin{cases} 90^\circ - (90^\circ - \beta') \sin \nu & (1) \\ -90^\circ + (90^\circ + \beta') \sin \nu & (2) \end{cases}$$

(1) if $\beta' > 15^\circ$

(2) if $\beta' < -15^\circ$

Behaviour of the yaw angle in the different attitude regimes



Attitude modelling of TOPEX/Poseidon

Nominal yaw steering model

2) Solar array pitch angle

Pitch angle	Occurrence	Description
$\gamma = 90^\circ + \nu$	$0^\circ < \beta' < 15^\circ$	Fixed yaw (flying forward)
$\gamma = 90^\circ - \nu$	$-15^\circ < \beta' < 0^\circ$	Fixed yaw (flying backward)
$\gamma = \arctan \left(\frac{\sin(\nu+90^\circ)\cos\beta'}{\cos(\nu+90^\circ)\cos\beta'\cos\psi - \sin\beta'\sin\psi} \right)$	$15^\circ \leq \beta' $	Sinusoidal yaw + transition regimes

Additionally:

A solar array pitch bias has to be applied to obtain the real solar array direction.

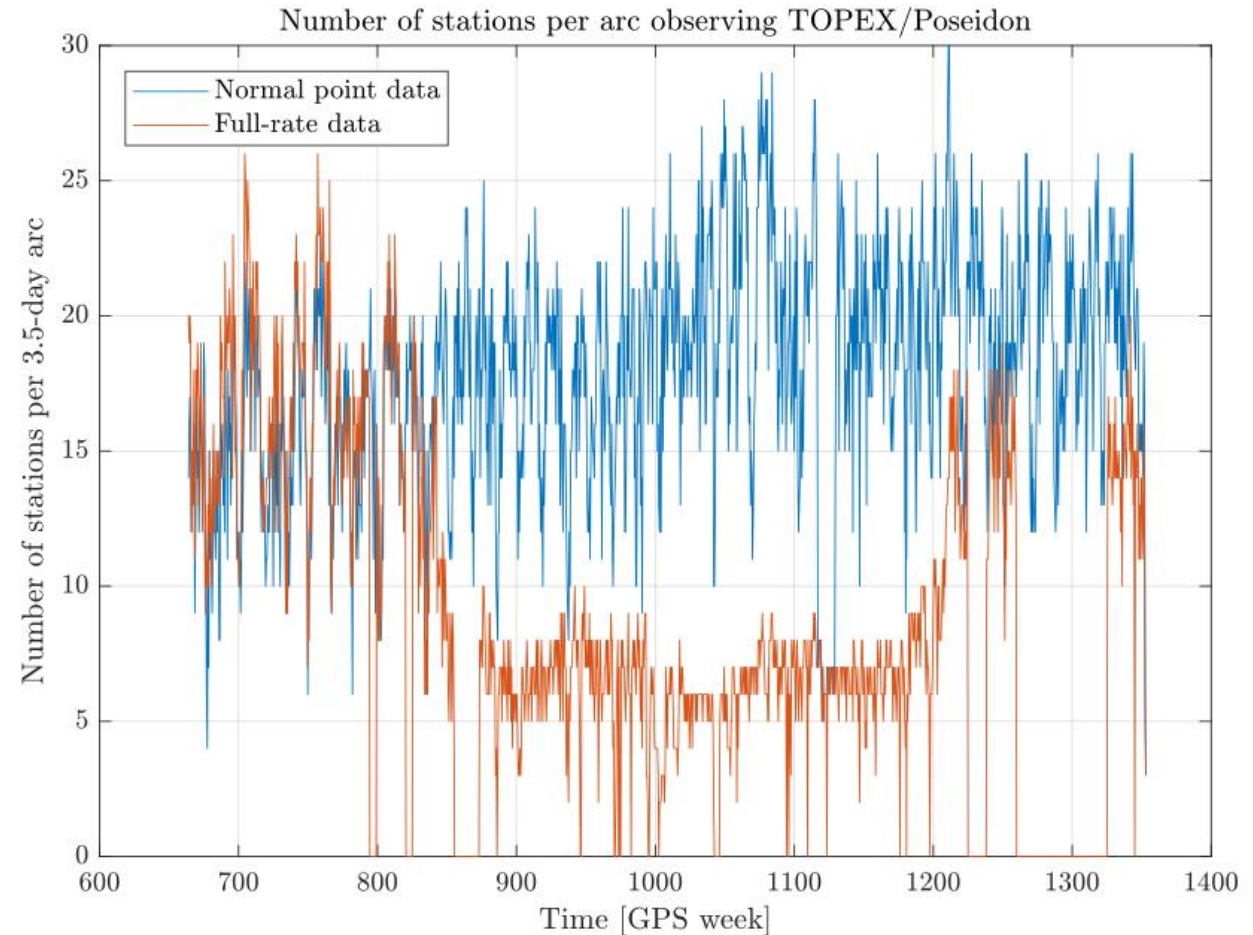
Estimation of the LRA phase centre correction function

Selection of data type (full-rate vs. normal point data)

- Full-rate data:
 - Raw observation data
 - Large number of observations
- Normal point data:
 - Combination of full-rate data
 - Significantly less normal point observations

Conclusion:

Normal point data is selected due to good observation coverage throughout the entire mission as well as the significantly larger number of observing stations than in the case of full-rate data.



Estimation of the LRA phase centre correction function

Setting for precise orbit determination

Background model	Description
Earth gravity field	EIGEN-6S (Förste et al., 2011)
Solid earth tides	IERS Conventions 2010
Ocean/atmospheric tides	EOT11a (Savcenko et al., 2012) up to degree/order 30
Atmospheric drag	NRLMSISE00 (Picone et al., 2002)
Reference frame	SLRF2014, version 200428
Precession/nutation	IAU2000A/IAU2006 model up to degree 10 (Mathews et al., 2002)
A priori EOP values	IERS EOP 14 C04 (Ray et al., 2003)
Orbit computation	Description
Observation type	SLR normal point data
Integration step size	30 seconds
Arc length	3.5 days
Estimated parameters	Keplerian elements (once per arc) Albedo scaling factor (once per arc, $\sigma = 0.01$) Solar radiation scaling factor (once per arc, $\sigma = 0.01$) Atmospheric drag scaling factor (every 12 h, $\sigma = 0.01$) Empirical accelerations (every 12 h, $\sigma = 0.01 \text{ m/d}^2$)

Estimation of the LRA phase centre correction function

Inspection of SLR residuals

$$SLR\ residual = observed\ SLR\ range - computed\ SLR\ range$$

In the following steps, combined SLR residuals are used:

$$combined\ residual = SLR\ residual + pass\ range\ bias$$

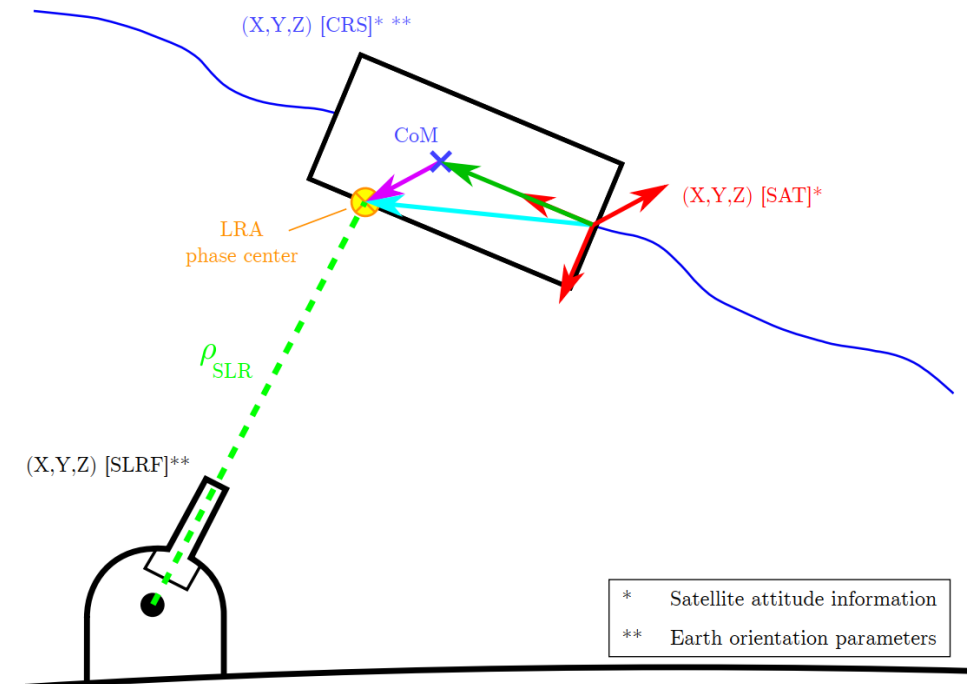
The pass range bias is estimated within the orbit computation per station and per pass.

Combined residuals have to be used to stabilize the uncorrected orbit and for a successful convergence of the orbit using the LRA correction function.

For the difference between using and neglecting the pass range bias, also see slide 14.

Note: Within the orbit computation to determine the combined residuals, no albedo scaling factor and no empirical accelerations are estimated to not absorb any LRA variations.

Schematic principle of the SLR technique



Estimation of the LRA phase centre correction function

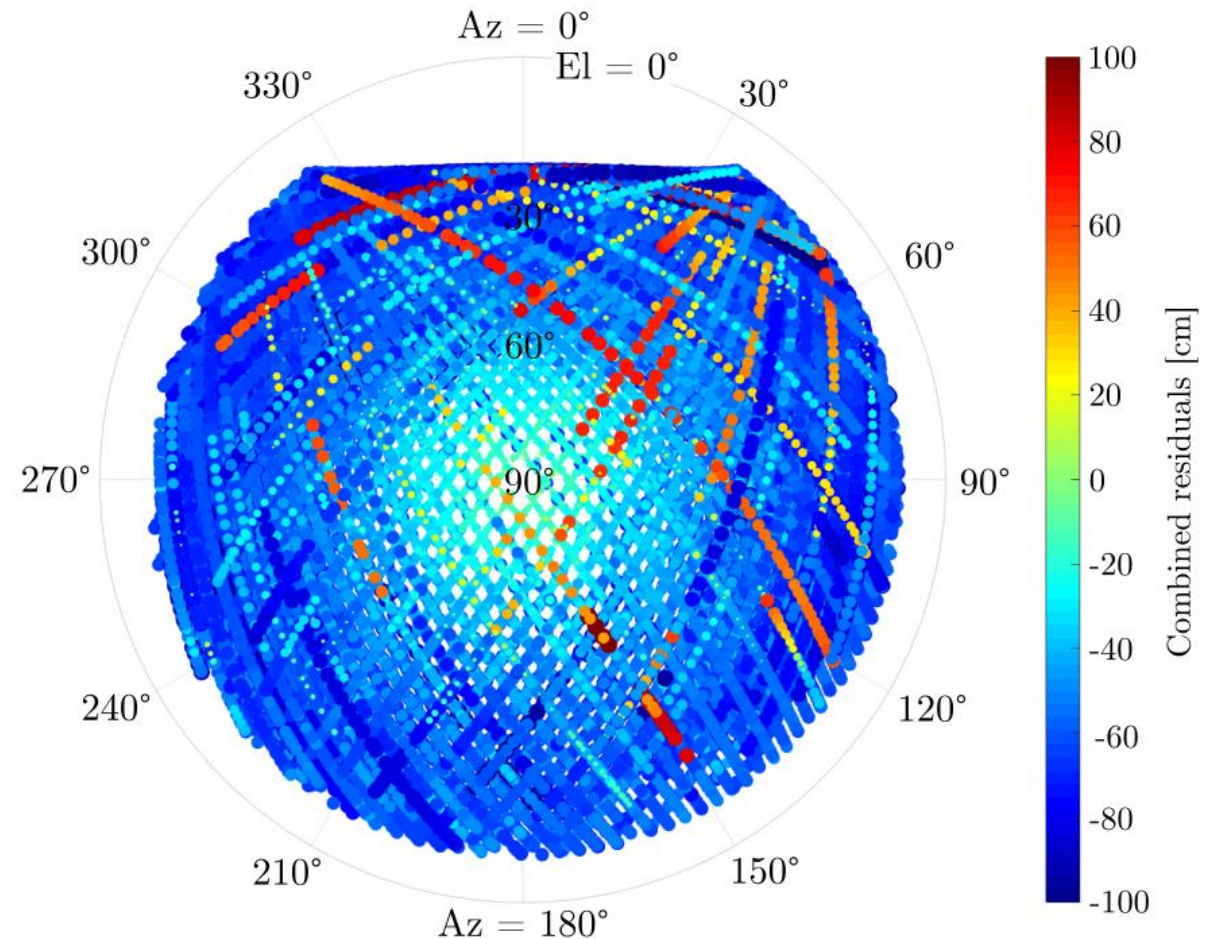
Inspection of SLR residuals

Analysis/inspection of the combined residuals of each SLR station over the entire satellite mission.

Example on the right: Wettzell (88341001)

- Detection and elimination of gross errors:
orange and red dots in the skyplot
- Hidden systematics:
Strong elevation dependency
Minor variability in azimuth direction
- Station dependent behavior:
Interrupted sight between the SLR ground station
and the satellite due to buildings or canopy

Skyplot of combined residuals (Wettzell 88341001)



Estimation of the LRA phase centre correction function

Parameter estimation

The general functional model of the LRA correction function is:

$$R = O + R_Z \cos(e) + [G_N \cos(a) + G_E \sin(a)] \cos(e)$$

with:

- a Observation azimuth [rad]
- e Observation elevation [rad]
- R Combined SLR residual (observation residual + pass range bias) [cm]
- O Offset [cm]
- R_Z Residual correction in zenith direction [cm]
- G_N Gradient in North direction [cm]
- G_E Gradient in East direction [cm]

An individual set of four parameters (O, R_Z, G_N, G_E) is estimated for each of the 74 SLR ground stations observing the TOPEX/Poseidon spacecraft.

Estimation of the LRA phase centre correction function

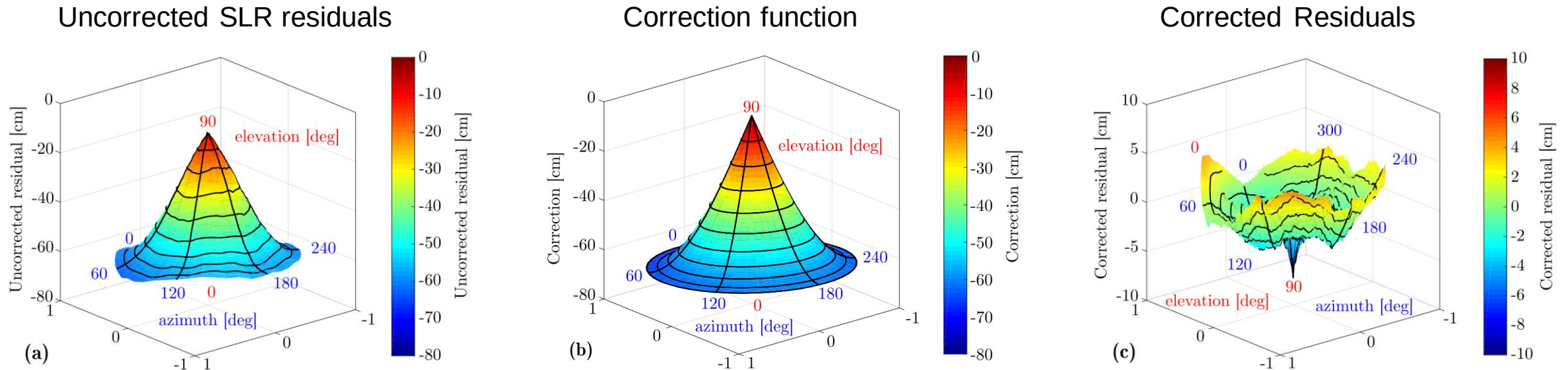
Parameter estimation

Estimated parameters for the station **Wettzell (88341001)**:

$$O = -3.8421 \text{ cm} \quad R_Z = -60.6347 \text{ cm}$$

$$G_N = -3.2395 \text{ cm} \quad G_E = 1.3104 \text{ cm}$$

Each SLR observation is improved by the value obtained from the correction function using the station-specific parameters.



Estimation of the LRA phase centre correction function

Parameter estimation

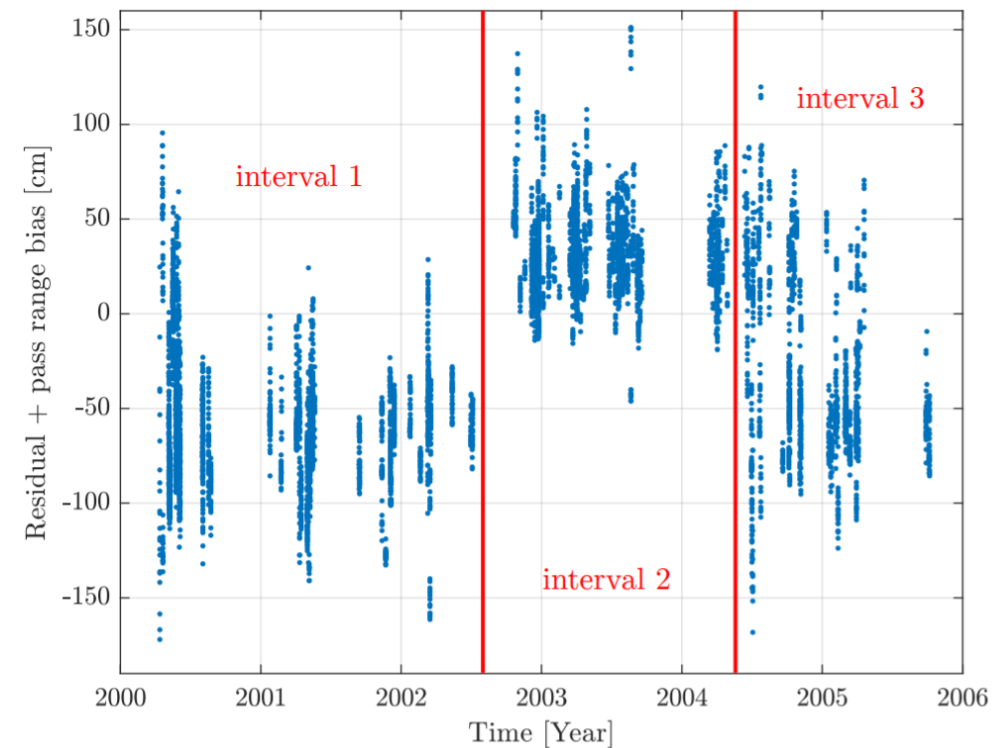
Estimated parameters for the station **Kiev (18248101)**:

- Three intervals of different SLR residual behaviour detected
 - Interval 1: until 2002-08-01
 - Interval 3: after 2004-07-01
 - Interval 2: between interval 1 and interval 3
- These residual systematics only appear at this station

Conclusion:

A set of four correction parameters is estimated for each interval to optimally correct the station residuals.

Combined residuals of station Kiev (18248101)



Estimation of the LRA phase centre correction function

Corrected residuals

Left plot: residuals of SLR observations not improved by the LRA correction function

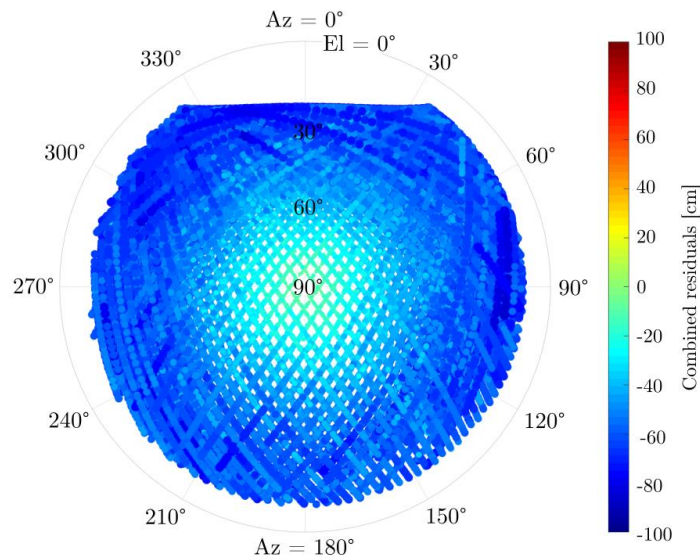
Middle plot: residuals of SLR observations improved by the LRA correction function based on only the SLR residuals

→ The orbit does not converge in the correct minimum

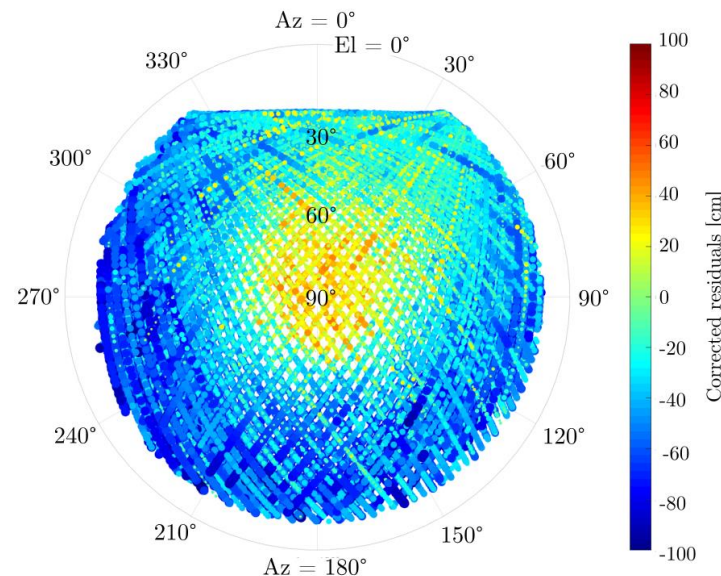
Right plot: residuals of SLR observations improved by the LRA correction function based on the SLR residuals and pass range biases

→ Successful orbit convergence achieved

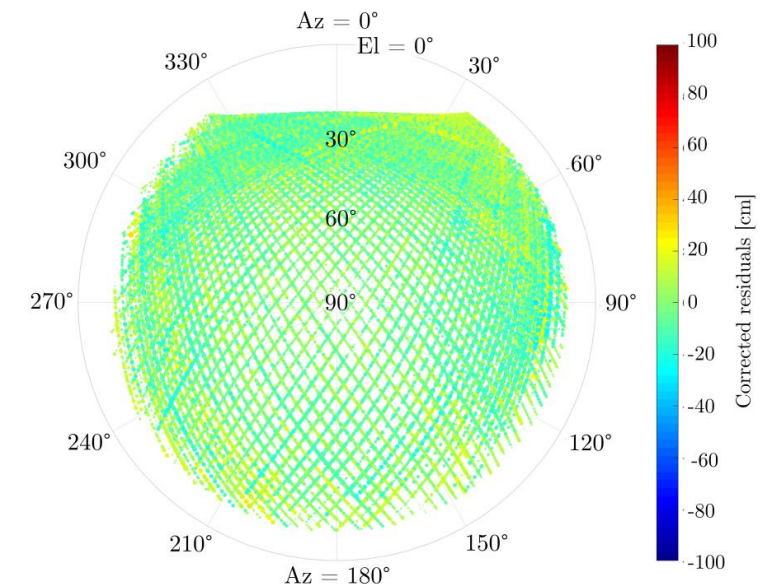
Skyplot of combined residuals (Wettzell 88341001)



Skyplot of corrected residuals (Wettzell 88341001)



Skyplot of corrected residuals (Wettzell 88341001)

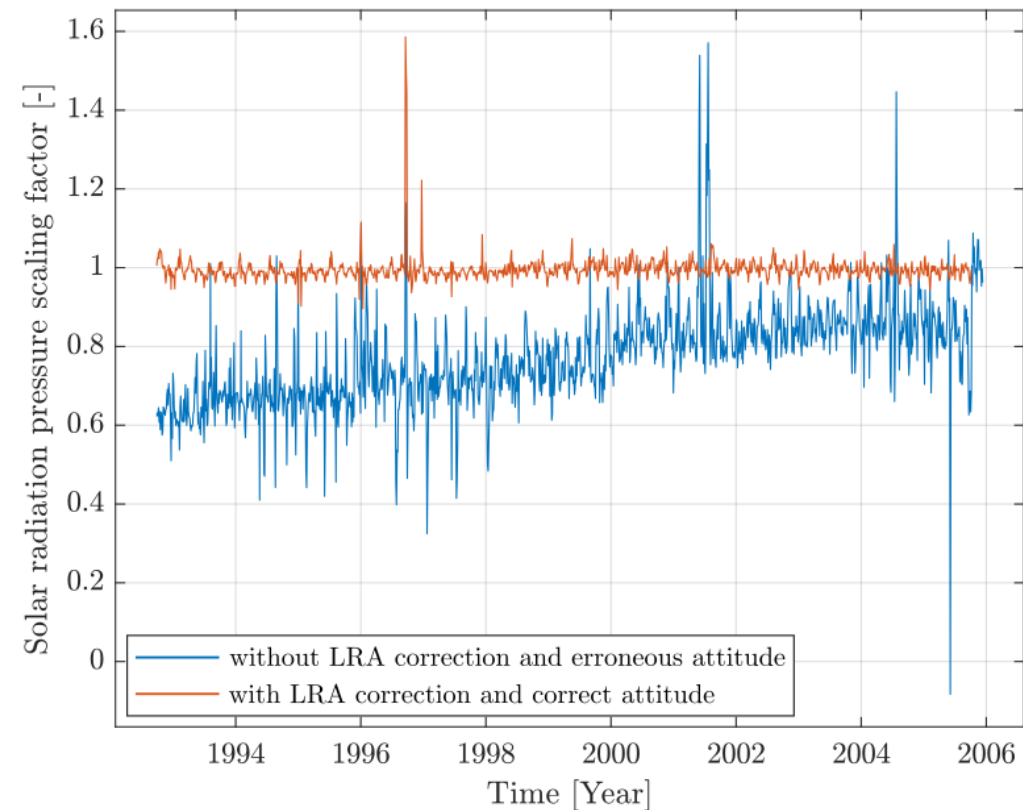
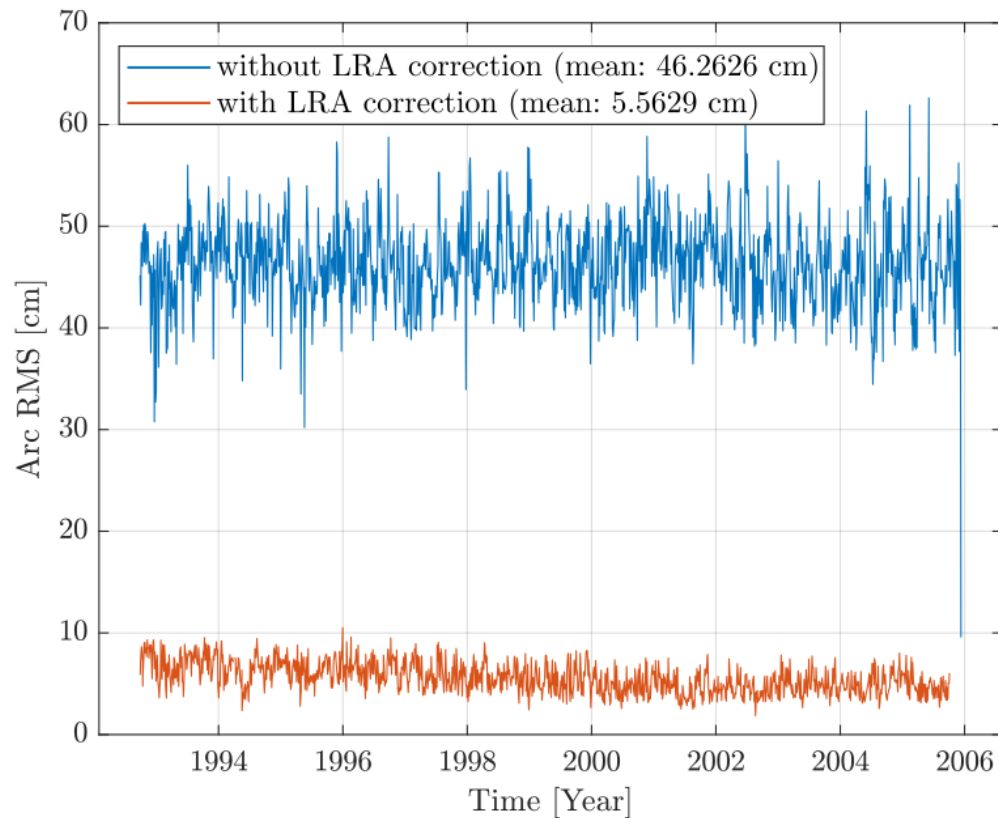


Orbit comparison

Internal DGFI comparison

Applying the LRA correction function to the SLR observations improves the mean orbit arc RMS from 46.26 cm to 5.56 cm. This is a reduction by ca. 88 %

The observation correction also improves the quality of orbit parameters estimated within the POD, e.g., the solar radiation pressure scaling factor is closer to its target value of 1.



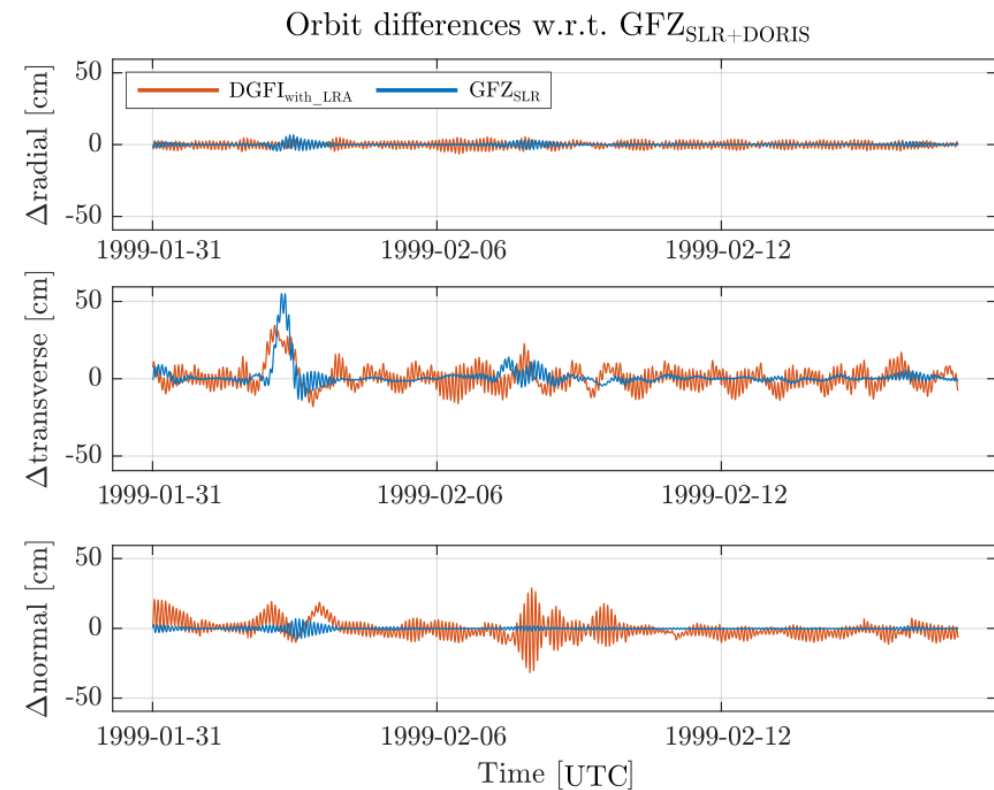
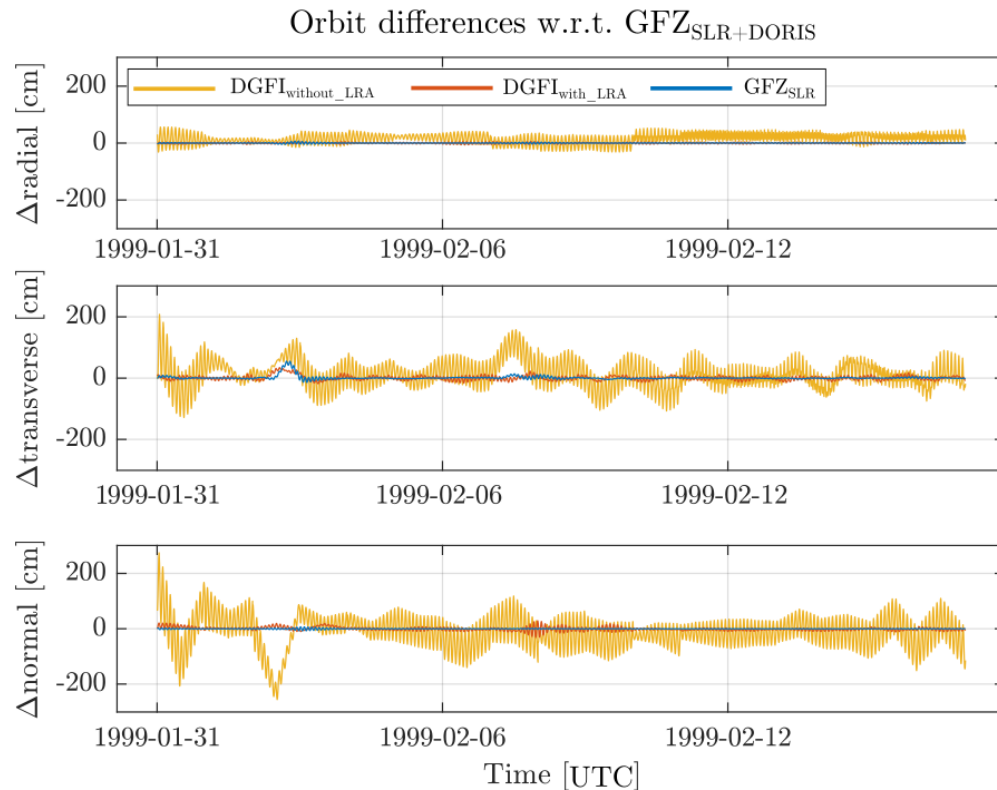
Orbit comparison

Comparison with external orbits

External orbits:

GFZ DORIS+SLR (VER13, Rudenko et al., 2018)

GFZ SLR-only (CCI22, Esselborn et al., 2018)



Orbit comparison

Comparison with external orbits

Mean and standard deviation of the orbit differences in radial, transverse and normal direction in the interval between 1999-01-31 and 1999-02-17:

Reference solution	GFZ SLR+DORIS			GFZ SLR
(all values in cm)	DGFI-TUM w/o LRA	DGFI-TUM with LRA	GFZ SLR	DGFI-TUM with LRA
Mean radial	15.626	-0.127	0.038	-0.165
Mean transverse	12.851	0.728	1.209	-0.480
Mean normal	-12.294	-0.680	-0.140	-0.534
Std. dev. radial	17.129	2.029	0.964	2.166
Std. dev. transverse	44.511	7.354	6.248	7.140
Std. dev. normal	60.530	6.211	1.072	6.450

Conclusion:

- Removal of the offset contained in the uncorrected DGFI solution in all components
- Significantly reduced standard deviation in the corrected DGFI solution
- Accordance of both GFZ solutions better due to similar POD settings

Conclusion

- Not ideally designed TOPEX/Poseidon LRA causes large phase centre variations limiting the orbit accuracy
- Precise orbit determination requires a higher orbit accuracy which is achieved by improving the SLR observations using a station-dependent correction function
- Applying the correction function, the entire mission arc-wise RMS fit of SLR observations improves by 88 % from 46 cm to 5.5 cm
- The improved DGFI-TUM orbit shows good agreement to external solutions
- An altimetry analysis with the enhanced orbit will further evaluate the quality of the orbit
- A paper about this topic will be submitted soon and a Fortran routine will be provided for external users upon request

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