Analysis of attitude dependent deficiencies in precise orbit solutions of Jason-3

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Introduction

The mission objective of the low earth orbiter (LEO) Jason-3 is to measure global sea-surface height. This is achieved by altimetry radar measurements. To interpret these measurements as accurately as possible, a precise orbit determination (POD) is required. The goal of this study is to identify deficits in the orbit determination. One of the characteristics of Jason-3 is that the satellite changes its attitude, depending on the β-angle. The LEO is in either yaw-steering or fixed-yaw attitude mode, whereby either the positive or negative x-axis of the satellite body fixed frame (SBFF) is pointing in the direction of flight (Fig. 1). Previous analyses have shown that different systematics in the resulting orbits are present depending on the attitude mode in which the satellite is operating. These systematics are analyzed further in this study. Data from two different satellite geodesy techniques are used in this study: the Global Positioning System (GPS) as one of the primary techniques for the POD of LEOs and Satellite Laser Ranging (SLR) for highly accurate distance measurements from ground stations to the retroreflector arrays of LEOs. On the one hand, GPS observation are used for the POD of Jason-3, on the other hand, corrections of the phase center offset (PCO) of the LEOs receiver antenna are estimated in the processing. The different attitude modes allow the estimation of corrections in all three components of the SBFF. Orbit comparisons show that in radial direction, which is of central importance for altimetry satellites, different systematic differences occur when comparing periods of different attitude modes (Fig. 2). Using SLR as an independent technique, offsets in the orbit frame can also be estimated when fixing the orbit to the GPS-based solution. Validity and sensitivity tests of the SLR analysis are performed, whereby artificial offsets are induced, for example by manipulating the PCO in the POD processing. The final objective of this study is to determine whether corrections of satellite-specific characteristics (PCO) exist which lead to a superior solution where the systematic differences of the PCO correction estimation and SLR validation of the different attitude modes are significantly reduced.

Precise orbit determination

In this study three different parametrizations were used; Reduced-dynamic (RD), Dynamic (using non-gravitational force modelling (NG)) and Dynamic including PCO correction estimation (NG w/ P.E.). All orbit solutions were parameterized by 6 Keplerian elements with additional piece-wise constant accelerations (PCA) in radial (R), along-track (S) and cross-track (W) direction every 6 min, whereby the contraints differ for RD and NG solutions. The details of the parametrizations and models used for the different solutions are given in the table below:

Parameter/Model	Reduced-dynamic	Dynamic w/o & w/ PCO est.
Attitude	Quaternions	Quaternions
Gravity field (static)	GOCO05s (120x120)	GOCO05s (120x120)
Gravity field (time varying)	IERS 2010 Conventions	IERS 2010 Conventions
Radiation pressure model	No explicit modelling	Macro model
Earth radiation	No explicit modelling	Albedo and Infrared
SRP coefficients	No explicit modelling	1/day & none
Empiricals	PCA in $R/S/W$ (5 nm/s^2)	PCA in $R/S/W$ (0.5 nm/s^2)
GPS orbits	CODE final products	CODE final products
GPS clock corrections	CODE final products, 5 s	CODE final products, 5 s
Ambiguities	Estimated (integer)	Estimated (integer)

Important to mention is that NG and the NG w/ P.E. solution differ by the estimation of a solar radiation pressure (SRP) scaling coefficient: the parametrization of the NG solution includes the estimation of 1 scaling factor for SRP per day. The NG w/ P.E. parametrization does not include this to prevent strong correlations between estimated PCO correction and SRP scaling factor.

Orbit comparison to external solution

An orbit comparison of the different solutions to an external solution provided by CNES shows systematic differences, which are different for the different attitude modes. In Fig. 2 daily mean values of orbit differences in radial direction are plotted. It is evident that for the fixed yaw attitude modes a bias between forward and backward orientation is present for the reduced-dynamic (RD) solution.

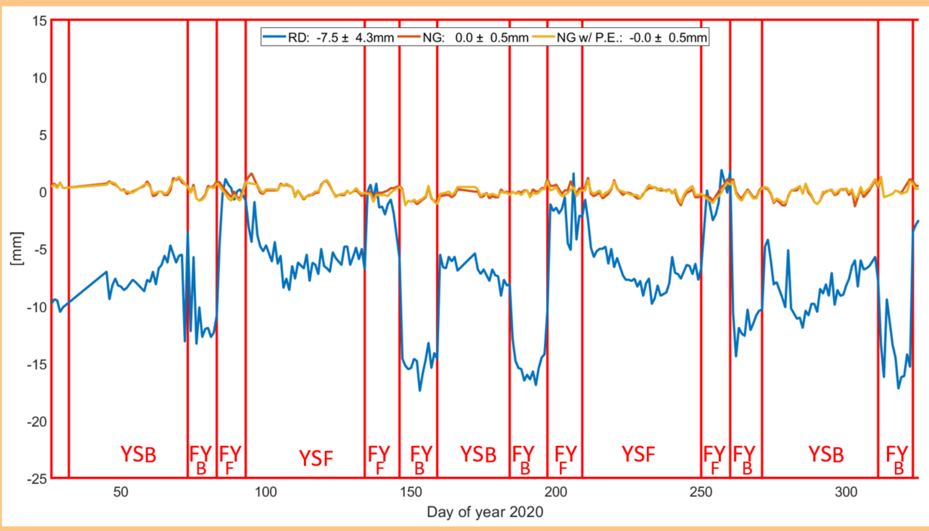

Figure 2: Mean values of orbit comparison (radial direction)

Whenever a yaw flip takes place, the orbit differences in the comparisons of the reduced-dynamic orbit solution to the reference solutions in radial direction, reveal a switch between ∼-15mm and ∼0mm and vice versa. Since the orbit parametrization of this solution has a high sensitivity on the PCO information, these switches indicate imprecise PCO information.

Jason-3 attitude modes

The attitude mode of Jason-3 changes depending on the β-angle (Couderc 2015) according to:

- $|\beta| > 15° \rightarrow$ Yaw-steering mode (YS)
- $|\beta| \leq 15° \rightarrow$ Fixed yaw mode (FY)
- $\beta = 0° \rightarrow$ Yaw flip

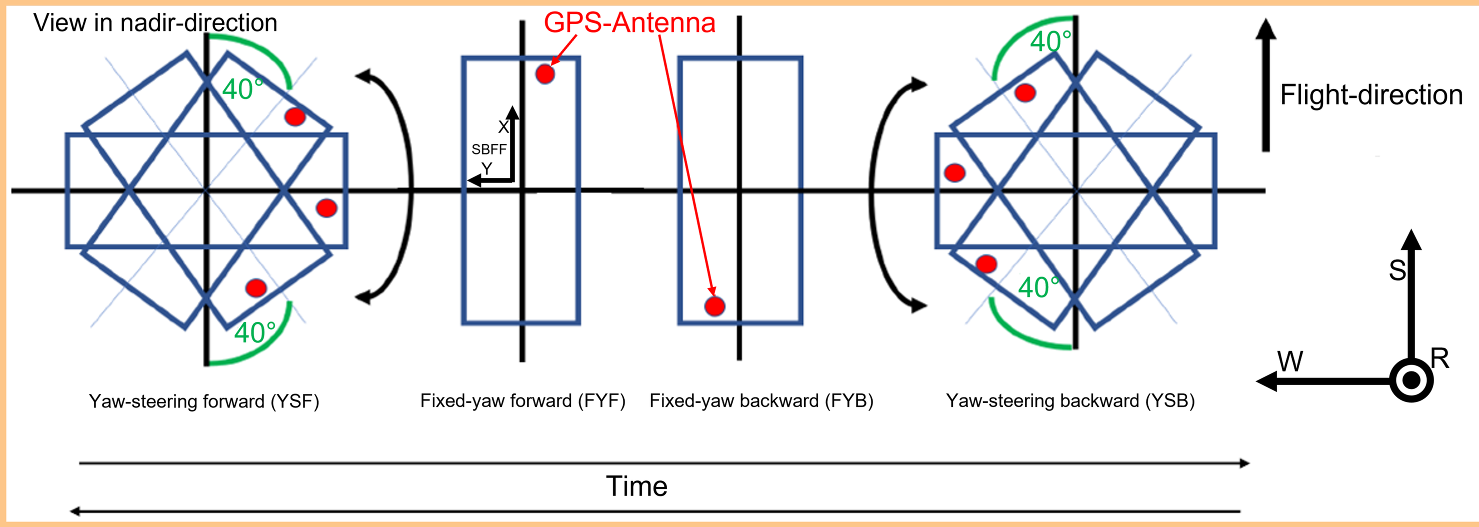

Figure 1: Jason-3 Attitude modes

The yaw-steering attitude mode period lengths are about 35 days and the fixed-yaw attitude mode periods of about 10 days. Fig. 1 illustrates the four different attitude modes whereby the position of the GPS antenna is indicated, as well as the rotation including its maximum elongation.The solar panels are rotated to point towards the sun at all times (Cerri and Ferrage 2015).

Relation between PCO correction and SLR validation

The change of attitude modes opens the possibility of disentangling PCO errors and model deficiencies in the POD of Jason-3. Fig. 3 explains how the SLR validation compares with the estimated PCO corrections for the different attitude modes, whereby the estimated corrections are estimated in the antenna frame (north (N), east (E) and up (U)). Based on this it is feasible to "manipulate" the PCO to further improve the POD of Jason-3 and therefore increase the precision of the resulting orbits as revealed by the SLR validation. The relations shown in Fig. 3 can be derived from the knowledge about the orientation of the satellite in the different attitude modes as shown in Fig. 1. Note that the GPS antenna is tilted by 15° towards the +X axis in SBFF (Couderc 2015) which causes that the relation between $N/E/U$ and $R/S/W$ is slightly more complicated than shown in Fig. 3.

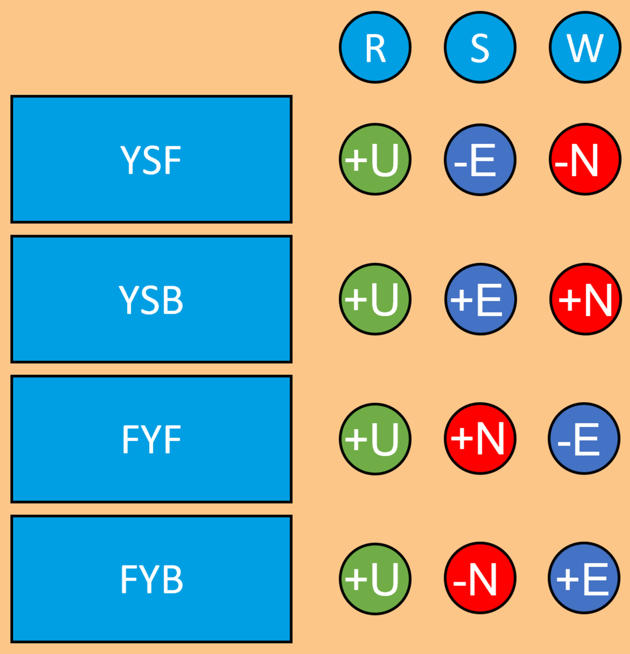

Figure 3: Relations N/E/U and R/S/W

Applied procedure

On the one hand, the aim of this study is to find out which PCO corrections would be beneficial for the POD of Jason-3, on the other hand, the sensitivity of the SLR validation including estimation of offsets in the local orbital frame shall be tested. The approach in this study is to use an iterative procedure, in which an initial PCO correction estimation and an SLR validation are performed first. Based on the initial PCO correction estimates, these values are corrected and a further orbit determination, as well as a subsequent SLR validation with bias estimation (e.g. Arnold et al. 2019) are performed. To check the results, the process of correction of PCO and re-estimation (including SLR validation) is performed in a second iteration. The results are shown in Fig. 4.

Results

The applied corrections after the initial step result from the mean values of the estimated PCO corrections. For the applied correction in U only the estimates from YSF/YSB were taken into account to not deteriorate the solution due to the systematic difference for the FYF/FYB attitude modes evident in Fig. 2.

Initial PCO estimation

PCO:

	YSF	YSB	FYF	FYB
N	15.1	15.0	-	-
E	-	-	3.4	3.5
U	8.6	10.0	3.6	13.6

SLR:

	YSF	YSB	FYF	FYB
R	0.1	0.5	0.9	1.5
S	17.3	4.6	10.8	17.2
W	5.6	-4.7	3.8	-7.8

	Applied correction
N	15.1
E	3.5
U	9.3

1. Iteration

PCO:

	YSF	YSB	FYF	FYB
N	0.3	-0.5	-	-
E	-	-	0.1	3.4
U	-0.6	0.4	-2.1	10.3

SLR:

	YSF	YSB	FYF	FYB
R	1.0	-4.7	7.4	6.6
S	11.0	8.2	29.1	1.6
W	-6.1	6.7	-3.1	-4.6

	Applied correction
N	-6.4
E	0.75
U	-9.3

2. Iteration

PCO:

	YSF	YSB	FYF	FYB
N	6.4	6.3	-	-
E	-	-	-0.8	-0.7
U	8.6	10.0	6.0	15.9

SLR:

	YSF	YSB	FYF	FYB
R	0.3	0.3	0.8	1.5
S	13.1	8.7	17.5	9.6
W	-0.7	1.6	0.7	-4.3

Figure 4: PCO estimation and SLR validation results

The applied corrections after the 1. iteration result from the SLR validation: since the estimated offsets in R changed inconclusive, the applied correction after the initial PCO estimation for U is undone ($-9.3mm$). For N the correction results from the determined offsets for YSF and YSB in W direction $(-(-6.1)mm + (6.7mm))/2 = 6.4mm$, taking into account the relations shown in Fig. 3 (reverse sign for YSF). For E a general offset $(((-3.1mm)+(-4.6mm))/2 = -3.85mm = \delta)$ is identified, which is probably due to a mismodeling of the solar radiation pressure. The applied correction is derived by computing $E = (-(-3.1mm) + (-4.6mm))/2 = -0.75mm$. Note that the corrections derived from the SLR validation have to be applied with an sign change.

Discussion

The initial PCO estimation reveals a significant offset in north direction in the antenna frame. Remarkable are also the different values for the estimated corrections in the up component comparing the two fixed yaw attitude modes. The SLR validation of the first iteration shows that the correction applied to the PCO in N direction, for example, in along-track direction (S), in the fixed yaw attitude modes, is reflected in the estimated offset (SLR) with opposite sign for forward and backward orientation. Also the correction applied to the east direction is visible in the along-track direction of the yaw-steering modes, when comparing the SLR validation results from initial and first iteration. The first and second iteration reveals that the radial levelling of Jason-3 (using the dynamic parametrization) can be manipulated but not improved by applying the estimated PCO correction (in U direction). The interpretation of these results is that if the estimated offset in the SLR validation are similar for the two fixed-yaw and yaw steering attitude modes respectively (including an opposite sign), this is due to an error in the PCO (or center of mass) information. If the estimated offsets in the local orbital frame have a general offset (mean values differ from zero), for example in cross-track direction for the fixed yaw attitude modes, this leads to the conclusion that a mismodelling in the POD is present, which could be an inappropriate SRP modelling due to the large area/mass ratio (Lemoine et al. 2019).

Summary and Conclusion

The results (shown in Fig. 4) reveal the need of a PCO correction: $N = (15.1 - 6.4)mm = +8.7mm$, and $E = (3.5 + 0.75)mm = +4.25mm$. If these corrections are applied, the SLR validation shows a small mean for radial and cross-track directions in all attitude modes. The residual offsets present in the SLR validation after the PCO correction stem most likely from orbit modelling issues, which need further investigation. In line with the results from Moyard et al. 2019, a bias is present for the fixed yaw attitude modes, in S direction (Fig. 4) and R direction (Fig. 2), when a yaw flip takes place, whereby a possible error source could be an imprecise information about the distance between GPS antenna and SLR retroreflector, which demands for further investigation.

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