Reducing Pointing Induced Errors in the GRACE Follow-On Laser Ranging Measurement Using Dedicated Calibration Maneuvers

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Introduction

The Laser Ranging Instrument (**LRI**) onboard GRACE Follow-On will measure the inter-satellite distance variations, in parallel to the K-Band Ranging (KBR) instrument. Imperfect satellite pointing causes an error in the LRI ranging-measurement, called Tilt-To-Length (**TTL**) coupling error: $\delta\rho_{\text{TTL}}$. It is the largest expected noise source in the LRI ranging measurement, along with laser frequency noise (cf. [2]). We propose calibration maneuvers using magnetic torque rods (cf. **figures 2,4,6**). These maneuvers can be used to determine the TTL coupling factors (**CFs**) and to compute a correction term. Similar approaches are being used to calibrate the KBR ("antenna offset correction") and also for center of mass (**CoM**) calibration (cf. [1]). Decisions on the following maneuver parameters have to be made:

magnetic moment activation, maneuver frequency, duration, geographic location

Least-squares estimation

- Assumed linear **TTL** error model: $\delta\rho_{\text{TTL}} = \sum_{i=1}^{3} \alpha_i \cdot \theta_i$
- estimation of linear **CFs** α_i for pointing angles θ_i, where $i = 1, 2, 3$ denotes the rotation axis (roll, pitch, yaw)
- Estimator covariance: $CV := \text{cov}(\hat{\alpha}) = \sigma^2(n)\left(\theta^T\theta\right)^{-1}$
- $\sigma^2(n)$ is the variance of the noise term (cf. **figure 7**)
- $\Rightarrow$ Standard deviations of **CFs**: $\sigma(\hat{\alpha}_i) = \sqrt{|CV_{ii}|}$

Maneuver placement

Shown below is a test case to investigate the optimal geographic location of maneuvers.

- Left (**figures 1,3,5**): Standard deviations of **CF** estimators along the orbit trajectory; colors indicate the STDs for a maneuver centered at that geographic location (50 orbital revolutions, simulated for December 2008, geomagnetic field model: IGRF-12)
- Right (**figures 2,4,6**): Pointing angles of maneuvers with optimal placement (marked on the left), i.e. where the estimation error is minimal for roll, pitch, yaw, respectively
- sinusoidal magnetic moment activation with frequencies 48.3, 50, 51.8 mHz in the x-, y-, z-axis rods
- maneuver duration = 300 s
- Assumption on the noise: $\sigma(n) = 10\,\text{nm}$

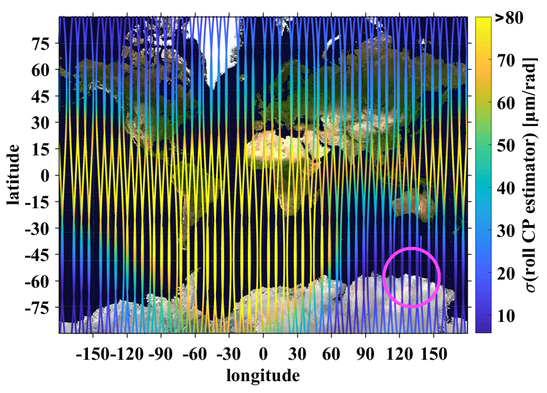

Fig. 1: Standard deviations of **roll CF** estimators

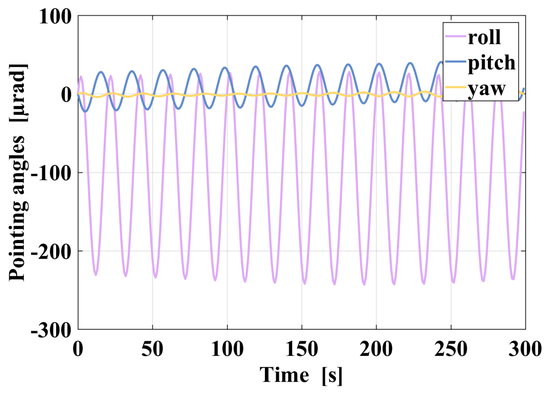

Fig. 2: Example of a rotation maneuver, optimized for **roll**

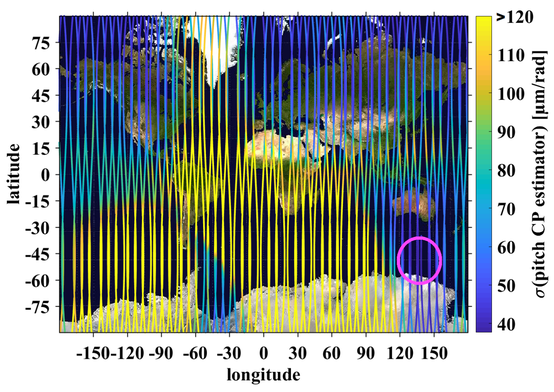

Fig. 3: Standard deviations of **pitch CF** estimators

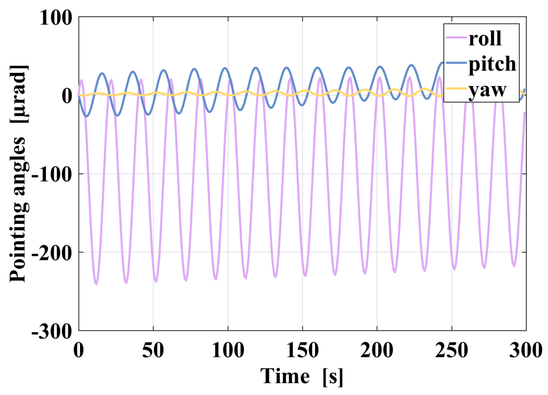

Fig. 4: Example of a rotation maneuver, optimized for **pitch**

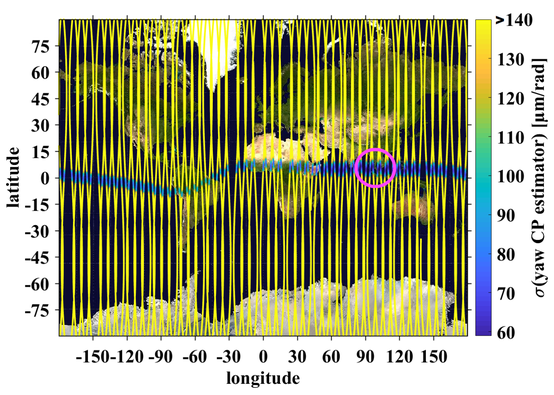

Fig. 5: Standard deviations of **yaw CF** estimators

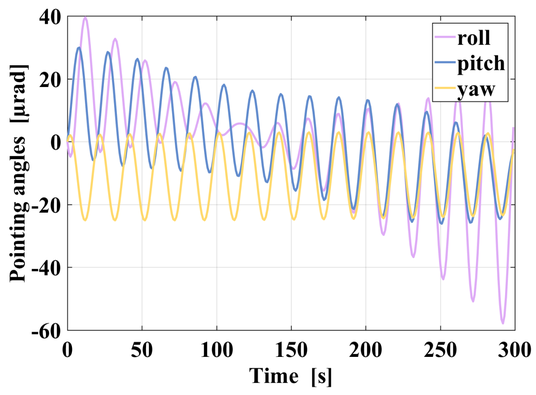

Fig. 6: Example of a rotation maneuver, optimized for **yaw**

lat / long [°]	STD **roll CF** [µm/rad]	STD **pitch CF** [µm/rad]	STD **yaw CF** [µm/rad]
-63 / 122	**6**	58	626
-53 / 130	14	**37**	546
6 / 101	62	85	**59**

Frequency bands

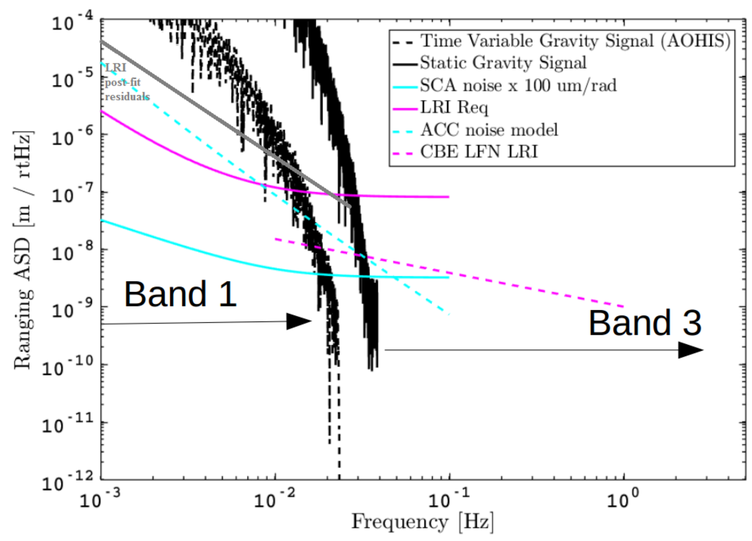

Fig. 7: Amplitude spectral density (ASD): noise terms in different maneuver frequency bands

- band 1 ($<$ 20 mHz): full gravity signal, use post-fit residuals
- band 2 (20–50 mHz): time-varying gravity signal, use pre-fit residuals
- band 3 ($>$ 50 mHz): no gravity signal, use ranging-measurements

Optimal maneuver design

One can use torques of either sinusoidal or square wave form. Feasible and useful durations range from 180 s to 600 s. Adjustments can be made for practical purposes. The optimal geographic location depends on the other maneuver parameters (cf. **figures 1,3,5**). We propose

- activating magnetic moments in all three axes, but ensure that all three **CFs** are estimated accurately
- a basic maneuver frequency of 50 mHz, with slightly different frequencies for each torque rod, in order to minimize correlations
- maneuver durations of 300 s

Full-scale simulations have shown that, after gravity field recovery, the TTL error is still present in the post-fit residuals (gray line in **figure 7**), such that those could also be used for **CF** estimation.

References

1. Wang F. (2003) Study on center of mass calibration and K-band ranging system calibration of the GRACE mission, PhD thesis
2. Darbeheshti N. et al (2017), Instrument data simulations for GRACE Follow-On: observation and noise models, Earth System Science Data