Implementation of GRACE and GRACE-FO observation covariance estimates at JPL

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Introduction

Background and Introduction

It has been shown that the processing of gravity field observations from GRACE data can benefit from introducing a realistic noise covariance matrix ([1]Kvas et al, 2019) for time-correlated observables. Building on this foundation, a similar framework for co-estimation of stochastic models for GRACE and GRACE-FO low-low and high-low satellite-to-satellite tracking observations is being implemented at JPL.

In a significant difference to previous work, GPS observations are introduced in the form of pseudoranges, instead of pre-processed kinematic orbit positions, giving insight into the correlation structure of these observations.

[1]Kvas et al, 2019: ITSG-Grace2018: Overview and Evaluation of a New GRACE-Only Gravity Field Time Series: (https://doi.org/10.1029/2019JB017415)

Satellite-to-satellite tracking observation types

At JPL, the following GRACE and GRACE-FO observation types are used in the estimation of Level 2 gravity field parameters:

- K-Band Ranging Instrument: Dual one-way observations, transformed into the Euclidean distance between the two spacecrafts centers of mass by application of a time of flight and antenna offset correction.
- Laser Ranging Interferometer: The round-trip observations on GRACE-FO are processed to represent the same Euclidean distance as the KBR.
- GPS Carrier Phase and Code: Ionosphere-free combination.

Dynamic orbit integration and force model errors

Satellite orbits are integrated in an a priori gravity field model using accelerations from background-models (e.g. AOD1B) and the on-board accelerometers. Where accelerometer data is not available for one of the spacecraft, the transplanted and transformed ACT1B data product is used.

Importantly, this implies that measurement error in the accelerometer data and model error pollutes the determined dynamic orbits. The noise models are estimated on satellite-to-satellite tracking observations reduced by these dynamic orbits. These noise models will thus capture some component of accelerometer and background model error.

Observation model

With reduced observations equations:

$$\underbrace{\begin{bmatrix} \boldsymbol{\Delta l}_{KBR} \\ \boldsymbol{\Delta l}_{GPS} \end{bmatrix}}_{\text{Reduced observations}} = \underbrace{\begin{bmatrix} \boldsymbol{A}_{KBR} \\ \boldsymbol{A}_{GPS} \end{bmatrix}}_{\text{Information equations}} \boldsymbol{x} + \underbrace{\begin{bmatrix} \boldsymbol{e}_{KBR} \\ \boldsymbol{e}_{GPS} \end{bmatrix}}_{\text{Residuals}}$$

A stochastic model is estimated from the post-fit residuals $\hat{\boldsymbol{e}}_{KBR}$ and $\hat{\boldsymbol{e}}_{GPS}$.
The stochastic model treats each observation group independently.
Gravity field parameters are resolved to degree and order 96.

Stochastic model

The covariance matrix for each observation group is described by a Toeplitz matrix created by the summation of several cofactor matrices:

$$\boldsymbol{\Sigma} = \sigma_1^2 \boldsymbol{Q}_1 + \cdots + \sigma_N^2 \boldsymbol{Q}_N = \sum_{j=1}^{N} \sigma_j^2 \boldsymbol{Q}_j$$

Each cofactor matric represents the correlation for one time lag between observations, as in the following abbreviated example:

$$\boldsymbol{Q}_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \boldsymbol{Q}_2 = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \qquad \boldsymbol{Q}_3 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

These matrices are then scaled by variance factors $\hat{\sigma}_j^2$ estimated from the post-fit residuals[1]. This Toeplitz matrix can be represented by a covariance function, or conversely, a power spectral density.

[1] see: Ellmer, 2018: Contributions to GRACE Gravity Field Recovery (https://doi.org/10.3217/978-3-85125-646-8)

Estimated stochastic models

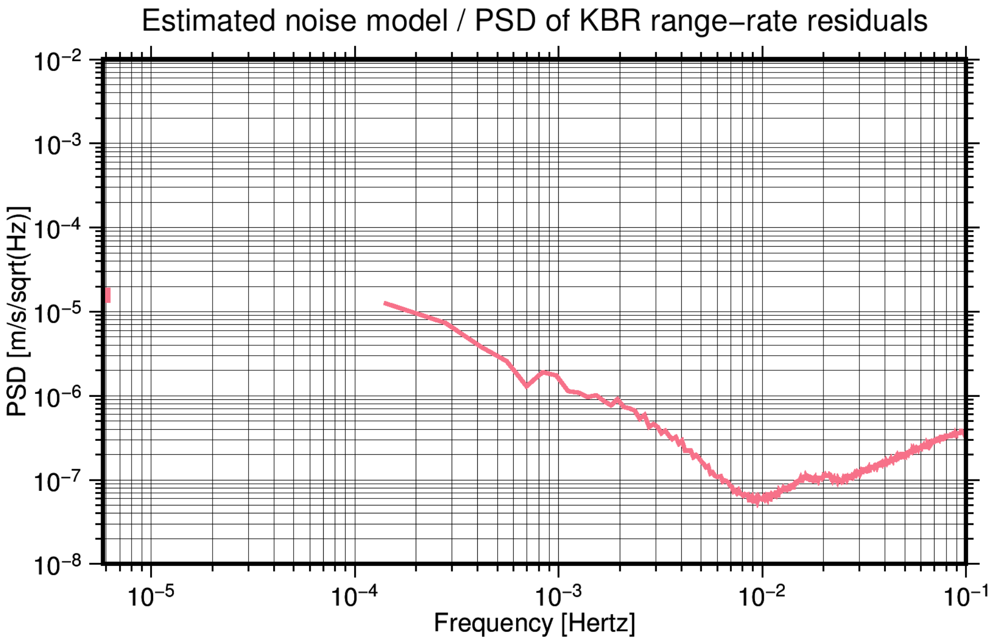
K-Band Ranging data

For K-Band data, used at 5s sampling, the longest sensible covariance length possible at JPL is 24 hours, as this is the duration for which internally consistent dynamic orbits are estimated. The following slides present the estimated power spectral densities for covariance lengths of 1, 2, 3, 6, 12, and 24 hours respectively. The covariance functions are estimated from post-fit residuals of gravity field estimated to degree and order 96.

PSD for GRACE-FO KBR data – December 2018

1 hour covariance length

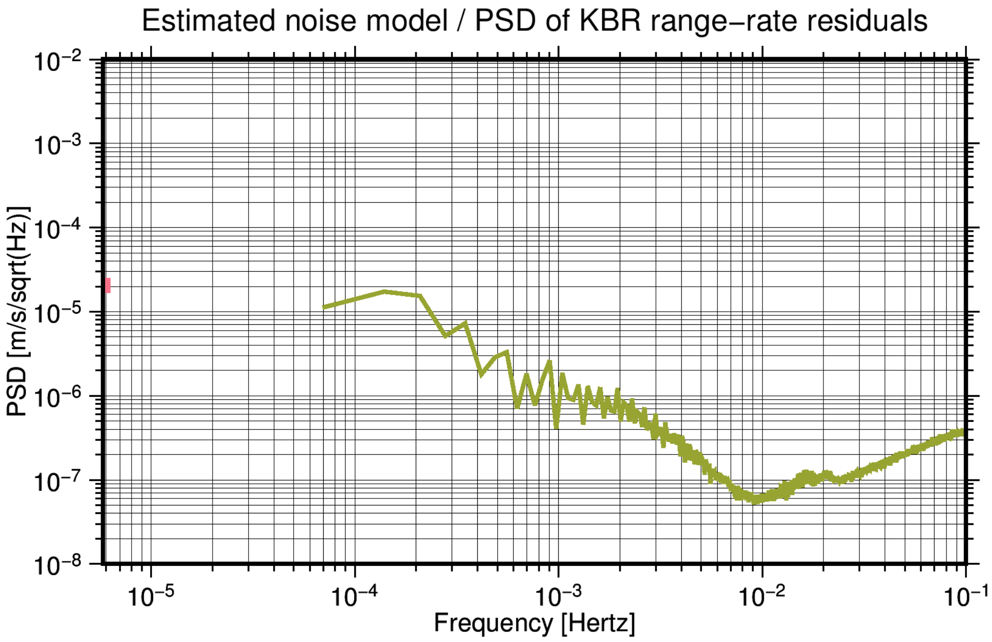
At a covariance length of 1 hour, the dominant features in the PSD of the low-low satellite-to-satellite tracking residuals are the two distinct branches meeting at a frequency of ~10 mHz. The right hand side of the spectrum corresponds to noise from the KBR instrument, the left-hand side to noise from the on-board accelerometer and background model error.



PSD for GRACE-FO KBR data – December 2018

2 hour covariance length

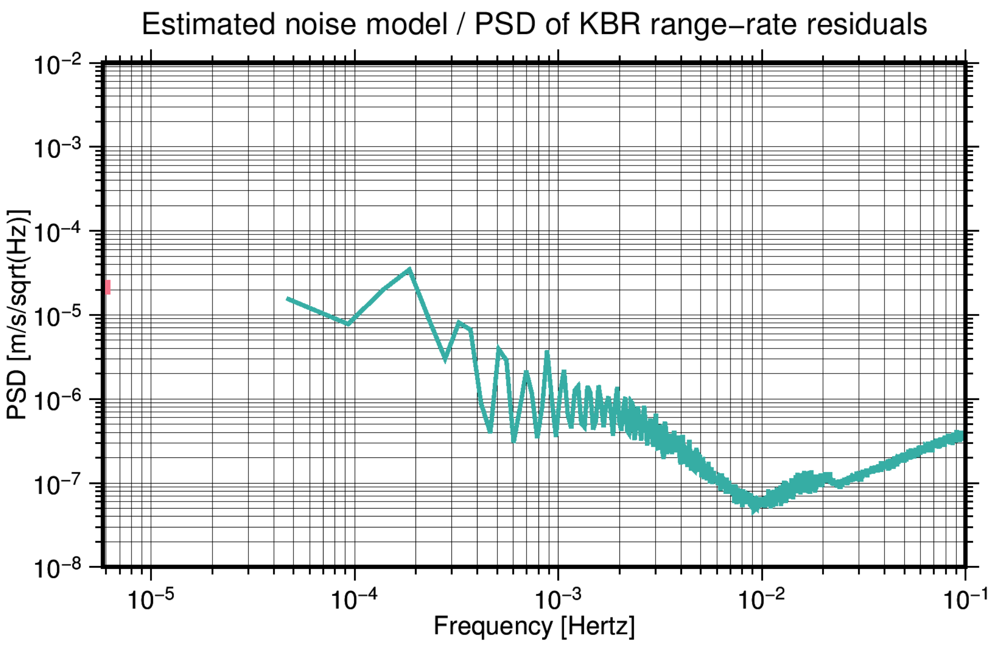
At a covariance length of 2 hours, the low-frequency power of the spectrum starts to increase.



PSD for GRACE-FO KBR data – December 2018

3 hour covariance length

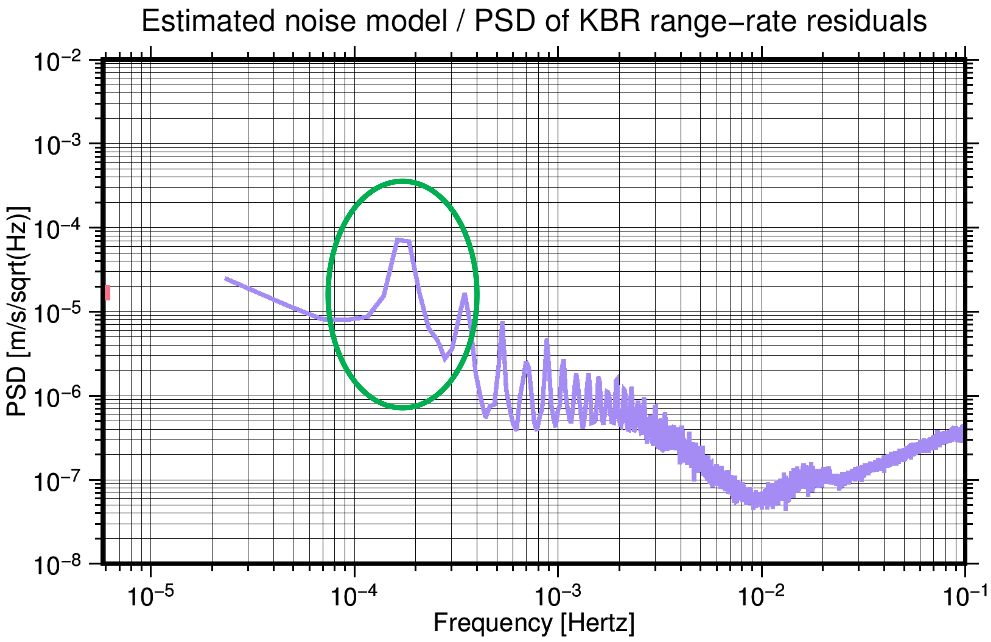
Longer covariance lengths allow for a finer recovery of the low-frequency part of the spectrum. Peaks and valleys in the PSD below 10 mHz correspond to multiples of the orbital frequency.



PSD for GRACE-FO KBR data – December 2018

6 hour covariance length

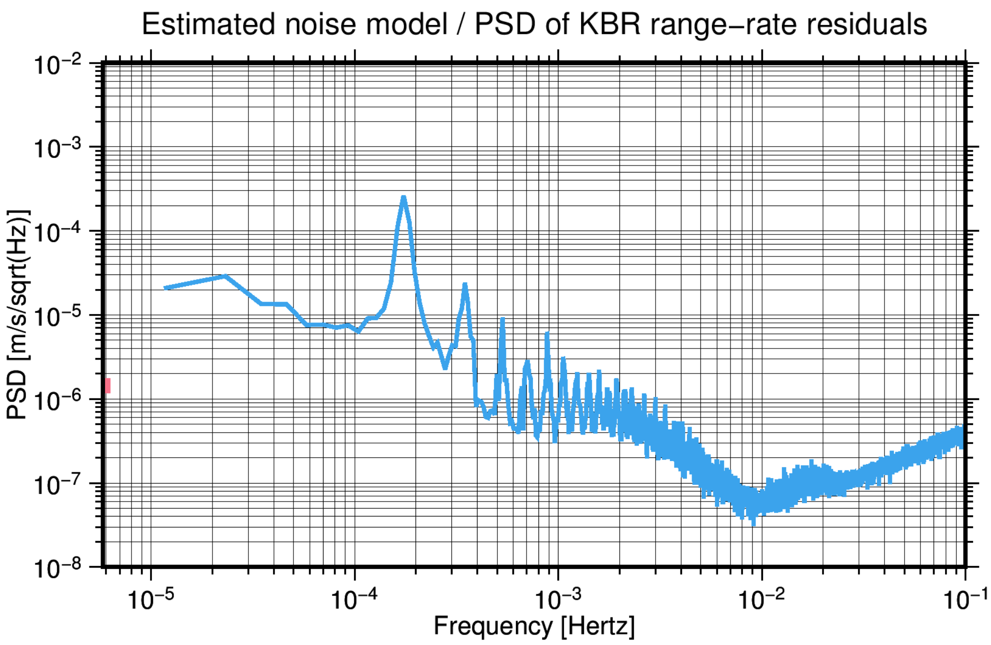
At a covariance length of 6 hours, the dominant peak at 1 cycle per revolution (~0.2 mHz) is becoming well defined.



PSD for GRACE-FO KBR data – December 2018

12 hour covariance length

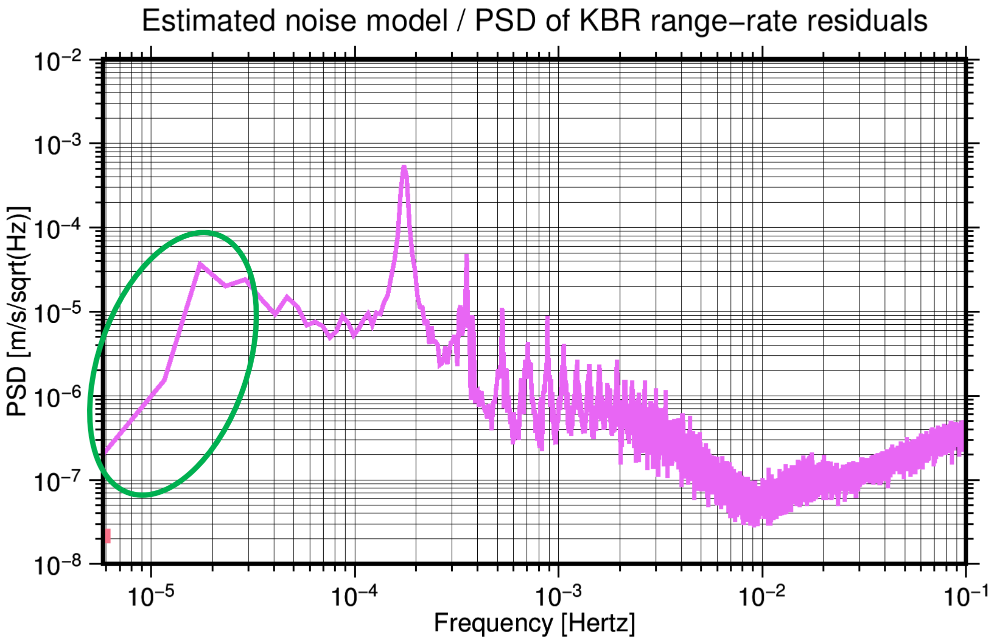
At a covariance length of 12 hours, the dominant peak at 1 cycle per revolution (~0.2 mHz) is well defined.



PSD for GRACE-FO KBR data – December 2018

24 hour covariance length

At a covariance length of 24 hours, the longest reasonably possible given current processing choices, the dominant peak at 1 cycle per revolution (~0.2 mHz) is well defined. At frequencies far beyond 1 cycle per revolution, the power in the residuals begins to drop off sharply, which leads to believe that the effective correlation length of the signal is adequately modeled using this parametrization.



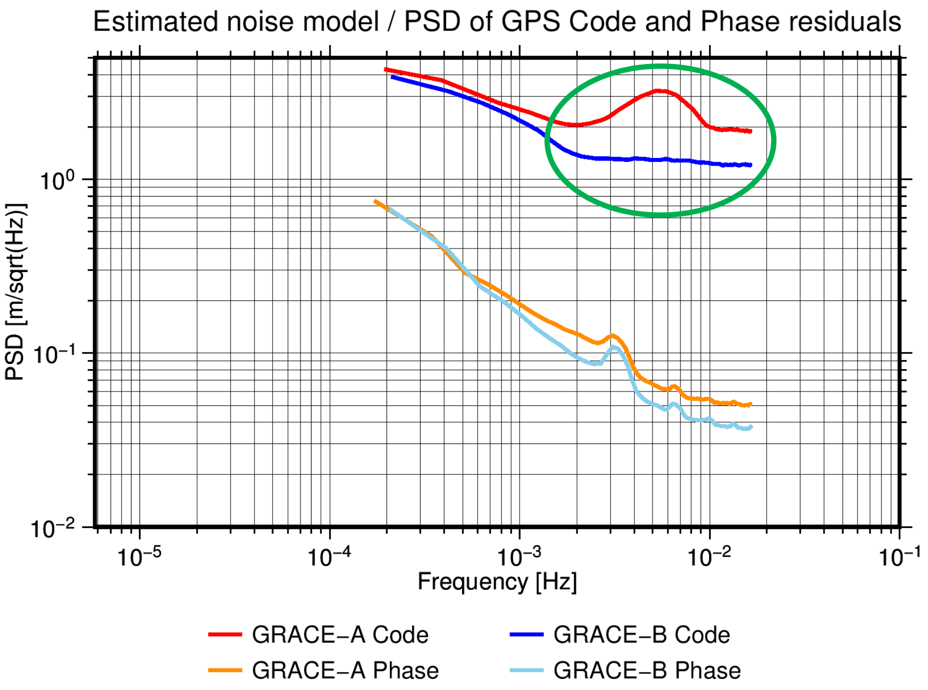
GPS Carrier Phase and Range data

For GPS data, used at 30s sampling, the covariance length is given by the observation duration for one GPS pass, approximately 20 minutes. For carrier phase observations, additional breaks for the covariance are introduced at signal breaks. One covariance function is estimated for each combination of observation type and receiving satellite, e.g. range on GRACE-A and range on GRACE-B are estimated independently of each other.

The following slides present these spectra for both GRACE and GRACE-FO solutions.

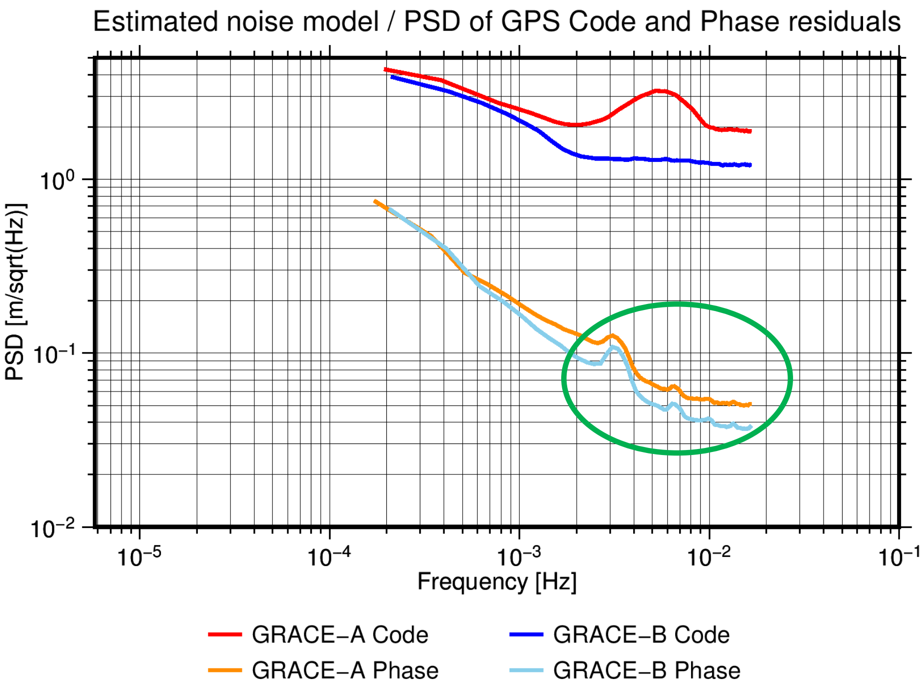
PSDs for GRACE GPS data – August 2008

GRACE-A Code observations have excess noise at frequencies around 6 mHz. In this month, GRACE-A is performing GPS occultation observations, which have lengths corresponding approximately to this frequency.



PSDs for GRACE GPS data – August 2008

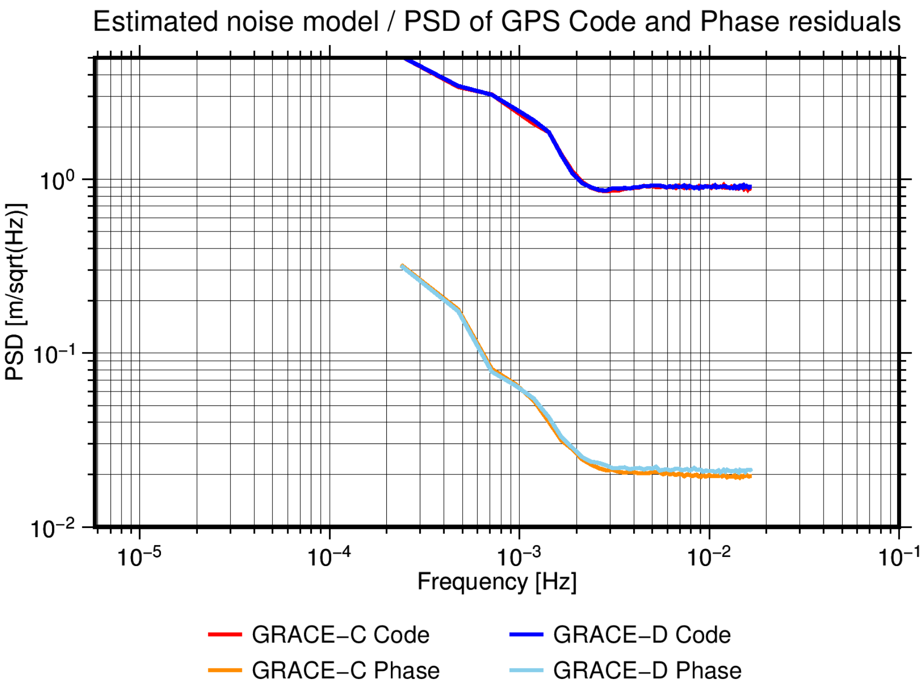
Both GRACE-A and GRACE-B Phase observations show excess noise at around 3 mHz, and overtones. This corresponds to periods of about 5 minutes, which is the resolution of the clock product used in processing these data.



PSDs for GRACE-FO GPS data – December 2018

For GRACE-FO, no spurious noise due to occultation observations is detected. The clock product is changed to 10s sampling, with no artifacts as observed in GRACE data visible on phase observations.

Both observation types exhibit a noise floor above ~2 mHz.



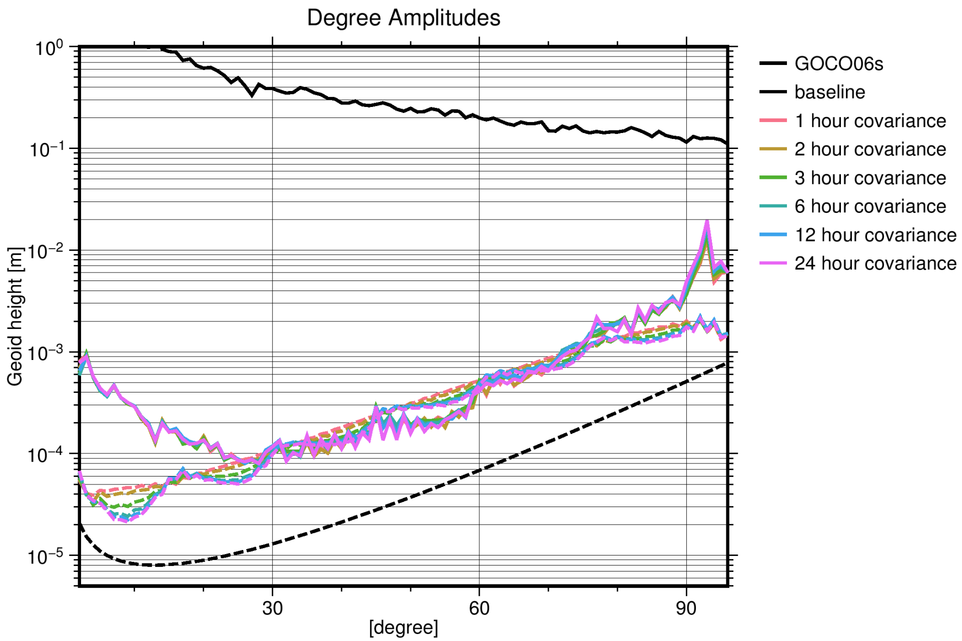
Gravity field formal errors

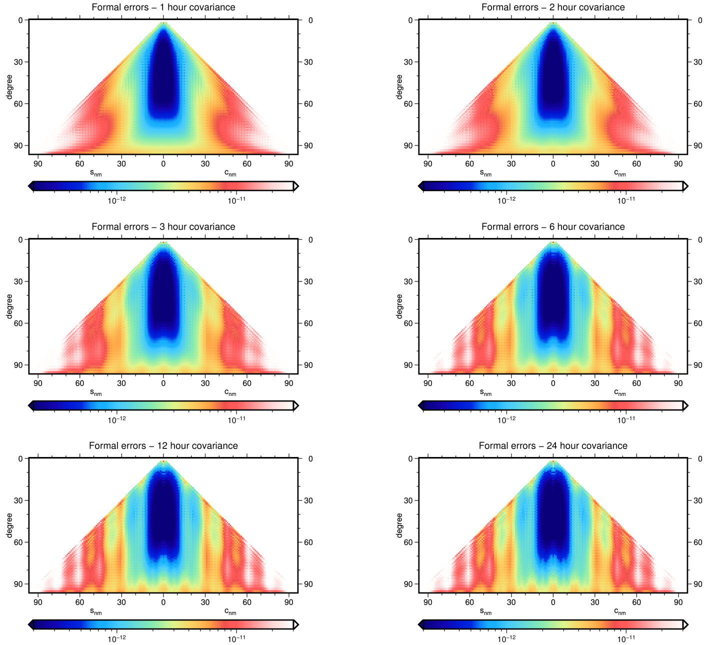
Gravity field formal errors

Employing the estimated stochastic models for low-low and high-low satellite-to-satellite tracking data leads to an improvement in formal errors of the estimated gravity field solutions.

The following slides present these formal errors in degree amplitude and spherical harmonic triangle form for one month of GRACE-FO data, December 2018.

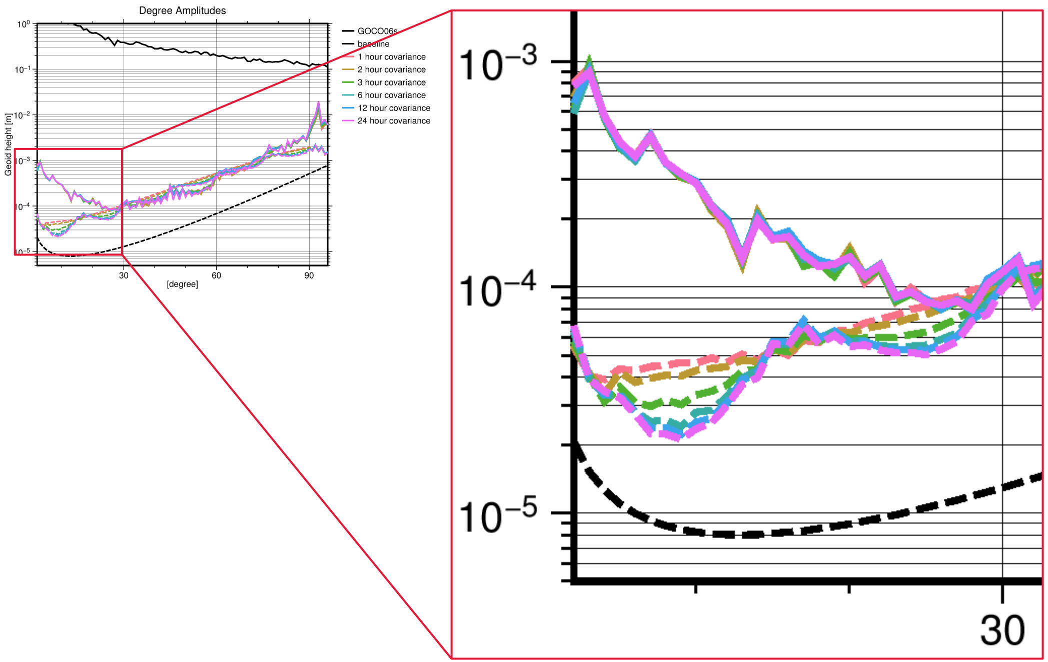
Comparison of formal errors between covariance lengths





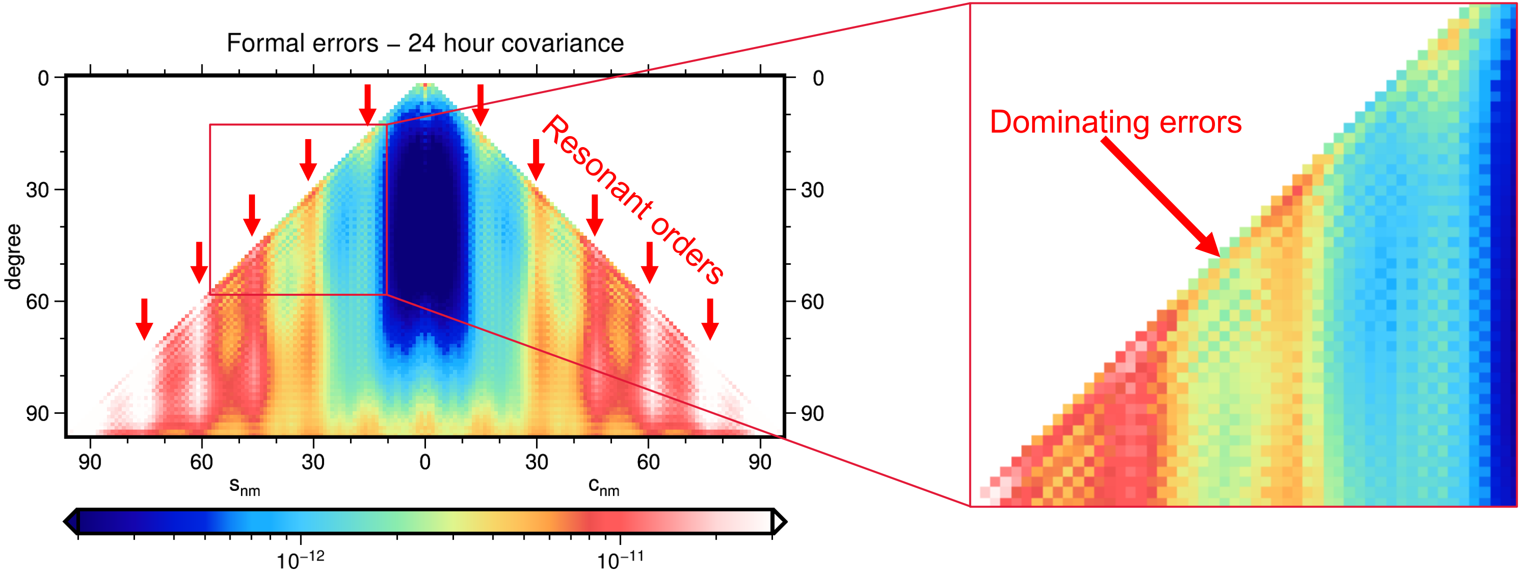
An increase in covariance length leads to marginal changes in the estimated gravity field, but significant changes in the estimated formal errors.

Formal errors in degree variance domain



Closeup of the reduction in formal error. The peaks at multiples of degrees ~15-16 are due to the orbital geometry of the GRACE-FO formation. The most drastic change in formal errors appears when increasing the low-low satellite-to-satellite tracking covariance length from 2 hours to 3 hours.

Formal errors for individual coefficients



For non-resonant orders, the formal error is dominated by near-sectorial coefficients of order ||degree-1||, i.e. for degree 25, the coefficients of order 24.

Summary

- JPL has developed the capability to estimate and apply full noise covariance matrices in its gravity field determination workflow.
- Formal errors of the spherical harmonics solutions are vastly improved.
- Use of this capability for the JPL RL07 data revision is under consideration.

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