

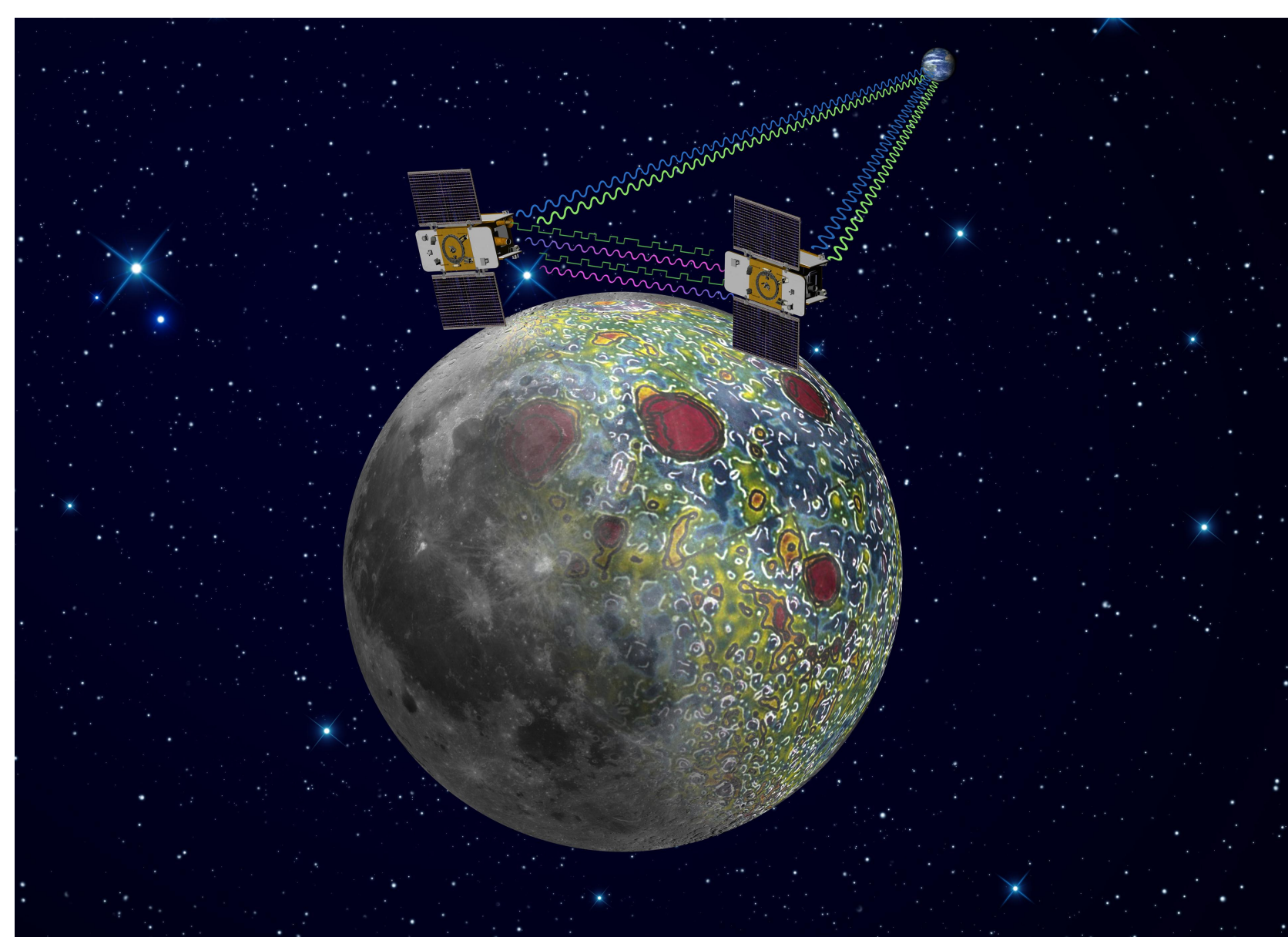
Latest Moon gravity field solutions from GRAIL data using the Celestial Mechanics Approach

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Introduction

To determine the gravity field of the Moon, the two satellites of the NASA mission GRAIL (Gravity Recovery and Interior Laboratory) were launched on September 10, 2011 and reached their lunar orbits in the beginning of 2012 (Zuber et al., 2013). The concept of the mission was inherited from the Earth-orbiting mission GRACE (Gravity Recovery and Climate Experiment) as the key observations consisted of ultra-precise inter-satellite Ka-band range measurements. Together with the one- and two-way Doppler observations from the NASA Deep Space Network (DSN), the GRAIL data allows for a determination of the lunar gravity field with an unprecedented accuracy for both the near- and the far-side of the Moon. The latest official GRAIL gravity field models contain spherical harmonic (SH) coefficients up to degree and order 1500 (Konopliv et al., 2014, Lemoine et al., 2014).



Doppler data processing in the Bernese Software

Besides the inter-satellite KBRR link, GRAIL orbit and gravity field determination is based on its Doppler tracking by several Earth-based stations of the DSN for the absolute positioning of the probes. Both one-way X-band and two-way S-band are available with an accuracy of 0.03 mm/s (~ 2 mHz) and 0.2 mm/s (~ 6 mHz), respectively. We process Doppler two-way observations using new implementations in the Bernese GNSS software (Bertone et al., 2015). Our modeling is based on the reference (Moyer, 2000) guidebook and it includes:

- Earth-fixed coordinates of the tracking stations
- Earth rotation and pole motion (IERS 2010)
- planetary ephemeris (e.g., DE421)
- Space-time frame transformations (IAU 2010)
- Relativistic effects on light propagation (Shapiro delay, ...)
- Atmospheric delay (troposphere only)

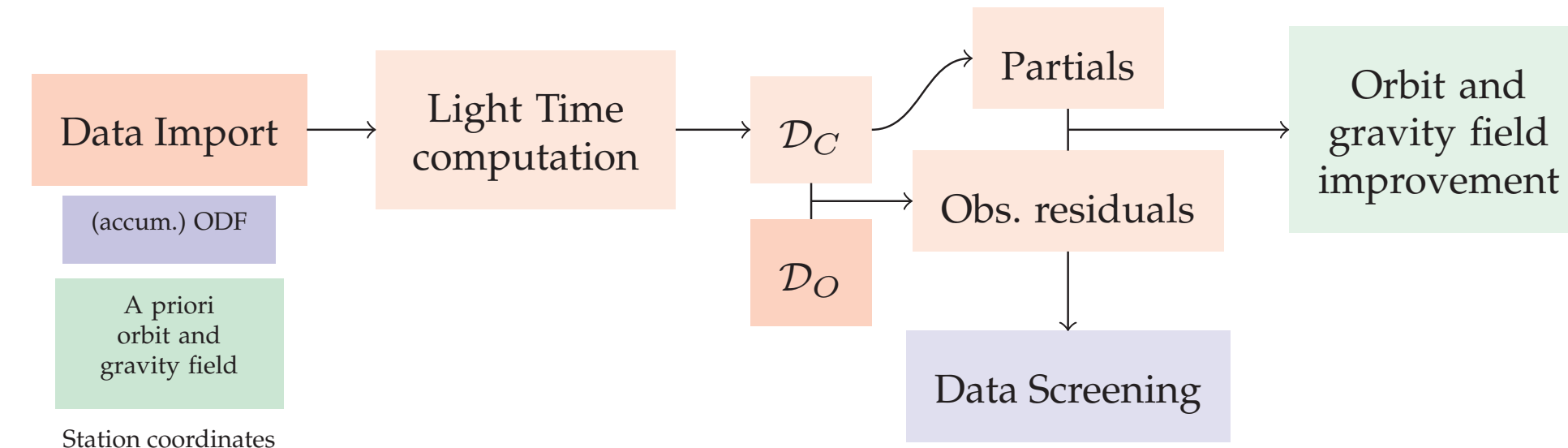


Figure 1: Processing flow of Doppler data, recently implemented in the Bernese (GNSS) Software. Doppler observations D_O from Orbit Determination Files (ODF) are imported to our internal format and eventually accumulated to the desired integration time. Orbit integration from a priori initial elements and parameters and an accurate modeling of light propagation are used to compute simulated Doppler D_C and hence Doppler residuals. The latter can be used to screen the observations or, along with the corresponding variational equations, to improve the "a priori" elements in an iterative orbit and gravity field improvement process.

We use the positions provided by the GRAIL navigation team as initial conditions for each daily arc and perform an orbit integration with the force model presented in the previous section. The initial orbital elements and, possibly, dynamical and stochastic parameters are then adjusted to the Doppler data (accumulated over 10 s) using a classical least-square procedure. Observations are screened for outliers by setting a threshold on the residuals and by applying an elevation cutoff at 25° .

Doppler orbit determination

Several tests were performed to show the impact of different background fields and parametrizations (dynamic or pseudo-stochastic) on the improved orbits. Fig. 2 (left) shows two-way Doppler residuals for GRAIL-A over days 71-73 of year 2012 as well as differences of the computed orbits w.r.t. GNI1B positions. Daily RMS of Doppler residuals and orbital differences over the PM phase are shown in Fig. 2 (right).

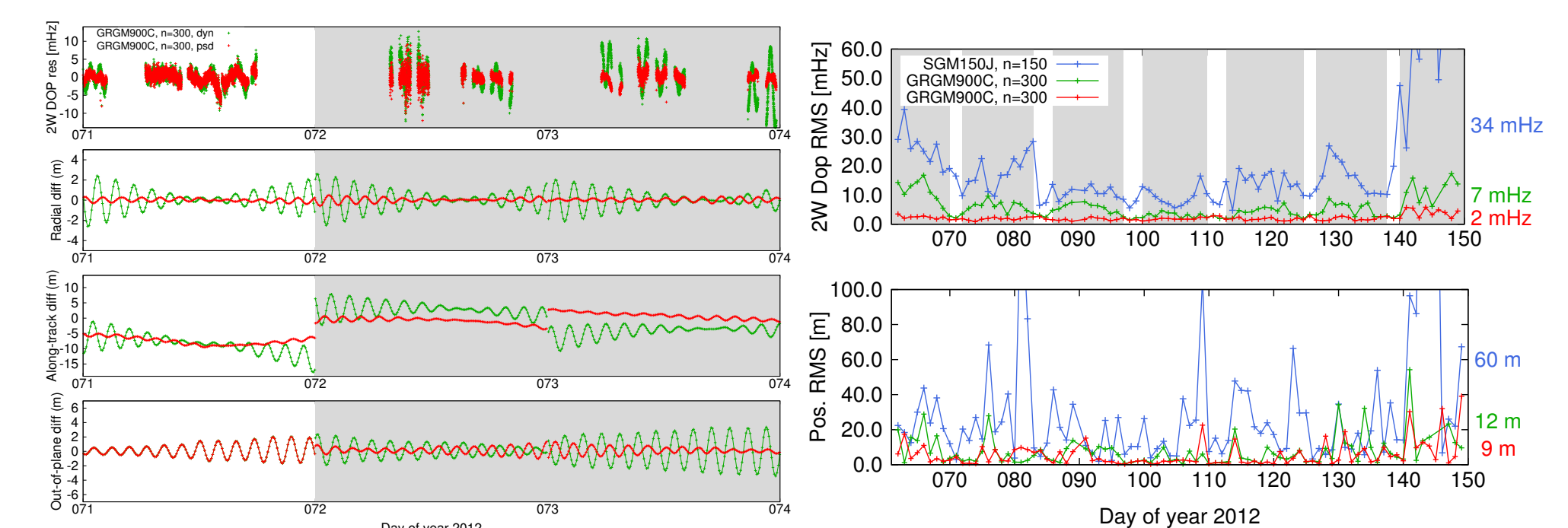


Figure 2: Left: (Top) Residuals from GRAIL-A Doppler fit using GRGM900C truncated to d/o 300 as background gravity field. Two different parametrizations are used: in green a purely dynamic orbit while in red we estimate a constant acceleration in S, a opr acceleration in R, and pulses in S and W directions every 30'. Shaded days represent geometries when less than 80% of the orbit is visible from Earth. (Bottom) Orbit differences w.r.t. GNI1B positions in the orbital frame. Right: (Top) Daily RMS of GRAIL-A two-way Doppler residuals using GRGM900C (up to d/o 300) and SGM150J as background gravity fields and different parametrizations. (Bottom) Daily RMS of orbit differences w.r.t. GNI1B positions.

Combined orbit determination

Doppler and KBRR data are combined on the Normal Equation (NEQ) level using a weighting appropriate to their relative accuracy ($1 : 10^8$). The resulting daily NEQs are then inverted to solve for the improved orbital parameters.

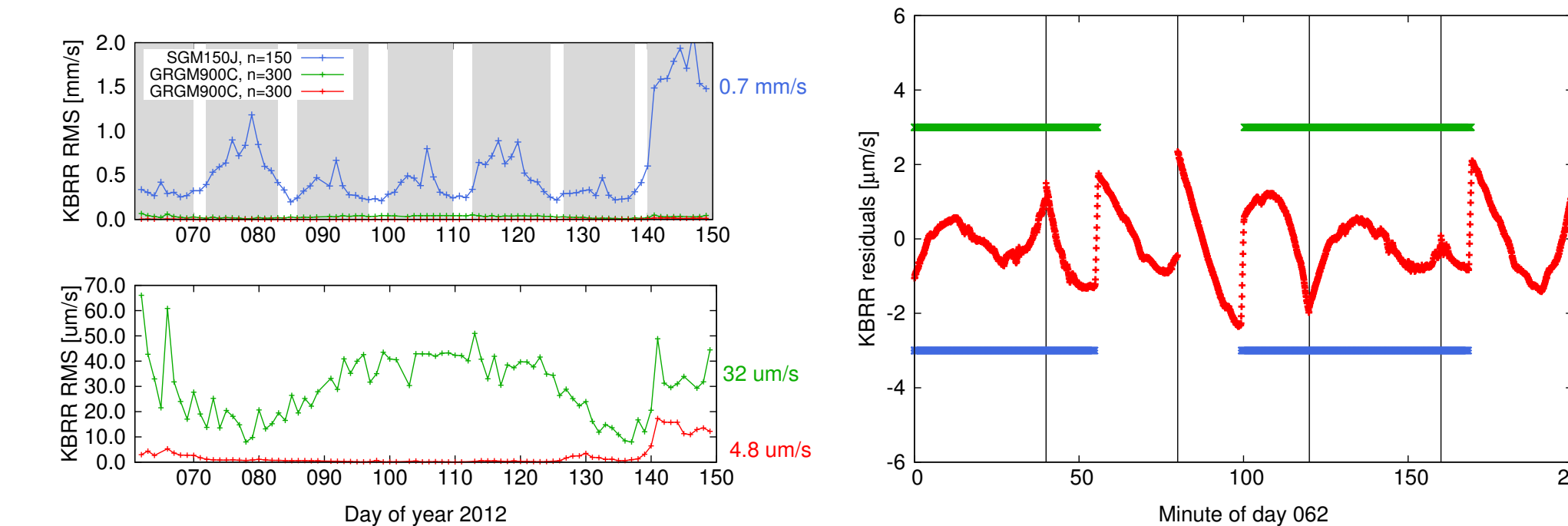


Figure 3: Left: Daily RMS values of the KBRR residuals in the combined (Doppler and KBRR) orbit solution. The lower plot is a zoom of the upper one. The fits are relatively bad when using the SELENE (SGM150J) gravity field and become better (more consistent) when introducing NASA's official GRAIL field GRGM900C (Lemoine et al., 2014), truncated at d/o 300. Right: KBRR residuals and time spans for which GRAIL-A (green) and GRAIL-B (blue) are in sunlight. Vertical black lines indicate locations of pseudo-stochastic pulses.

Fig. 3 (left) shows the global RMS of KBRR residuals over the PM phase. KBRR-residuals over several hours of day 62 when using the gravity field GRGM900C up to degree and order 660 as background field are shown in Fig. 3 (right). Compared to the expected noise level of around $0.05 \mu\text{m/s}$, the residuals are still relatively large. The green and blue bars indicate the time spans during which each satellite is in sunlight. The obvious correlation between these time spans and the large discontinuities suggests that radiation pressure modeling is crucial since the chosen parametrization is not able to fully compensate the deficiency.

Gravity field from Doppler and KBRR data (d/o 200)

The orbits determined in the first combined orbit determination serve as a priori information for a common orbit and gravity field estimation based on daily arcs. A classical least-squares adjustment is used. The daily normal equation systems (NEQs) are stacked to weekly, monthly and finally three-monthly NEQs, which are then inverted.

Fig. 4 shows several d/o 200 solutions computed from different a priori gravity fields. The solution represented by the green curve was computed using GRGM900C (up to d/o 660) as background field, 30' pulses in S and W directions, a constant acceleration in S and opr accelerations in R. Our AIUB-GRL200B solution (Arnold et al., 2015) obtained from GNI1B and KBRR data is shown (in gold) as comparison. We also present a d/o 200 solution (red curve) using SGM150J as background field and 60' pulses in all directions. It shows a significant improvement w.r.t. SGM150J for all degrees except for the lowest ones.

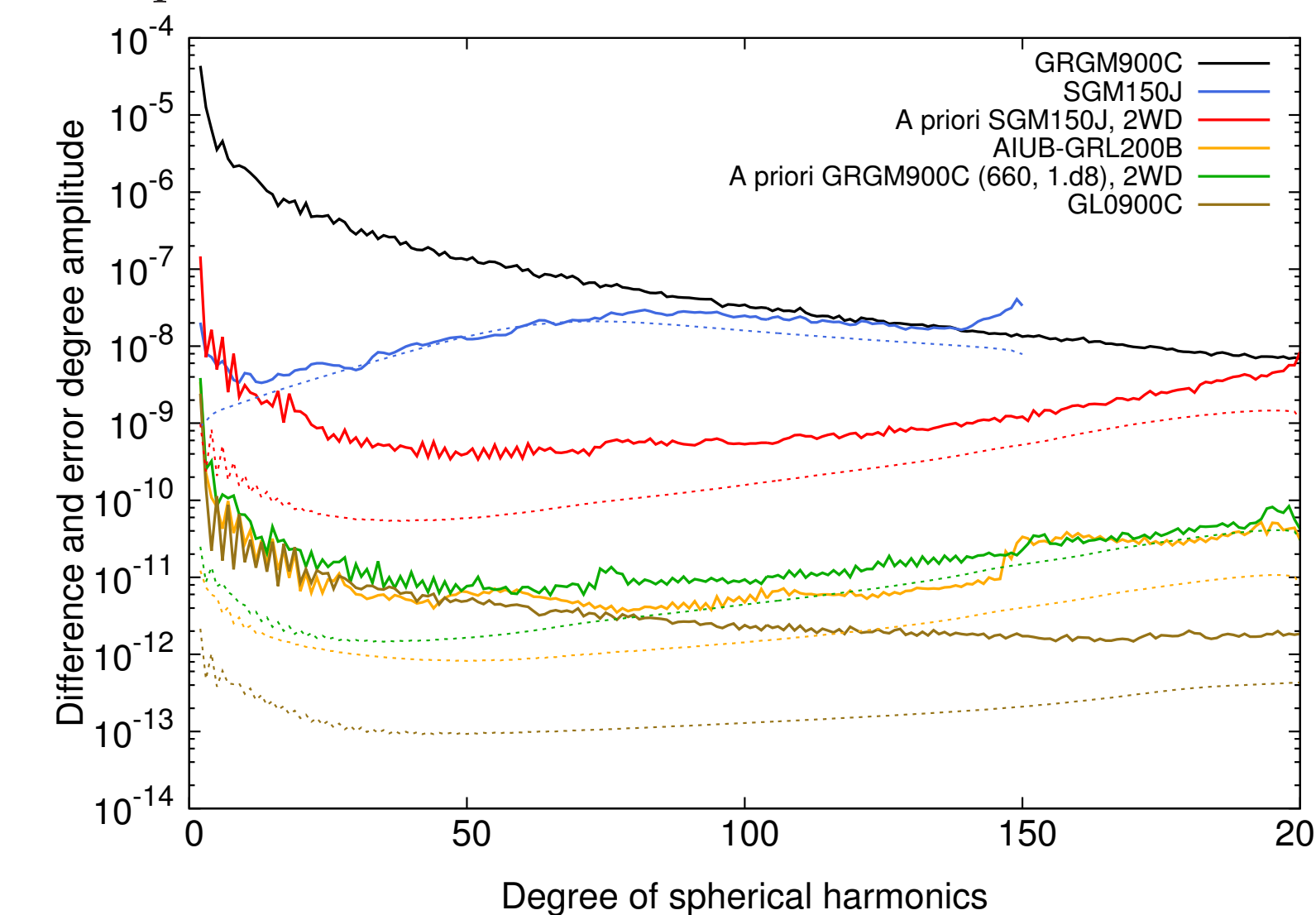


Figure 4: Difference degree amplitudes (solid) and formal errors (dashed) of degree-200 solutions based on the a priori field GRGM900C (up to d/o 660) and using Doppler - green - or GNI1B data - gold -, of a d/o 200 solution based on SGM150J (red) and of SGM150J itself (blue) w.r.t. GRGM900C.

S. Bertone, D. Arnold, A. Jäggi, G. Beutler, and L. Mervart

Astronomical Institute, University of Bern, Bern, Switzerland

Figure 5 (left) shows that KBRR residuals are significantly reduced when using our SGM150J derived d/o 200 gravity field instead of the SGM150J field itself. In particular, the large differences between the "face-on" and "edge-on" days almost disappears. Also, we see a strong correlation between the amplitude of out-of-plane pulses and the angle of the orbital plane with the line-of-sight.

Table 1 shows the amplitude of the pseudo-stochastic pulses in all direction using several a priori gravity fields.

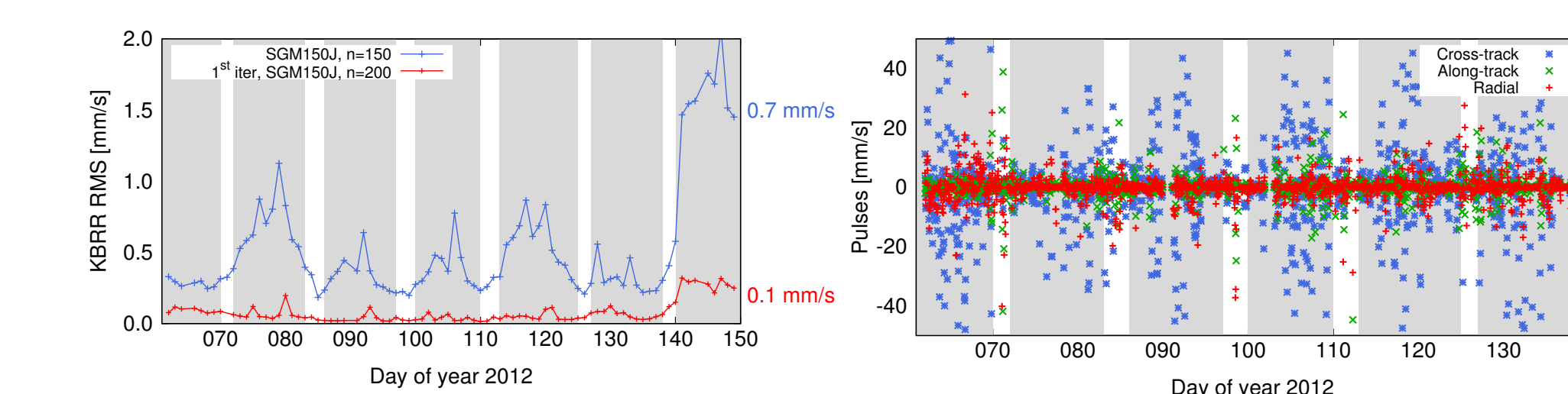


Figure 5: Left: Daily RMS values of the KBRR residuals in the combined (Doppler and KBRR) orbit solution based on the SELENE (SGM150J) gravity field (blue) and on our extended d/o 200 solution (red) based on SGM150J. Right: Amplitude of the pseudo-stochastic pulses in all directions along the PM phase (background d/o 200 solution based on SGM150J). Shaded days represent geometries when less than 80% of the orbit is visible from Earth.

| Model | Radial | Along-track | Out-of-plane |
|------------------------|----------------------|---------------------|-----------------------|
| SGM150J | -0.1752 ± 6.4565 | 0.0157 ± 4.9821 | -0.3102 ± 14.6112 |
| 1 st it SGM | -0.1745 ± 5.4248 | 0.0260 ± 3.7746 | 0.2713 ± 16.3501 |
| GRGM900C | -0.0401 ± 0.7666 | 0.0061 ± 0.3441 | 0.0074 ± 0.8012 |

Table 1: Mean and standard deviation (mm/s) of pseudo-stochastic pulses based on several gravity field solutions over the PM phase.

We recently adapted our processing to allow for larger solutions and are now studying an adapted parametrization to start the iteration process which should finally lead to an improved fully independent solution.

Conclusions

- The adaption of the CMA from GRACE to GRAIL allows for good-quality lunar gravity fields obtained entirely within the Bernese GNSS Software.
- We present our first d/o 200 solutions for the lunar gravity field computed from original GRAIL Doppler and KBRR data, hence showing our ability to extend our activities to the analysis of planetary missions data.
- Our gravity field solutions are so far computed without explicitly modeling non-gravitational forces and demonstrate the potential of pseudo-stochastic orbit parametrization.
- **Outlook:** extended gravity field solutions (up to d/o 300), inclusion of one-way Doppler data from the PM phase and solar radiation pressure modeling.

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Contact address

Stefano Bertone
Astronomical Institute, University of Bern
Sidlerstrasse 5
3012 Bern (Switzerland)
stefano.bertone@aiub.unibe.ch

