IMPROVING THE GEOMETRY OF KAGUYA EXTENDED MISSION DATA THROUGH REFINED ORBIT SOLUTIONS

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Introduction

The Japan Aerospace Exploration Agency's (JAXA) SELenological and ENgineering Explorer (SELENE) mission to the Moon was launched in September 2007 and consisted of three spacecraft: a main satellite (henceforth called Kaguya) with 11 instruments and two sub-satellites (part of the gravity experiment). The Kaguya mission was the first of several late 2000's missions that marked a return to the exploration of the Moon and it achieved many firsts. Today, Kaguya data are of fundamental importance and are highly complementary to data acquired by several earlier and later instruments, including of the Apollo Metric and Panoramic Cameras, the Moon Mineralogy Mapper (M^3), and LRO's Wide and Narrow Angle Cameras (WAC and NAC).

Kaguya's primary mission (PM) lasted from October 20, 2007 until October 31, 2008, and the extended mission (XM) lasted from November 1, 2008 until the controlled impact of the main satellite on the lunar surface on June 10, 2009. Kaguya's average altitude was 100 km during the PM and it was lowered to 50 km during the XM, with some periods having an even lower altitude. As a consequence, **Kaguya science products using XM data have an increased spatial resolution**. However, the geodetic position quality of these products is much worse than that of those acquired during the PM: radio tracking of Kaguya (conventionally necessary for determining the spacecraft's orbit precisely) was reduced after the PM, and the loss of momentum wheels resulted in frequent thrusting to maintain attitude, which further degraded the orbit determination accuracy. As a result, **the degraded orbit quality during XM** (at a level of several km compared to 10-30 m during PM) **severely limits the scientific value of these high-resolution data**.

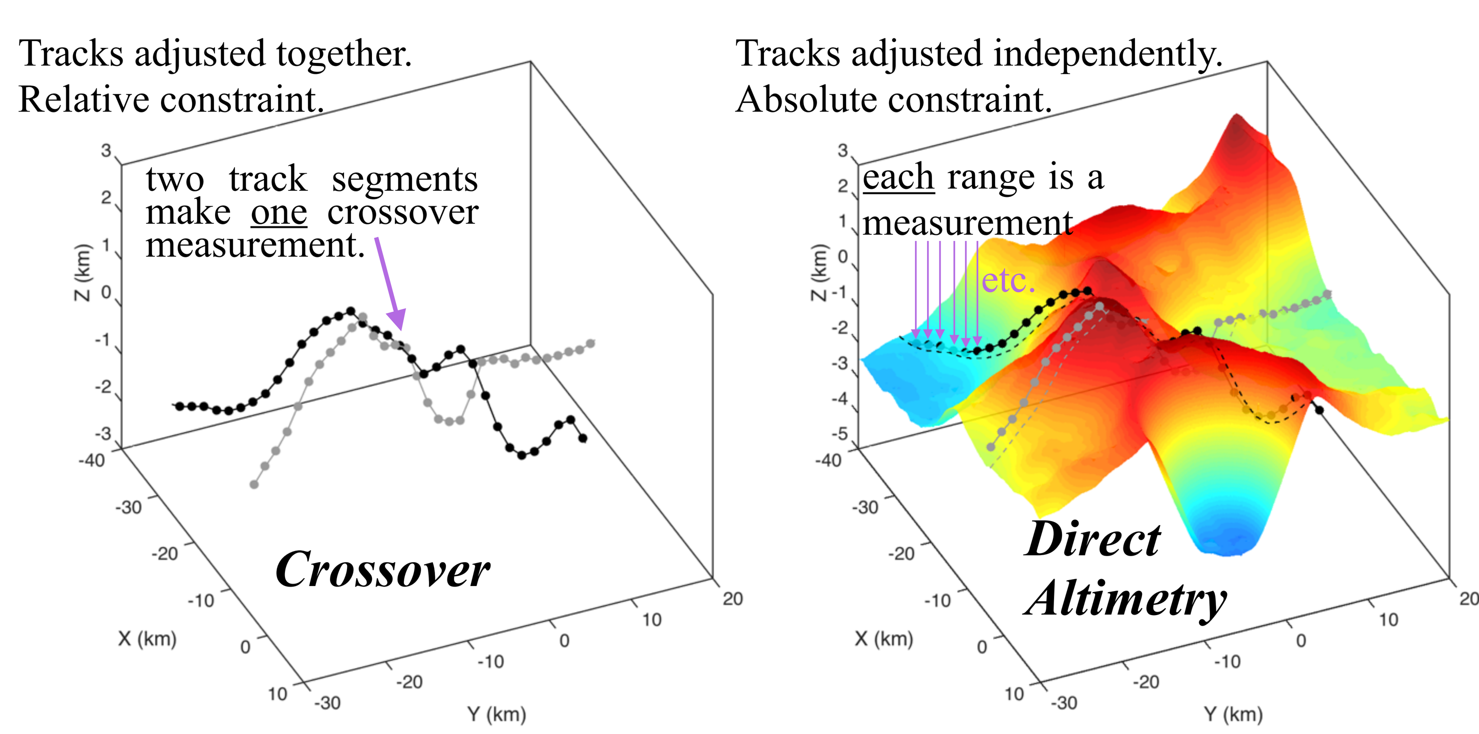
Here, we show how making use of recent advances in lunar knowledge improves the geometry of the Kaguya XM data. **We re-determine the XM orbits for the main satellite by using improved gravity field models of the Moon**, derived from data of the Gravity Recovery and Interior Laboratory (GRAIL) mission, and by **using a new data type that combines Kaguya laser altimetry** (LALT) **with improved knowledge of the lunar topography from laser altimeter data** of the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter (LRO).

Processing method

Currently archived orbits for the Kaguya XM were determined with pre-GRAIL gravity field models and sparse radio tracking. In our analysis, we apply two innovations: we use recent GRAIL gravity field models in our reanalysis of the Kaguya radio tracking data, and we use a new data type using Kaguya laser altimetry.

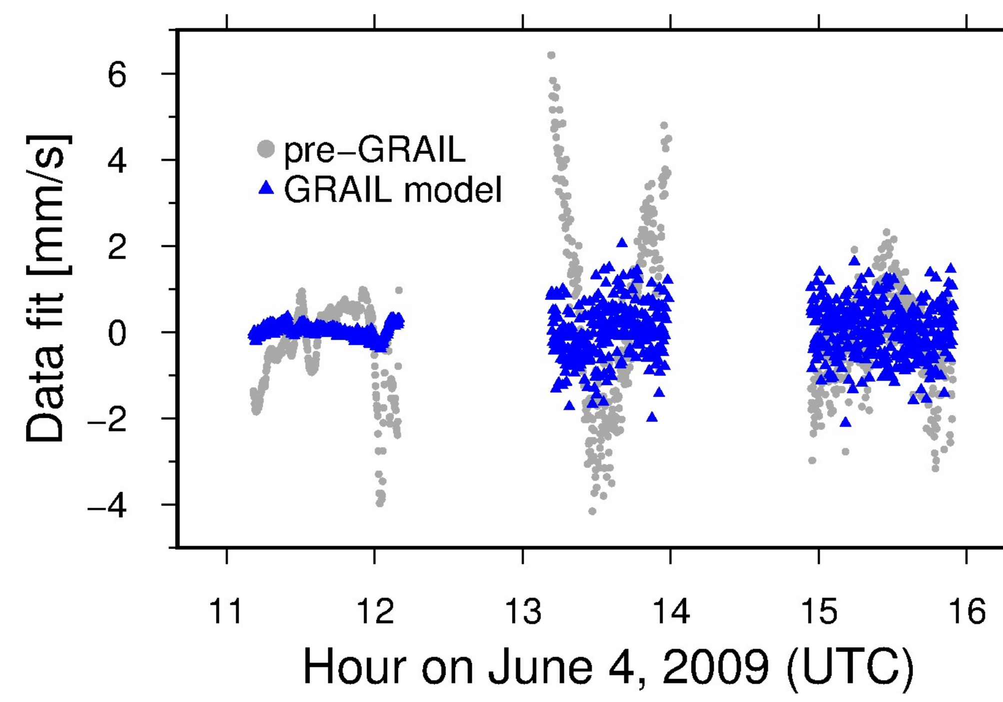
GRAIL gravity models can improve the orbit quality significantly, as was demonstrated with LRO, where it was shown that orbit reconstruction quality did not deteriorate despite the loss of tracking data. **We use the GSFC GRAIL model GRGM900C** (Lemoine et al. 2014, GRL) **up to degree and order 270**, following results for LRO orbit determination (Mazarico et al., 2017, PSS).

Altimetry data from LALT have been used to improve the orbit quality for Kaguya in the form of crossovers for the primary mission: when two altimetry tracks intersect, they should measure the same topography, given that the lunar topography is mostly static (tidal signals have a maximum displacement of ~50 cm), and discrepancies between crossovers can thus be assigned as orbit errors. However, **due to the slow rotation of the Moon and the polar orbits of these satellites, crossovers occur overwhelmingly near the poles**. They are also computationally intensive to use. However, with an accurate basemap from a combination of Kaguya Terrain Camera (TC) and LOLA data, **SLDEM2015**, **we can directly use the entire LALT tracks and minimize the discrepancies with LOLA topography**. This technique has been used successfully for Earth applications (on ICESat to calibrate pointing and improve pointing accuracy). **The resulting Kaguya orbit will be geodetically accurate and directly tied to the LRO/LOLA frame**. We call this new measurement type *direct altimetry*.



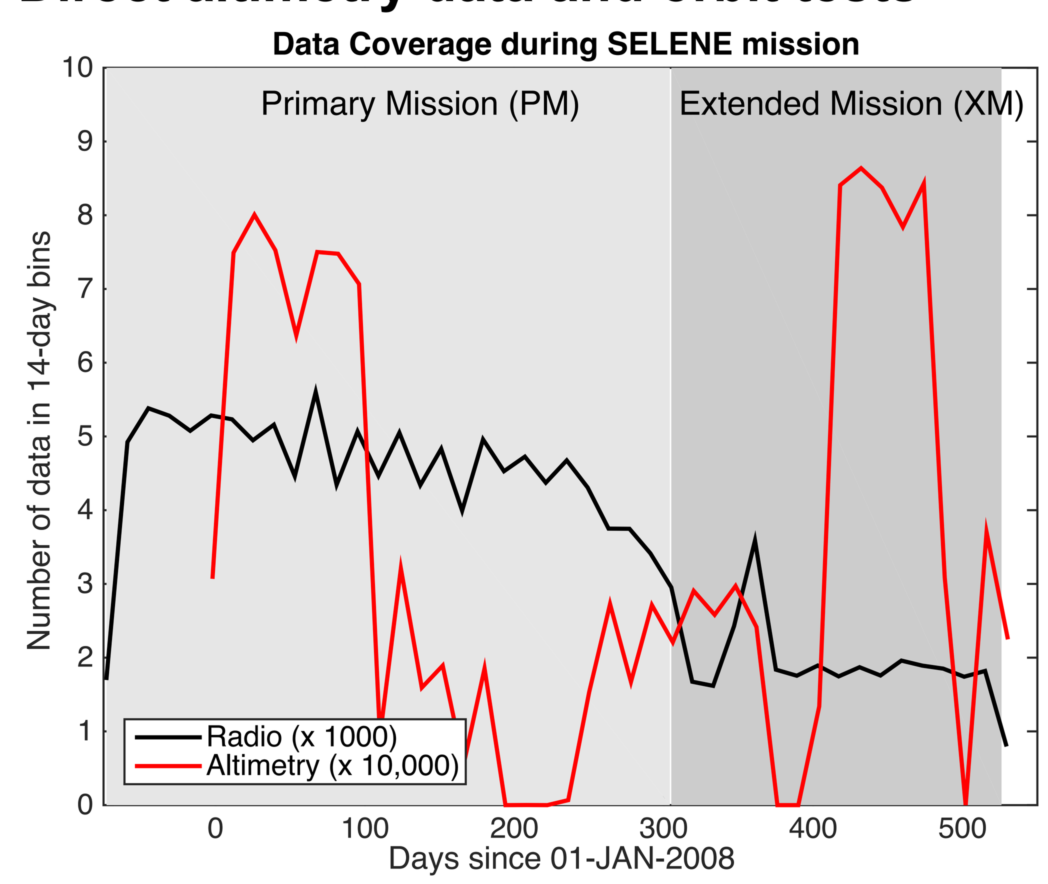
A comparison of crossover measurements (left) and direct altimetry (right). Crossovers are rare, but direct altimetry is available over the whole profile, and the direct comparison with LOLA topography is unambiguous and geodetically strong.

Influence of GRAIL gravity models

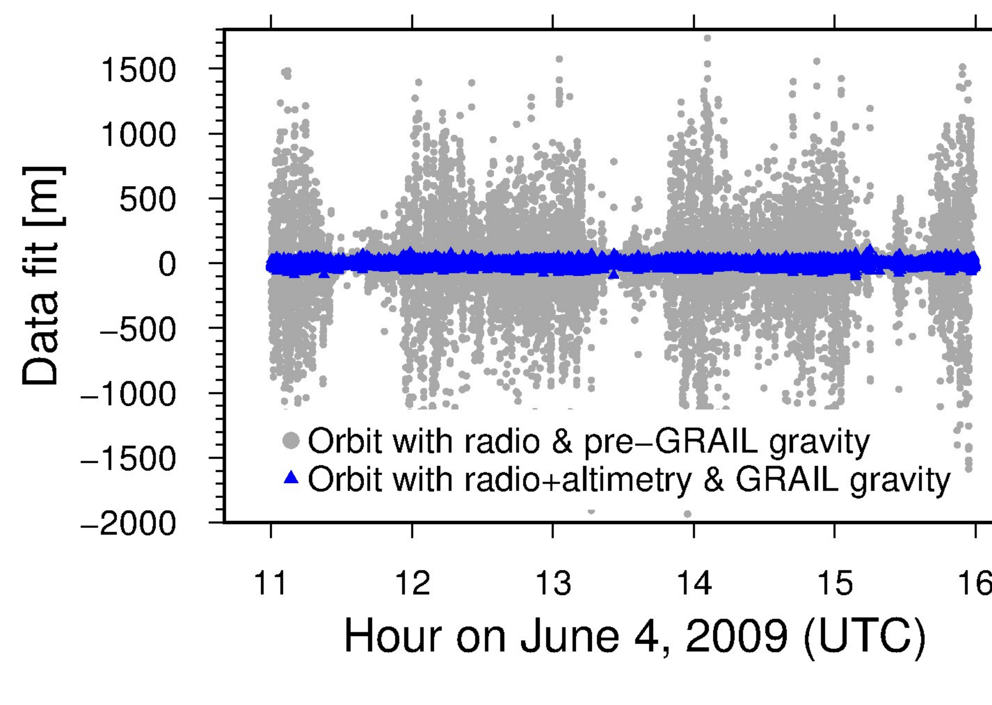


Doppler residuals for an arc in the late extended mission (Kaguya pericenter at 10 km above the surface). **The GRAIL gravity model removes systematic effects from the Doppler residuals**.

Direct altimetry data and orbit tests

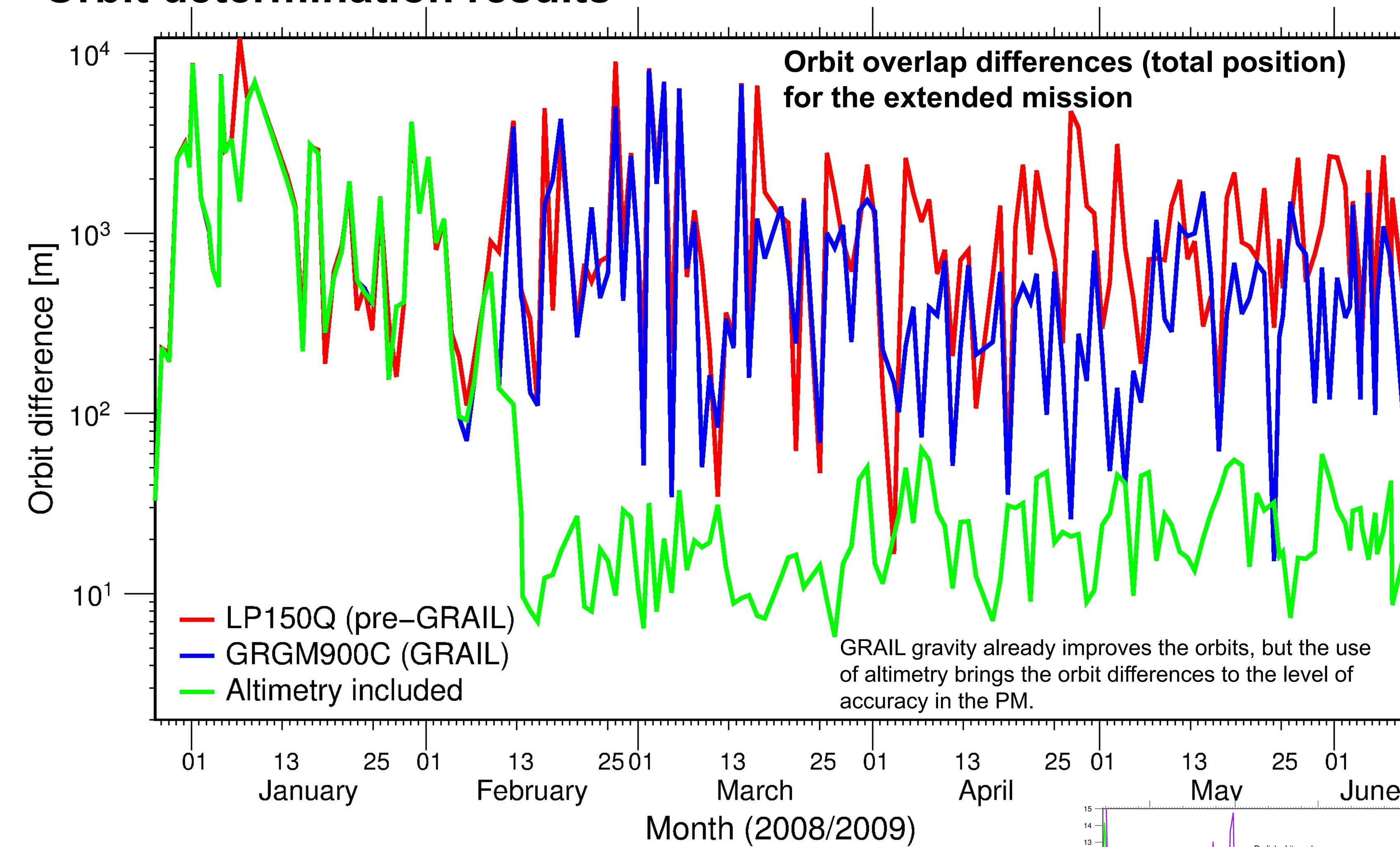


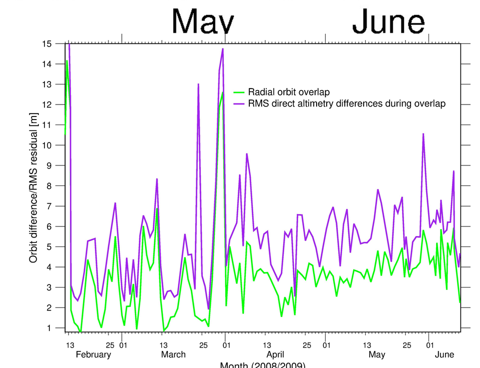
LALT data were acquired during the primary mission, but due to a drop in laser power it was only intermittently used after April 14, 2007. Loss of a momentum wheel in July 2008 decreased the time between angular momentum desaturation events, limiting time for LALT observations and also degrading the orbit accuracy needed for topography. Radio tracking was reduced after the end of the primary mission, further impacting orbit accuracy and thus value of LALT for topography. After lowering the orbit to 50 km (on average), LALT energy was sufficient for operations and it was turned on again, and collected near continuous data after February 12, 2009, until the end of mission on June 20, 2009.



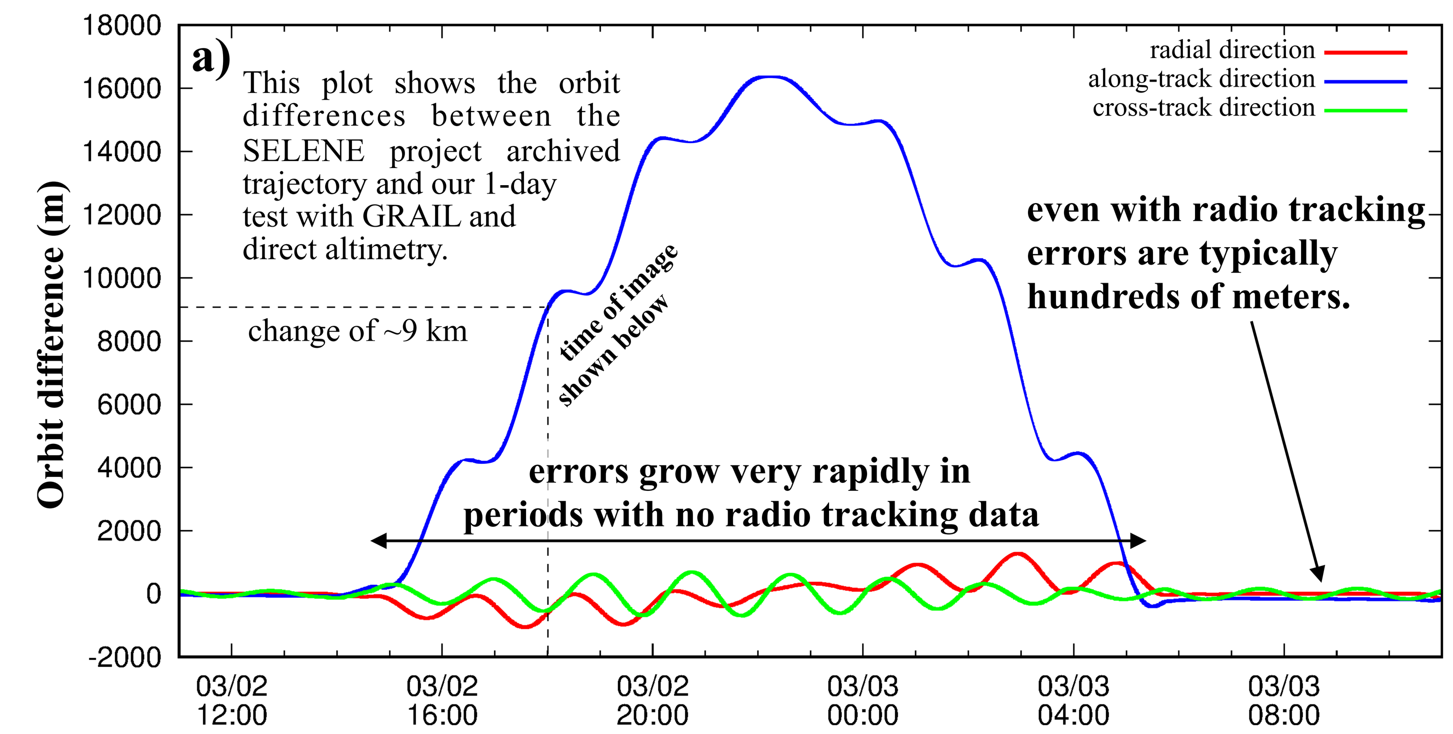
Residuals for direct altimetry data on the same test period as above. Using the currently archived orbits, the altimetry residuals show large variations with respect to LOLA topography, indicating the degraded quality of these orbits. By determining the orbits with the GRAIL model and direct altimetry, the residuals for altimetry are at several tens of meters, indicating the new orbit accuracy that can be achieved.

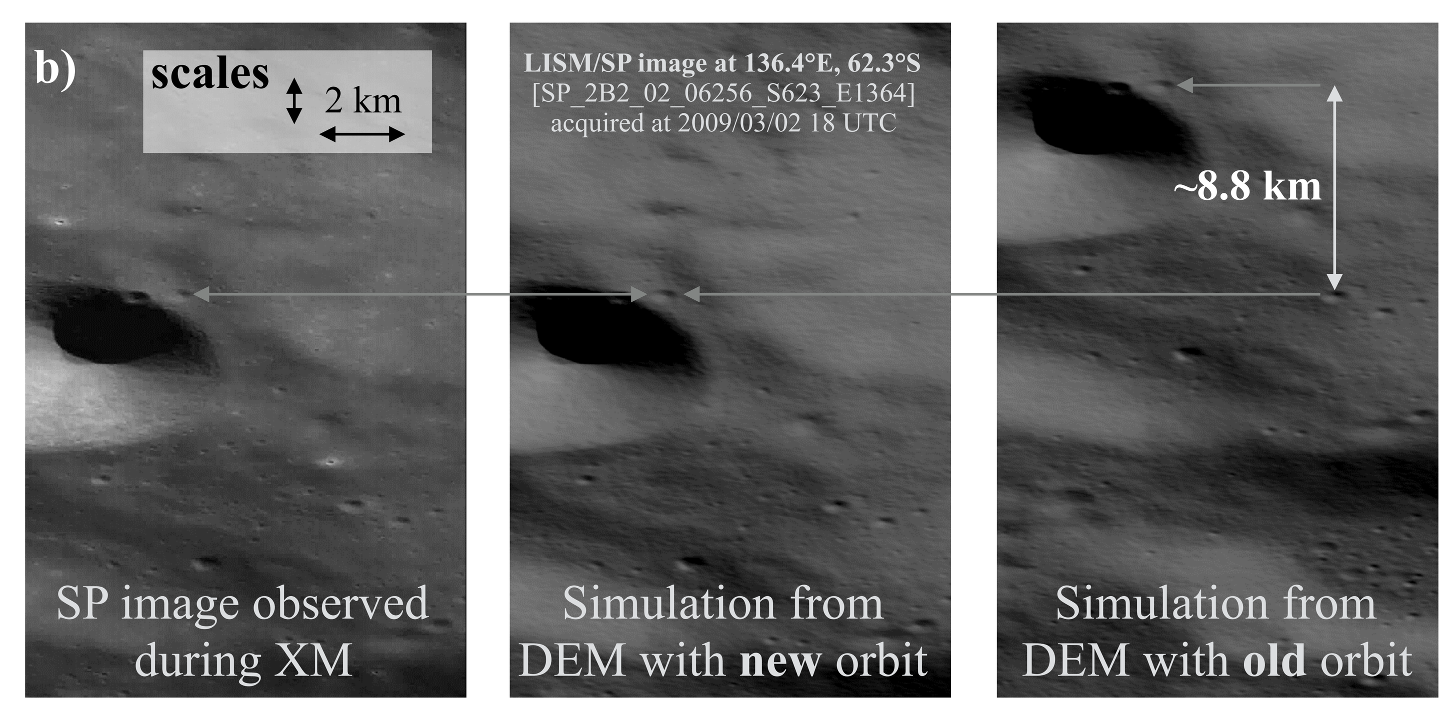
Orbit determination results





We determined the Kaguya orbit during the XM (Dec. 2008-June 2009), using GRAIL gravity and altimetry. Orbit overlaps (above) are a measure of orbit consistency and a good proxy for orbit accuracy. Including altimetry data greatly improves the overlaps, bringing the orbit quality to the same level as achieved during the PM. The RMS of altimetry differences during overlaps (right) is very consistent with the overlaps in the radial direction.





Orbit differences between the newly determined orbit and the currently archived orbit are large (a). This is further shown using a context image from the Spectral Profiler (SP) instrument (b). We simulated this image from a LALT-TC Digital Elevation Model, using both the existing orbit and our new trajectory determined with a GRAIL model and altimetry. If the orbit has errors, the observed and simulated images would show discrepancies, as is indeed the case for the old orbit. **The new orbit resolves this discrepancy**. This thus shows that GRAIL gravity combined with altimetry improves the Kaguya XM orbits, and, consequently, the geometry of Kaguya data collected during XM.

Summary and Outlook

We are analyzing the Kaguya tracking data together with Kaguya LALT data to improve the orbits for the extended mission. **The use of GRAIL gravity can bring down the orbit errors from several km to several hundreds of meters** (with only sparse radio tracking data, orbit errors below 100 m are difficult). **The inclusion of direct altimetry data greatly improves the orbits**: **levels of a few tens of meters are possible**, on par with the precision of the primary mission.

We will archive the final updated orbits for general use. Finally, **we will use these orbits to create a pilot test mosaic** (~10°x10° in size) **from Kaguya TC data for the Hadley Rille region.** This geodetically controlled mosaic will serve as validation of our methods, and as a starting point to possibly recalibrate and reprocess the entire Kaguya XM data set.