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

Sander Goossens[1,2], Erwan Mazarico[2], Lisa Gaddis[3], Brent Archinal[3], Trent Hare[3], Emerson Speyerer[4], Yoshiaki Ishihara[5], Junichi Haruyama[5], Takahiro Iwata[5], Noriyuki Namiki[6]. [1]Center for Research and Exploration in Space Science and Technology, University of Maryland Baltimore County, Baltimore MD, USA (email: sander.j.goossens@nasa.gov); [2]NASA GSFC, Code 698, Greenbelt MD, USA; [3]U.S. Geological Survey, Astrogeology Science Center, Flagstaff, AZ, USA; [4]Arizona State University, School of Earth and Space Exploration, Tempe, AZ, USA; [5]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan; [6]National Astronomical Observatory of Japan, Mitaka, Japan.

**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 3 spacecraft: a main satellite (Kaguya) and two sub-satellites. Kaguya carried a total of 11 science instruments, augmented by a radio science experiment and a high-definition camera for public outreach [1]. The sub-satellites were part of the gravity/radio science experiment. The science instruments were designed to address several areas of study: the elemental distribution, mineralogical distribution, the topography of the lunar surface, the sub-surface and lunar interior, and the plasma environment [2]. 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 [1]. 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 (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 [3,4]) severely limits the scientific value of these high-resolution data.

Here, we show how making use of recent advances in lunar knowledge can improve the geometry of the Kaguya XM data. We redetermine 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 [5], and by using improved knowledge of the lunar topography from laser altimeter data of the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter (LRO) [6].

**Methods**: Currently archived orbits for the Kaguya XM were determined with pre-GRAIL gravity field models [3]. We use recent GRAIL gravity field models [7] in our reanalysis of the Kaguya tracking data. These models 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 [8].

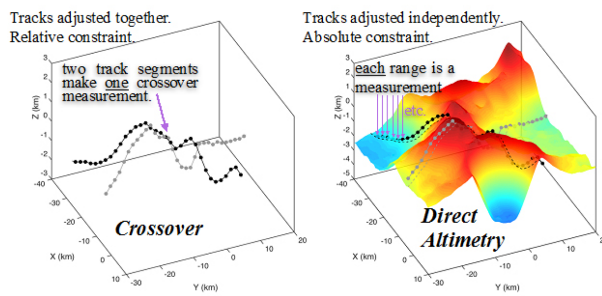


**Figure 1:** Altimetric crossovers are compared with our new data type, direct altimetry. Comparing the ranges directly against a precise LOLA topography model is unambiguous, geodetically stronger, and available over the whole altimetric profile's length.

In addition to using GRAIL gravity models, we will use a new and unique altimetric measurement type in the orbit determination process. We can exploit Kaguya Laser Altimeter (LALT) data as a direct geodetic tracking measurement to adjust the orbit so that the LALT topography profiles fit the high-accuracy LOLA topography basemap (see Fig. 1). As a result, the Kaguya orbit will be geodetically accurate and directly tied to the LOLA/LRO frame.

Altimetry data from LALT have been used to improve the orbit quality for Kaguya [4] in the form of crossovers: when two altimetric tracks intersect, they should measure the same topography, given that the lunar topography is mostly static (given tidal signals have a maximum displacement of ~50 cm), and discrepancies

| Data Used | Gravity | Radial [m] | Along-track [m] | Cross-track [m] | Total [m] |
|---|---|---|---|---|---|
| Radio only | pre-GRAIL | 10.57 | 1327 | 2239 | 2602 |
| Radio only | GRAIL | 0.53 | 58.1 | 99.5 | 115.2 |
| **Radio & Altimetry** | **GRAIL** | **0.67** | **5.0** | **8.0** | **9.5** |
| **Altimetry only** | **GRAIL** | **0.83** | **13.8** | **4.0** | **14.4** |

**Table 1**: Results for overlap analysis which is a measure of the quality and precision of the orbit.

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. With an accurate basemap from a combination of Kaguya Terrain Camera (TC) and LOLA data [9] however, we can directly use LALT tracks and minimize the discrepancies with LOLA topography. This improves the coverage of the tracking and the orbit quality itself [8].

**Results**: In Table 1 we show orbit overlap results for (1) a case using only Doppler and a pre-GRAIL gravity model (which shows the level of orbit precision for the orbits for Kaguya that are currently archived), (2) a case using only Doppler with a GRAIL model, (3) a case with a GRAIL model using both radio tracking and altimetry, and (4) a case with a GRAIL model and altimetry only. The results show that the use of both GRAIL gravity and altimetry data improve the orbit quality drastically: the orbit quality improves from a few km to the level of ten meters. The results in Table 1 for the case using radio data only emphasize the improvements due to GRAIL gravity itself: currently archived orbits with a km level precision can be improved to a precision of slightly more than a hundred meters just by virtue of using a GRAIL model. Including altimetry data can further improve the precision, to a level of ten meters for this case. In addition, the result using altimetry data alone in Table 1 shows that the altimetry is really key to the improvements in orbit quality, since it gives even better results than the case using radio only.

To further illustrate the impact that improved orbits have on Kaguya XM data analysis, we show image-matching results in Figure 2. A context image from the Spectral Profiler (SP) instrument was simulated using a LALT-TC Digital Elevation Model, using either the existing orbit, or a new trajectory determined with a GRAIL model and altimetry. If the orbit has errors, the observed and simulated image show discrepancies, as is indeed the case for the old orbit. The new orbit resolves this discrepancy. An orbit comparison shows that in this case the orbit correction was as large as 8 km, again showing how the combination of GRAIL gravity and altimetry can improve the Kaguya XM orbits, and, consequently, the geometry of Kaguya data collected during the XM. We will archive the updated orbits. 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 the entire Kaguya XM data set.

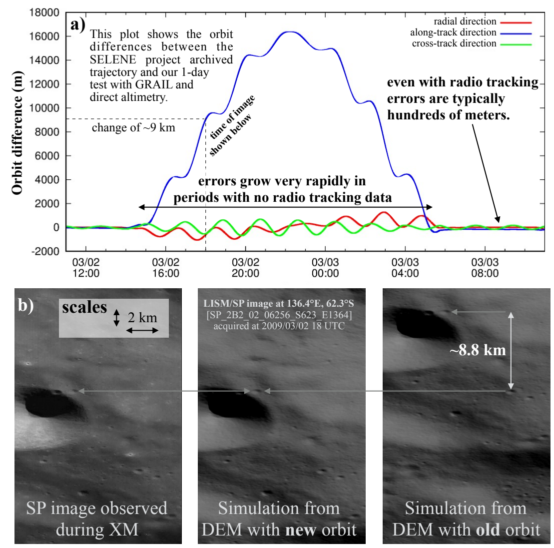


**Figure 2:** Orbit differences (top) between the archived orbits and our new orbits. Comparison of simulated images (bottom) with SP context image. The old orbit results in a simulated image with an ~8.8 km offset. The combination of GRAIL gravity and direct altimetry greatly improves the Kaguya XM orbit quality.

**References:** [1] Kato, M. *et al.* (2010), *Space Sci. Rev.*, doi:10.1007/s11214-010-9678-3. [2] Kato, M. *et al.* (2008), *Adv. Sp. Res.*, doi:10.1016/j.asr.2007. 03.049. . [3] Goossens, S. *et al.* (2009), *Proc. JAXA Astrodyn.*, Sagamihara, Japan, pp. 247-256. [4] Goossens, S. *et al.* (2010), *J. Geod.*, doi:10.1007/s00190- 011-0446-2. [5] Zuber, M.T. *et al.* (2012) *Science* doi: 10.1126/ science.1231507. [6] Smith, D.E. *et al.* (2017), *Icarus*, doi:10.1016/j.icarus.2016.06.006 [7] Goossens, S. *et al.* (2016), *LPSC XLVII*, abstract 1484. [8] Mazarico, E. *et al.*, (2017), *Planet. Sp. Sci.*, doi:10.1016/j.pss.2017.10. 004. [9] Barker, M. *et al.* (2016), *Icarus*, doi:10.1016/j. icarus.2015.07.039.