UPDATED KAGUYA EXTENDED MISSION ORBIT PRODUCT FOR IMPROVING THE GEOMETRY OF THE EXTENDED MISSION DATA. Sander Goossens[1,2], Erwan Mazarico[2], Lisa Gaddis[3], Yoshiaki Ishihara[4]. [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]National Institute for Environmental Studies, Tsukuba, Japan.

Introduction: The Japan Aerospace Exploration Agency's (JAXA) SELenological and ENgineering Explorer (SELENE), or "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. It was launched in September 2007 and consisted of 3 spacecraft: a main satellite 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]. Kaguya data are of fundamental importance and are highly complementary to data acquired by several earlier and later instruments, including the Apollo Metric and Panoramic Cameras, 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 [2,3]) severely limits the scientific value of these high-resolution data.

Here, we have redetermined 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 [4], 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) [5]. Through the analysis of orbit overlaps, we estimate the precision of our new orbits to be at the level of several tens of meters or better.

Methods: Currently archived orbits for the Kaguya XM were determined with pre-GRAIL gravity field models [2]. We use recent GRAIL gravity field models [6] 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 [7]. In Figure 1 we show how systematic features disappear from tracking data residuals when using a GRAIL model, indicating a better modeling of the forces acting on the spacecraft.

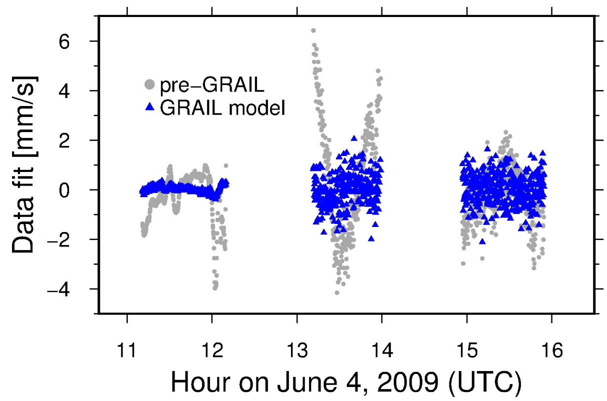

Figure 1 Doppler residuals for low-altitude Kaguya data. Using a GRAIL gravity model reduces the systematic effects significantly.

In addition to using GRAIL models, we 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. As a result, the Kaguya orbit will be geodetically accurate and directly tied to the LOLA/LRO frame. We use an accurate basemap from a combination of Kaguya Terrain Camera (TC) and LOLA data [8], and 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 [7].

Results: We have analyzed the Kaguya XM data using a GRAIL model and including the direct altimetry measurement type. We processed the data in continuous times of span (called arcs) of on average one day. We weighted the Doppler data at 1 mm/s, and we varied the altimetry data weights between 10 m and 20 m. In order to assess the precision of the new orbits, we performed an orbit overlap analysis. We recast our arcs with a twelve-hour offset from our original arcs, so that each original arc has an overlap in time of 12 hours with these new arcs. We determine the orbits for this new set of arcs, and we then compute the orbit differences between the two sets during overlapping times. These differences are indicative of the precision of the orbit. Such an overlap analysis is often used in precise orbit determination to assess orbit precision. In Figure 2 we show overlaps for the archived orbits (labeled "pre-GRAIL"), for orbits that use a GRAIL model and Doppler data (labeled "GRAIL"), and for the orbit using both the GRAIL model and the additional altimetry data. Altimetry data were consistently available from February 13, 2009, until the end of the mission, and Figure 2 shows that the orbit overlaps are greatly improved during this period. We can now achieve orbit overlaps of ~20 m whereas previously they were at the kilometer level. The use of a GRAIL model also improves the orbits before this period, but the lack of tracking data and the constant thrustering onboard the spacecraft limit the improvements that can be achieved.

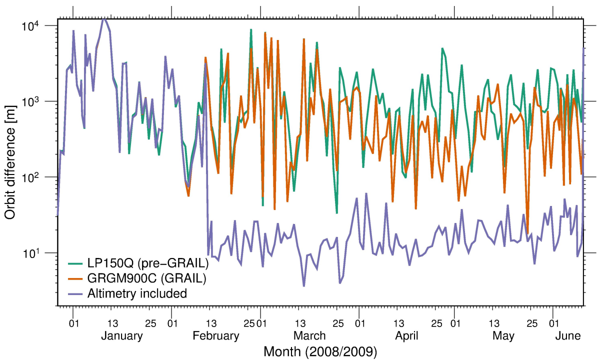

Figure 2 Orbit overlap results for runs with various gravity models and data sets. The combination of GRAIL models and altimetry data greatly improve the orbit precision.

To illustrate the impact of these updated orbits, we derived lunar topography from LALT, using the previous, archived orbits, or the new orbits. We show maps in stereographic projection for the south pole in Figure 3. The new orbits greatly improve the derived topography, as there are no artifacts due to track geolocation errors.

We will archive our updated orbits for public use. Finally, we will use these orbits to create a pilot mosaic (~10°x10° in size) from Kaguya TC data for the Hadley Rille region [9]. This geodetically controlled mosaic will serve as validation of our methods, and as a starting point to possibly recalibrate and restore the entire Kaguya XM data set.

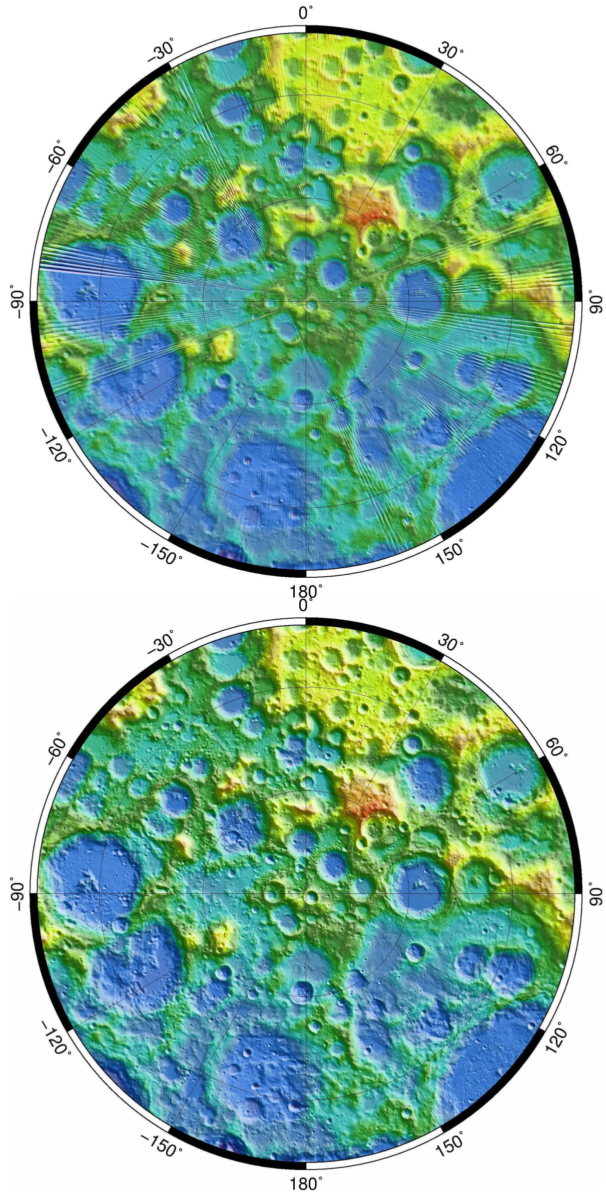

Figure 3 Lunar topography in polar stereographic projection covering 77˚S-90˚S, using the archived orbits (top) and the new orbits (bottom). With the new orbits, there are no artifacts due to geolocation errors as there are with the old orbits.

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