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Improving the geometry of Kaguya extended mission data through refined orbit determination using laser altimetry

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Abstract

The Japan Aerospace Exploration Agency's (JAXA) Kaguya spacecraft carried a suite of instruments to map the Moon and its environment globally. During its extended mission, the average altitude was 50 km or lower, and Kaguya science products using these data hence have an increased spatial resolution. However, the geodetic position quality of these products is much worse than that of those acquired during the primary mission (at an altitude of 100 km) because of reduced radiometric tracking and frequent thrusting to maintain spacecraft attitude after the loss of momentum wheels. We have analyzed the Kaguya tracking data using gravity models based on the Gravity Recovery and Interior Laboratory (GRAIL) mission, and by making use of a new data type based on laser altimeter data collected by Kaguya: we adjust the spacecraft orbit such that the altimetry tracks fit a precise topographic basemap based on the Lunar Reconnaissance Orbiter's (LRO) Lunar Orbiter Laser Altimeter (LOLA) data. This results in geodetically accurate orbits tied to the precise LOLA/LRO frame. Whereas previously archived orbits show errors at the level of several a level of several tens of meters. When altimetry data are not available, the combination of GRAIL gravity and radio tracking results in an orbit precision of around several hundreds of meters for the low-altitude phase of the extended mission. Our greatly improved orbits result in better geolocation of the Kaguya extended mission data set.

Keywords

orbit determination; Moon; data reduction techniques

1. Introduction

The Japan Aerospace Exploration Agency's (JAXA) SELenological and ENgineering Explorer (SELENE) mission to the Moon (Kato et al., 2010) was launched in September 2007. Kaguya, as it was also known, was the second of several missions in the time frame 2000–2010 that marked a return to the exploration of the Moon. The first was the SMART-1

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mission (Foing et al., 2018), and others included the Indian Chandrayaan-1 mission (Goswami et al., 2006), the Chinese Chang'E-1 mission (Huixian et al., 2005), the Lunar Reconnaissance Orbiter (LRO) mission (Chin et al., 2007), and the Lunar Crater Observation and Sensing Satellite (LCROSS) mission (Schultz et al., 2010). These were further complemented by the Gravity Recovery and Interior Laboratory (GRAIL) mission (Zuber et al., 2013a), the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission (Elphic et al., 2014), and the Chang'E 2–4 spacecraft.

Kaguya consisted of 3 spacecraft: a main satellite and two sub-satellites (called Rstar and Vstar). The main satellite carried a total of 11 science instruments, augmented by a radio science experiment and a high-definition camera for public outreach (Kato et al., 2010). The instruments on the main satellite were designed to address outstanding issues in several different areas of study: the elemental distribution, mineralogical distribution, the topography of the lunar surface and sub-surface, and the plasma environment (Kato et al., 2008). As such, the instruments included an X-ray spectrometer, a gamma-ray spectrometer, a multi-band imager, a spectral profiler, a terrain camera, a lunar radar sounder, a laser altimeter, a magnetometer, a charged particle spectrometer and a plasma experiment (Kato et al., 2010). The sub-satellites were part of the gravity experiment. Kaguya achieved many firsts, among which the first dense global topography using the Laser Altimeter (LALT) instrument (Araki et al., 2009) and the first mapping of the farside gravitational field of the Moon (Namiki et al., 2009) are of particular interest for this work. Kaguya acquired new data sets that paved the way for the renewed focused scientific examination of the Moon. Today, Kaguya data are of fundamental importance and are highly complementary to data acquired by several earlier and later instruments, including data of the Apollo Metric and Panoramic Cameras (Doyle, 1970), the Chandrayaan-1 Moon Mineralogy Mapper (M3) (Pieters et al., 2009), and the LRO Wide and Narrow Angle Cameras (LROC WAC and NAC (Robinson et al., 2010)). For example, Kaguya's Terrain Camera (TC) data provide context for the analysis of NAC images (*e.g.*, Hurwitz et al., 2013).

Its 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. The main satellite's average altitude was 100 km during the PM. During the XM, Kaguya's periapsis altitude was gradually lowered to allow for low-altitude observations of the magnetic field, maintaining the altitude at an average height above surface of 50 ± 30 km, with the periapsis over the South Pole-Aitken area because of previously observed strong magnetic anomalies around this basin (*e.g.*, Tsunakawa et al., 2014; Tsunakawa et al., 2015). As a consequence, Kaguya science products such as the TC camera image products using XM data have an increased spatial resolution (*e.g.*, $\sim 5\text{--}8$ m/pixel for TC).

In order to fully extract the relevant information from the instruments at their desired resolution, precise geolocation of the measurements is extremely important. This precision is controlled by quantities such as the pointing accuracy and the quality of the orbit reconstruction, and both these factors have a large impact on the accuracy of the retrieved data for instruments such as the altimeter and imagers (*e.g.*, Haruyama et al., 2008; Araki et al., 2008, 2009, 2013), especially after individual images or profiles are combined into maps

or mosaics. The orbits for Kaguya during the PM have a precision of 10–30 m because of improved gravity fields produced during the mission and the combination of strong tracking data types (Goossens et al., 2011c). Unfortunately, orbital errors for Kaguya are much larger during the XM, on the order of several km, or even more at times (Goossens et al., 2009). This is due to the larger gravitational perturbations on the spacecraft, a reduced radiometric tracking schedule of the satellite by stations on Earth, and spacecraft attitude control issues as the result of the loss of the reaction wheels which resulted in near-constant thrusting. XM data thus currently have poor geodetic accuracy, which largely prevented higher-level data products from being archived at high resolutions. For instance, topography is computed from the laser data in a straightforward manner using the spacecraft orbit and attitude information (e.g., Araki et al., 2008, 2009, 2013), and orbit quality is thus of great importance as orbital errors can be mapped directly into errors of the topography products. Araki et al. (2013) label the tracking as “insufficient” during the XM due to the aforementioned issues in orbit determination, and as a consequence these LALT data were not used in the SELENE topographic products. Spectral Profiler data were also found to be largely degraded after the orbit was lowered (Barker et al., 2016b). In addition, there is the possibility of inconsistent geolocation in the case that analysis of XM data resulted in separate corrections that were applied per instrument.

Here, with the goal to improve the geolocation of Kaguya XM data, we take advantage of two lunar data sets that were not available during the Kaguya mission: updated topography from the Lunar Orbiter Laser Altimeter (LOLA) onboard LRO (Smith et al., 2016), and updated models of the gravity field of the Moon from the GRAIL mission (Zuber et al., 2013b). We re-determine the Kaguya XM orbits, for the span October 31, 2008 until June 10, 2009, using the latest GRAIL gravity field models, and using laser altimetry data from LALT as a supplementary tracking type, by adjusting LALT altimetry tracks to best match accurate lunar topography. The latter was demonstrated in Mazarico et al. (2018) for LRO orbit determination. We show here that with these improvements, we can obtain an orbit precision of several tens of meters or better when LALT data are available, as derived from orbit overlap analysis, whereas the originally archived orbits show overlap discrepancies of several kilometers. Such improved orbits greatly enhance the analysis of the entire Kaguya XM data set. Our orbits will be made publicly available (for the location, see Section 5 and the Acknowledgments).

This paper is structured as follows. In Section 2 we describe the data and techniques we use to determine Kaguya’s orbit. We show results such as data fit and orbit overlap differences in Section 3. We show how the new orbits improve the geolocation of Kaguya XM data with a few examples in Section 4. In Section 5 we discuss the results, especially the interplay between possible pointing biases and orbit errors, and we finish with conclusions. Finally, in the remainder of this paper, when we write “Kaguya” we refer to the main orbiter, and with “SELENE” we in general refer to the entire mission and its products (as products such as gravity field models can also include data from the sub-satellites).

2. Data and Kaguya Orbit Determination

Tracking data for the multi-satellite SELENE mission consisted of various data types: in addition to standard Doppler tracking data from Earth stations to the main orbiter and the relay satellites separately, 4-way tracking data between the relay satellite Rstar and the main orbiter were collected, as well as differential Very Long Baseline Interferometry (VLBI) measurements using the two sub-satellites. The collection of 4-way data was stopped after December 26, 2008, because of the reaction wheel failure. The exception was a period towards the end of January, 2009, where 4-way data that would fill in an existing gap in data coverage were specially obtained (Matsumoto et al., 2010). The sub-satellite involved in the 4-way experiment crashed on the lunar surface on February 12, 2009, while the extended mission was still ongoing. This ended the collection of both 4-way and differential VLBI data, and here we therefore only focus on the use of standard 2-way Doppler tracking data, complemented by altimetry. For completeness: a description of the 4-way data and its processing can be found in Matsumoto et al. (2010), while the VLBI data analysis for precise orbit determination is discussed in Goossens et al. (2011b). Orbit determination using these tracking data types simultaneously is described in Goossens et al. (2011c). In this section, we first briefly describe the data available during Kaguya's XM, followed by a discussion of how we determine the Kaguya orbits using both 2-way tracking and altimetry data.

2.1. Radio and Altimetric Data During Kaguya's XM

Doppler tracking for Kaguya was acquired at the S-band frequency using JAXA's Ground Network stations, with locations in Japan, and overseas on the Canary Islands, in Australia, and in Chile. Coordinates for the stations are provided in Matsumoto et al. (2010). Such station coverage ensures the possibility of continuous tracking, and Kaguya was indeed tracked continuously during its PM. However, after completion of the PM, and thus after achieving Kaguya's science goals, tracking during the XM was reduced by largely suspending tracking from the overseas stations (Matsumoto et al., 2010). We illustrate this in Figure 1 where we plot the amount of radio tracking throughout the Kaguya mission. This Figure shows a quick drop in the number of radio observations when the XM period starts (on November 1, 2008), with the exception of a peak with increased radio tracking data towards the end of January, 2009, which coincides with the aforementioned period where additional 4-way data were collected.

Figure 1 also shows the amount of LALT data collected. As can be seen, LALT collected most of its data during two distinct periods: at the start of the mission, and during the XM. We refer to Araki et al. (2013) for a detailed description of operational history of LALT. We point out here that LALT operated intermittently after April 14, 2008, when it experienced a sudden decrease in laser power. The instrument was completely stopped from operating after December 26, 2008 when the spacecraft suffered the loss of a second reaction wheel, and thus had to switch to a thruster mode in order to maintain its attitude. On February 11, 2009, normal operations of LALT resumed, collecting a wealth data until the end of the mission, as can be clearly seen in Figure 1. Finally, when comparing the number of data points between

radio and altimetry as listed in Figure 1, we note that the Doppler data have a count interval of 10 s, whereas the LALT data were collected every second.

2.2. Orbit Determination With Radio and Direct Altimetry Data

Precise orbit determination applies high-precision force and measurement modeling to numerically integrate the equations of motion of a satellite. Computed observations are compared to the actual observations, and their discrepancies, called residuals, are reduced by adjusting parameters that describe the forces acting on the satellite and the measurements used. We use the GEODYN software (Pavlis & Nicholas, 2017), developed and maintained at NASA Goddard Space Flight Center (GSFC), to analyze the Kaguya data. GEODYN has been used for orbit determination and the determination of geodetic parameters using data from many planetary and terrestrial orbiters. Specifically for the case here, GEODYN was used to determine the SELENE Gravity Models (SGM) based on historical and SELENE data (Namiki et al., 2009; Matsumoto et al., 2010; Goossens et al., 2011b,a). It was also used for the orbit determination using multiple data types as described in Goossens et al. (2011c). The software uses a batch least-squares approach to adjust parameters (e.g., Montenbruck & Gill, 2000; Tapley et al., 2004).

For Kaguya orbit determination in this work, we process the data in continuous spans of time called arcs. Because Kaguya was three-axis stabilized, angular momentum desaturation (AMD) events occur. While they are in general force-neutral, small spurious accelerations are typically being induced on the spacecraft during these events, so for the gravity field modeling, arcs were limited in length by the occurrence of these events to prevent corruption of the estimated gravity field models (Matsumoto et al., 2010; Goossens et al., 2011b). AMD events occurred every 12 hours until July 23, 2008 (still during the PM), when one reaction wheel failed. After this, there were AMD events every 6 hours, until December 26, when the second reaction wheel failed, as mentioned earlier. Following this wheel failure, Kaguya used its thruster system to maintain attitude. For the analysis here, we are not concerned with gravity field model estimation, and we can thus extend the arcs beyond the AMD events, by taking their effects into account in our processing. We do this with the goal to produce orbit reconstruction without gaps between arcs, as much as possible. Orbit correction maneuvers and other events on the spacecraft where the instruments were shut down (and no tracking data were available) still result in a few gaps, but otherwise our resulting orbits are connected without gaps. We list the gaps in our orbits in Table 1.

Our arcs are on average two days long until December 26, 2008, and after that, because the spacecraft went into thruster mode, we limit the arc length to one day. There were a few periods in 2009 where the reaction wheels were used again, and thus AMD events occurred: a few days in January (12, 21, 22 and 30), a period in February (1, 13–16), and a long stretch in March (1–21). Generally, AMD events can impart residual accelerations on the spacecraft. We can model these effects in two different ways: as (constant) accelerations over the short period of time that the AMD event lasted, or as instantaneous changes in spacecraft velocity timed at the middle of the AMD duration interval. We tested both for the period November–December in 2008, and while they mostly have the same results, for some arcs we noticed that the instantaneous change resulted in better orbit overlaps (for a discussion of overlaps

and results, see Section 3). Since our goal is to obtain the best, most consistent orbits for Kaguya, we selected the AMD model that gives the best overlaps for each arc. For the arcs in 2009, we modeled the AMD events as constant accelerations. We apply a constraint of 1 mm/s^2 to these accelerations, and 1 mm/s to the instantaneous velocity changes.

During the times that the satellite was thrusting to maintain its attitude, we estimate empirical accelerations to account for this effect, and to absorb other orbital errors. The accelerations we estimate are the sine and cosine amplitudes of an acceleration with a period equal to the orbital period (also called 1 cpr, from cycle-per-revolution), in the along-track and cross-track directions. Orbital errors can be shown to be mostly resonant effects at this 1 cpr frequency (*e.g.*, Colombo, 1989). We also estimate a constant acceleration in the along-track direction, and found that some arcs also benefit from estimating a constant acceleration in the radial direction. This means 5 or 6 acceleration amplitudes per set, and we estimate two such sets in one arc. We apply a constraint of $1 \text{ } \mu\text{m/s}^2$ to these accelerations. Other parameters that we estimate in our processing are: the initial state at the start epoch of the arc of Kaguya, consisting of the position and velocity of the spacecraft (these parameters have no constraint and are thus free to adjust), a scale factor for the solar radiation pressure force (with a nominal value of 1 and a standard deviation of 0.1), and pass-by-pass biases for the Doppler data (unconstrained as well). A pass is a set of (near-)continuous tracking data from the same station, usually consisting of the entire period that the spacecraft was visible from that station, unless there were gaps during that tracking period for some reason.

We account for the following forces acting on the spacecraft in our processing: the gravity field of the Moon (we use different models, see the next section), third body perturbations from all the planets and Pluto, based on the Jet Propulsion Laboratory's DE421 ephemerides (Folkner et al., 2009) which also describes the Moon's coordinate system, solid body tides expressed with the potential degree 2 Love number k_2 , and solar radiation pressure. For the latter we model the spacecraft, including its solar panel, as a set of plates (*e.g.*, Marshall & Luthcke, 1994), and we account for the spacecraft's orientation in inertial space by using the telemetered quaternion information from star trackers. The scale factor that we estimate accounts for errors in the properties of the plates such as reflectivities (for which we do not have manufacturer values, but based on knowledge of other satellites). The values for this scale factor usually are around 1–1.2.

GEODYN also includes high-precision models of the measurements. We account for the effects of solid Earth tides, and ocean tidal loading per tracking site. We model the atmospheric delay on the Doppler data using the Hopfield zenith delay (Hopfield, 1971) and the Niell mapping function (Niell, 1996). We do not include ionospheric delays in our processing of the Kaguya data. The bias that we estimate on the Doppler data on a pass-by-pass basis accounts for such unmodeled effects. GEODYN also includes general relativistic effects on the Doppler data.

The altimetry data are modeled as round-trip light times from the LALT instrument to the lunar surface and back. For precision modeling of both these data types, we need to know the position of the phase center of the High-Gain antenna (HGA) and of the LALT instrument gate. We list the locations with respect to the center-of-mass used in our

processing in Table 2, and we note that Araki et al. (2013) also discussed LALT's position. While the center-of-mass moved during the mission, we did not take this into account, as the effects are likely too small to influence the data. We use the mass of the spacecraft when modeling solar radiation pressure, and we use a value for the spacecraft mass per arc that is obtained from the AMD information file, which keeps a record of the spacecraft mass after each maneuver.

Doppler data can be considered standard tracking data for (planetary) spacecraft, and they have been described elsewhere in detail (*e.g.*, Thornton & Border, 2000). GEODYN's modeling of these data is fully compliant with the formulation as given in Moyer (2000). We note that the Kaguya data were not ramped (for ramped data the transmit frequency varies linearly with time) like Deep Space Network (DSN) interplanetary data.

Laser altimetry data have been used before for planetary orbiters, mostly in the form of crossovers: when two ground tracks of two different orbits cross, they should essentially measure the same topography if there are no, or only small, dynamic effects present. At GSFC, the use of laser altimetry for planetary orbit determination was developed for Mars Global Surveyor (Rowlands et al., 1999), and it was shown that the inclusion of crossovers indeed helped improve the low-degree coefficients of a spherical harmonic expansion of a model of Mars' gravity field (Lemoine et al., 2001). Crossovers were also planned for LRO using LOLA data. In Rowlands et al. (2009) it was shown how multi-beam crossovers can improve the orbit determination and altimeter calibration, both of which are important for obtaining the desired quality for the LOLA products such as lunar topography. During the first mission phases of LRO, crossovers helped improve the orbit precision (Mazarico et al., 2012). Because the quality of the radio tracking was better than anticipated, and because of the availability of gravity models from the GRAIL mission, the benefits from crossovers for orbit quality were deemed to be marginal compared to the computational effort needed to process them, and they are currently not used in LRO orbit determination (Mazarico et al., 2018). Finally, crossovers were also used for Kaguya orbit determination, and Goossens et al. (2011c) showed that they help improve the orbit quality, with an estimated precision of the orbits of around 20 m. Attempts were also made to use crossovers during Kaguya's XM because of the return to normal operations of LALT, but they did not result in improvements and the efforts were dropped (Goossens et al., 2009).

However, with the much improved topography available from LOLA, Mazarico et al. (2018) presented the use of altimetry as a direct measurement by comparing the ranges to already known topography. This measurement is based on efforts initially developed for the calibration of Earth laser altimeters (Luthcke et al., 2000), and also used in the Near-Earth Asteroid Rendezvous (NEAR) mission (Zuber et al., 2000), where altimeter ranges from the spacecraft are compared to low-resolution, smooth ocean or asteroid shape models in order to improve pointing or calibration parameters. In Mazarico et al. (2018), these altimetry ranges were used to compare profiles with known topography to directly adjust the position of the spacecraft: given the pointing of the spacecraft and the current spacecraft position estimate, the bounce point can be computed, and a topographic height at the bounce point can be determined. This can then be compared directly to the topographic height given by the accurate basemap. The discrepancy between the measured height and basemap height

then provides a direct constraint on the spacecraft position. In addition, compared to (differential) crossovers where two tracks give only one crossover measurement, the entire altimetry track can be used for this absolute measurement, making it a stronger data type geometrically. With a high-resolution LOLA basemap, this results in geodetically accurate orbits tied to the precise LOLA/LRO frame.

We now use this data type, in combination with radio tracking, for Kaguya orbit determination using LALT data. We use the SLDEM2015 shape model (Barker et al., 2016a), which was created from a combination of LOLA data and Kaguya TC data, as the topography basemap. This shape model has an effective resolution of about 60 m at the equator, and a vertical accuracy of 3 – 4 m. SLDEM2015 covers $\pm 60^\circ$ and outside of this we use the 512 ppd LOLA topographic grid. We note that the LALT footprint at the surface is typically 20 m from an altitude of 50 km, due to the beam divergence of 0.4 mrad (Araki et al., 2008). For our baseline orbits, we use tiles of the shape model SLDEM2015 at different resolution, depending on the latitude. The resolution of the tiles is symmetric around the equator, and the resolutions are listed in Table 3. We discuss the effect of different resolutions in Section 3.

Finally, when performing orbit determination with different data types, the relative data weights are important since they determine the contribution of each type to the orbit estimate. S-band Doppler data are usually reported to have an error of around 1 mm/s at 60 s count interval (*e.g.*, Thornton & Border, 2000). Although we use Doppler data at a count interval of 10 s, which would imply a larger error, we weigh the Doppler data uniformly at 1 mm/s and we will show that our Doppler fits are generally better than this. This was also the overall weight used for Doppler data in the SELENE gravity field models (Matsumoto et al., 2010; Goossens et al., 2011b). LALT data were reported to have a range resolution of 1 m and a range accuracy of around 5 m (Araki et al., 2008, 2009). To account for systematic effects we will weigh the LALT data at 10 or 20 m.

3. Results

We now present the results of our orbit determination for Kaguya using Doppler and altimetry data. We processed the data in different combinations of data and gravity field models, to separate the effects of data and models. We first processed the Doppler data using the LP150Q model, which is a model based on Lunar Prospector (LP) data (Konopliv et al., 2001). We then used the GRAIL Gravity Model GRGM900C (Lemoine et al., 2014) up to a maximum degree of 270, while still using only Doppler data. Finally, we used GRGM900C and added the direct altimetry data for use together with Doppler data. In this section, we present results for the data fits (Section 3.1), we evaluate orbit accuracy by computing orbit overlap differences (Section 3.2), we compare our orbits with previously archived orbits (Section 3.3), and we investigate the influence of the chosen maximum degree of the gravity field models and the resolution of the topography basemaps (Section 3.4).

3.1. Data Fit

We present results for the data fit in order to evaluate how well the different gravity models, and our orbit parametrization, describe the tracking data. We present values for the root-

mean-square (RMS) of the fit for Doppler and altimetry data per arc in Figure 2. The Doppler fit plot is for the case when only Doppler data were used.

Doppler data were uniformly weighted at 1 mm/s, and the fits reported for Kaguya are typically better than that (Matsumoto et al., 2010; Goossens et al., 2011b,c). Indeed, the fit for the Doppler data is on average close to 0.5 mm/s. For the higher altitude phase of the XM, both LP150Q and GRGM900C fit the data equally well. This means that LP150Q already describes the spacecraft orbit well, despite its lower resolution and despite the fact that it was estimated without farside data. We also discussed this in the framework of LRO orbit determination and GRAIL model evaluation in earlier work (Mazarico et al., 2013, 2018). This however does not mean that GRGM900C at $l_{\max}=150$ will perform similarly as LP150Q, where l is the spherical harmonic degree. We discuss this in more detail in Section 3.4.

At lower altitudes, the GRAIL model fits the Doppler data better, and the fits are more stable than those for the LP150Q case. During the transition from higher to lower orbits (around January 2009), fits for the Doppler data are larger than 1 mm/s, and both models show the same level of fit. For this period, we investigated relaxing the constraints on the empirical accelerations, as well as estimating more sets of them in one arc, yet the fits never go down to the level of the other arcs. We surmise that the influence of the lowering of the periapsis is what is keeping us from reaching the normal level of fit. Unfortunately altimetry data were also not available during this period, as Figure 2B shows, as they would have been able to provide better constraints on the spacecraft position.

The fit for the altimetry data is very consistent, at a level between 5 and 10 m for most arcs. We weighted the altimetry data at 20 m, and a few select arcs at 10 m, based on orbit overlap differences (see next section). As with the Doppler data, the value for the RMS of fit is generally smaller than the assigned weight. Both data types could thus be assigned smaller weight values, but as stated in Section 2.2, we choose slightly higher values to account for systematic effects. A few arcs have fits larger than average, and despite careful editing and consideration of different orbit parametrizations (again, more and/or loosely constrained accelerations), we could not obtain lower fits for these arcs. We indicate arcs with altimetry data with circles in Figure 2, and we note that not all arcs in the early period (end of October until December 26, 2008) have altimetry data. A few of the early arcs, around November 7, have only a limited time period of altimetry as LALT was not yet fully operational at that time. This can mean that for a two-day arc, only a part of the arc has altimetry data coverage. We discuss this in the framework of orbit overlaps in the next section.

Doppler fit for arcs with altimetry included are shown in Supplementary Figure S1. This plot is of interest since it shows how the Doppler fit is affected by the inclusion of altimetry. As always, the relative weighting of two different data types is difficult. As Figure S1 shows, the Doppler fit values increase for the low-altitude arcs when combined with altimetry. In the next section we will show that the orbit precision is not affected by this.

3.2. Orbit Precision Assessment Using Overlap Analysis

Orbit overlap analysis is a standard tool in orbit precision assessment. We create two separate arcs that start at different times but share a certain time period. We fit the data for both arcs using the same models and parametrization, and then we compute the orbit differences during the overlapping part. Apart from systematic errors, these orbit differences show the consistency of the computed orbits, which is considered a measure of the orbit precision. For our arcs, the orbit overlaps are either one day or 12 hours, for the two-day or one-day arcs, respectively. In Figure 3 we show the root-sum-square (RSS) orbit overlap differences, computed as the square root of the sum of squares of differences in 3 orthogonal directions (also called total orbit overlap error). We show the RMS of overlap differences for the separate directions radial (from the center of the Moon to the spacecraft position), along-track (in the flight direction) and cross-track (normal to the orbital plane) in Figures S2–S4.

We again show overlaps for the three cases. For the higher-altitude phase, when there are no altimetry data available, both the LP150Q and GRGM900C results show similar overlaps. For the lower altitude phase, GRGM900C's overlaps are in general better than those from LP150Q, as is to be expected. While the overlaps for the LP150Q case are often above 1 km during this period, those for GRGM900C can go down to several hundreds of meters due to its better modeling of the lunar gravity field. We demonstrate this further in Figure S5, where we show a pass of Doppler residuals with respect to LP150Q and GRGM900C, showing how the latter removes systematic signals.

The overlaps improve drastically when altimetry data are included. For arcs in the early period, the overlaps with altimetry data are typically better than 100 m, and sometimes much better. There are a few arcs that have altimetry data but still have relatively large overlap values. We found that for these arcs, altimetry data was only available during the first half of the first arc, and that there were only few altimetry data during the second arc of the overlapping pair. This means that the only constraints on the orbit during the overlap come from a few Doppler tracking passes. As the overlaps for the cases using only Doppler data show, the tracking was insufficient to bring the orbit overlaps to the level of tens of meters. We illustrate this in more detail in Figure S6, where we show the orbit differences for one arc as a time series, indicating also the data coverage for that arc.

For the latter part of the XM when LALT was operating nominally, the orbit overlaps are very consistent, at a level of a few tens of meters. This is an improvement of two orders of magnitude over the previously archived orbits. The arcs that showed poorer altimetry fits in Figure 2 do not show outliers in overlap differences. As stated in Section 3.1, we varied the altimetry data weight between 10 m and 20 m. We computed overlaps for both cases, and for our final orbit product (and the results shown here) we selected those arcs with the smallest overlap differences. We did the same with the arcs that have the AMD events modeled as either constant accelerations or instantaneous velocity changes.

Clearly, the inclusion of the altimetry data greatly improves the orbit consistency, by virtue of having constraints throughout the arcs on the spacecraft position rather than having only a few scattered tracking passes. The satellite's thrusting mode further complicates the orbit determination, but with altimetry we can mitigate these effects with a more robust estimation

of empirical accelerations. These are much less well-determined when using only Doppler data. The orbit precision for the XM is now on a par with that of the PM, which is at the level of 10–30 m (Goossens et al., 2011c), whereas the XM orbits previously showed variations at the level of kilometers.

3.3 Orbit Differences With Previously Archived Orbits

The case using only Doppler data with the LP150Q model closely resembles the processing as applied for the previously archived Kaguya orbits, yet there are some differences: the earlier orbits partly used the SGM100h model based on SELENE, and for this work we reanalyzed the arcs to obtain the best possible fits with our current processing. Therefore, in Figure 4 we present the differences between the previously archived orbits, and the orbits we recomputed for this work. During the period when altimetry were not available the differences are not too big, but still can be substantial. During periods when altimetry data are available, the differences are on the order of kilometers. The improved overlap results for the new orbits suggest that these differences are indeed improvements.

3.4. Influence of the Gravity Model and Altimetry Grid Resolutions

We now investigate the effects of the maximum degree of the chosen gravity field model, and of the resolution of the topography grids when processing the altimetry data. Pointing errors also directly influence the analysis of LALT data (Araki et al., 2009, 2013) and may interchange with orbit errors. We will address this in Section 5. We investigate the effects of gravity field model resolution by varying the maximum degree when determining the orbits. In Figure 5 we show the RMS of fit for the Doppler data, and orbit overlap results, for our processing using only Doppler data and the GRGM900C model. Our baseline processing uses GRGM900C up to a maximum degree and order of 270, and here we present additional results using the model up to either degree 150 or 660. The former was chosen because it is also the resolution of LP150Q, and the latter because that is roughly the degree up to which the GRAIL models are currently used for global geophysical analysis (*e.g.*, Neumann et al., 2015).

Obviously, the Doppler fit is much poorer for the low-altitude arcs when using GRGM900C up to degree 150 instead of 270. For most of the low-altitude arcs, the fit is in fact poorer than that for the LP150Q model. The orbit overlaps with $I_{\max}=150$ are also larger than those for the case using $I_{\max}=270$, as is to be expected. This can be understood from the following: as stated in Section 3.1, LP150Q was determined without farside data, and as a result, *individual* coefficients are not determined as precisely as those for the GRAIL model. Yet their *combined* acceleration still manages to predict the trajectory for spacecraft in similar, near-circular, near-polar orbits, especially at higher altitudes. The LP150Q coefficients can thus also be considered as lumped coefficients, which are (a set of linear) combinations of gravity coefficients that describe a particular signal in good agreement with the data (*e.g.*, Wagner & Klosko, 1977). In other words, it can be considered a tailored model, performing specifically well for a Lunar Prospector-like orbit. For the best orbits, we recommend using the GRAIL models at sufficient resolution: for low-altitude orbits we recommend at least $I_{\max} = 270$. The data fit for GRGM900C used up to degree 660 is almost identical to the fit

at $l_{\max} = 270$. Orbit overlaps using only Doppler data and GRGM900C up to $l_{\max} = 660$ are mostly slightly better than those using the model up to degree 270, except for a few arcs.

Figures S7 and S8 show the fit for altimetry data and overlap differences, respectively, when using GRGM900C at different maximum degrees, in combination with Doppler and altimetry data. Interestingly enough, the altimetry fit is not much affected by the maximum degree of the gravity field model, and neither are the overlap differences. The altimetry fit is still at the level of 10–15 m, only slightly poorer in some arcs than when using GRGM900C at $l_{\max} = 660$, and the orbit overlap differences are also not much larger. This shows the strength of having continuous data to constrain the orbit, as dynamical mismodeling of the gravitational accelerations in this case can be absorbed well by the estimation of empirical accelerations.

Finally, we investigate the effects of the resolution of the topography basemaps. In Figure 6, we show orbit overlaps using GRGM900C at a maximum degree of 270, with varying resolutions for the grids. A coarser grid, with a resolution of 64 ppd globally (~ 500 m/pixel at the equator), still results in reasonable overlap differences at a level of around a hundred meters. We also investigated the use of a denser grid at the poles while leaving the rest of the grid at a resolution of 64 ppd, because all orbits cover the polar areas. However, we found no significant difference. Increasing the global resolution to 128 ppd (~ 250 m/pixel at the equator) improves the orbit differences considerably and brings them very close to the results of our variable-high-resolution grids (see Table 3).

In summary, the orbit overlaps with altimetry and GRGM900C at a maximum degree of 660 are slightly better than those when using the model up to degree 270. The differences are not very big, and thus our results, as well as earlier results by Mazarico et al. (2018), indicate that $l_{\max}=270$ is sufficient to achieve precise orbits. We also obtain the best results with our variable-high-resolution topography grids. Our final orbit product uses altimetry with these grids, and GRGM900C at $l_{\max} = 660$.

4. Kaguya Extended Mission Data Geolocation Improvements

We now discuss briefly the broader impact of our improved orbits on the Kaguya XM data. Improved orbits result in improved geolocation of the data taken during Kaguya's low-altitude phase. We will show this in this section with two examples: by showing the newly geolocated LALT data, which now by design have to be close to the LOLA topography, and by showing the results of image simulation with Kaguya Multiband Imager (MI) and Spectral Profiler (SP) data using the previously archived orbits and our new orbits.

In Figure 7 we show topography of the lunar poles derived by processing the LALT data based on the previously archived orbits and the new orbits. It is clear that the new orbits result in a much sharper topography map without artifacts. Obviously, because the orbit was adjusted such that the LALT data fit the SLDEM2015 basemap, this should be the case. Nevertheless, we note that no profile was excluded from the maps, indicating the high quality and robustness of these orbits. This Figure thus serves in a way similar as Figure 2B that shows the post-fit altimetry RMS.

Given the large areas shown in Figure 7, only clear radial or very large along-track orbit errors are visible. Therefore, we show a close-up of the poles, from 88° to 90° latitude for both poles, in Figure 8. Here, the differences in topography between the two orbit sets are very clear: the old orbits show substantial errors. As a result, topography derived from the old orbits sometimes misses features entirely. The topography from the new orbits on the other hand is smooth and close to that derived from LOLA. We state (again) that LALT collected data at a rate of 1 Hz, while LOLA data were collected at a rate of 28 Hz. As a result LOLA's products are much denser and have a higher resolution (*e.g.*, Head III et al., 2010; Zuber et al., 2012).

The LALT-based topography maps are of course not independent of our orbit processing. To show the impact of improved geolocation on other Kaguya data sets, we now turn to independent data from the MI and SP instruments. Both these instruments were part of the optical observation system onboard Kaguya called the Lunar Imager/Spectrometer (LISM), which also included TC. MI was a high-resolution multi-spectral imaging instrument with 9 bands in the visual and near-infrared region (Kodama et al., 2010; Ohtake et al., 2010), and SP was a spectral profiler in the visible and near-infrared regions as well with a small field of view (500 m footprint at a nominal altitude of 100 km) (Matsunaga et al., 2001, 2008). When SP was taking images, MI often took simultaneous context images.

Using the previously archived orbits to analyze MI and SP data, it is known that MI/SP data from the XM have geolocation issues. This is demonstrated in Figure 9. We took a typical SP image taken during Kaguya's XM, Figure 9A, and using knowledge of the spacecraft position and viewing geometry, we simulate the image as seen by SP at the time that the image was taken, using a digital elevation model based on TC data. We use either the new orbit (Figure 9B) and the previously archived orbit (Figure 9C). We did this for 191 images, but show only one result in Figure 9. The simulated image using the spacecraft position from the new orbit matches the actual image (ground truth), while the simulated image using the previously archived orbit shows a large offset in the locations of features on the surface, indicating that for the latter the spacecraft position is not correct. Knowing the scale of the image and the size of the image area, it can be inferred that there is an offset of about 9 km. We further demonstrate this by showing orbit differences between the previously archived orbit and our new orbit using the GRAIL model and altimetry data in Figure 9D. Assuming that the precision of the new orbit is at around 20 m, from orbit overlap analysis discussed in the previous section, we consider this orbit to be close to the true spacecraft position and thus infer differences between this orbit and the previously archived one as errors on the latter. And indeed, at the time of image acquisition, we find a difference of close to 9 km in along-track direction between the two orbits.

The orbit for this particular time span had radio tracking coverage at the start and end. Figure 9D shows smaller errors during times when tracking data were available, at a level of 100 – 200 m, similar to what we showed earlier in Figure S6. Due to the lack of data constraints on the orbit, the errors quickly increase in the time between passes, when using only radio tracking. The use of altimetry that covered the entire span of the arc greatly improves the orbit precision. Figure 9 thus unmistakably shows the benefit offered by our

improved orbits on other Kaguya XM data sets, especially those that are sensitive to geolocation errors.

5. Discussion and Conclusions

We have analyzed the Kaguya XM data using a GRAIL gravity field model and including the direct altimetry measurement type, where we use altimetry data from the LALT instrument and compare the resulting tracks directly with the SLDEM2015 model basemap (a lunar digital elevation model using LOLA and Terrain Camera data). We processed the data in continuous spans of time (called arcs) of on average two days prior to December 26, 2008, when Kaguya lost its second reaction wheel, and of on average one day after that until the end of the mission. Radio tracking data were available less frequently than during the PM with mostly only several passes per day. Altimetry data were available intermittently from the start of the XM until December 26. LALT operations were then stopped until February 13, 2009, and after that they were consistently available until the end of the mission. We weighted the Doppler data at 1 mm/s, and we varied the altimetry data weights between 10 m and 20 m. Doppler data typically fit at around 0.5 mm/s, and the altimetry data fits have an RMS of between 5 and 10 m.

In order to assess the precision of the newly determined orbits, we performed orbit overlap analysis. Differences during two overlapping arcs are indicative of the precision of the orbit. The use of GRAIL gravity field models improves the low-altitude orbits to a level of several hundreds of meters or better, but the lack of tracking data and the constant thrusting onboard the spacecraft to maintain its attitude limit the improvements that can be achieved without altimetry data. When altimetry data are available, we can now achieve orbit overlap differences of several tens of meters, whereas previously the orbits show differences at the level of several kilometers. The inclusion of the altimetry data type thus greatly improves the orbit consistency, and Kaguya XM orbits now have a precision that is on a par with that of the Kaguya PM orbits.

We advise using GRAIL gravity field models at sufficient resolution. PreGRAIL models of lower resolution such as LP150Q can perform well, but their individual coefficients do not relate to the actual gravity field as well as a GRAIL model. As a result, GRAIL models may need a higher resolution but they will outperform pre-GRAIL models at lower altitudes. Our results for Kaguya show that a maximum degree and order of 270 is sufficient. Consistently lower orbits may benefit from larger maximum degree values. For orbits at a nominal altitude of 100 km, we see no significant differences in orbit precision performance between LP150Q and a GRAIL model, consistent with earlier findings of the evaluation of GRAIL models, and LRO orbit determination (Mazarico et al., 2013, 2018). Our recommendation for the degree of GRAIL models is for orbit reconstruction in the way presented in this work. We recognize that operationally there may be different requirements where large gravity field models are more difficult to handle.

Mazarico et al. (2018) presented orbit results with altimetry data only and found that this supports orbit reconstruction of excellent quality. While we did not analyze a case with only altimetry, we do note that the case with using altimetry data and a GRAIL model of lower

resolution (a maximum degree of 150) results in orbits with an estimated precision of around 50 m or better, as derived from overlaps. In this case, dynamical errors from an insufficient gravity field model were compensated for by the estimation of empirical accelerations, which was robust due to the constraints from the continuous altimetry. This level of orbit precision is not that different from that from using the GRAIL model at a higher resolution. This provides further support for the consideration of the use of simple laser altimeters or similar instruments to aid orbit determination in future lunar exploration.

Because our improved orbits rely heavily on the use of altimetry data, pointing errors can also have an effect on the retrieved orbits. A change in pitch or roll angle can correlate and thus trade off with a change in along-track or cross-track position, respectively, and the effects are not necessarily readily separable. However, knowledge of the pointing of Kaguya is listed to have an accuracy of 0.025° (Sasaki et al., 2003), and despite the use of thrusters to maintain attitude during XM after December 26, 2008, there are no indications that the performance of the star trackers degraded. The thruster mode could also conceivably induce jitter on the spacecraft which could affect the attitude determination. If there were severe pointing biases of such a nature, they likely would not interchange with orbital adjustments, because our orbit solutions are smooth since they are fully dynamical. We did not include parameters to absorb such effects, and we would thus expect larger altimetric residuals or systematical signatures in these residuals if such a signal were present, yet we did not see such a signal in the residuals. Other than errors in the knowledge of the pointing of the spacecraft bus, there is also the possibility that there is a pointing bias between the LALT instrument and the spacecraft body. For a satellite such as the Ice, Cloud, and land Elevation Satellite (ICESat), specific calibration tests were performed, and laser altimetry can be used to correct for pointing biases, improving the accuracy of one of the main science products (Luthcke et al., 2000; Luthcke et al., 2005). For Kaguya, no such active maneuvers were performed and thus no comparable data are available, and moreover, results from the primary mission do not indicate there is a large offset (Araki et al., 2013). If such an offset is present, it is small and thus could not interplay with orbit adjustments to explain the large improvements that we see in orbit overlaps. To verify the impact of changes in the pointing, we processed the data and additionally estimated pointing biases: one constant offset per arc in roll and pitch (there is no sensitivity to yaw for a single-beam altimeter). The altimetry fits were nearly the same except for a few arcs, and the overlaps also did not change significantly. The resulting arc-by-arc pointing adjustments are also difficult to interpret and may be more related to the size of the LALT footprint or other mismodeling effects. A more systematic examination of the pointing using PM data might yield more reliable results and we leave that for future analysis. Finally, our image matching analysis as presented in Figure 9 provides additional support for the pointing effect being small. If large pointing errors were to be compensated by orbit adjustments, this would introduce noticeable discrepancies for our image matching tests in areas with large topographic variations because of viewing angle effects. However, we did not encounter such discrepancies for images in both the PM and XM.

Our greatly improved orbits result in better geolocation of the Kaguya XM data and thus have a broad impact on its use. We illustrated this by reprocessing the LALT data into topography maps of the lunar poles. The new orbits greatly improve the derived topography,

as there are no artifacts due to track geolocation errors. Of course, we adjusted the orbits such that the altimetry tracks are consistent with the SLDEM2015 grid, so this is not a truly independent test. Verification with independent data was performed by simulating images taken with Kaguya's MI and SP instruments. Simulated images derived by using the previously archived orbits show offsets of surface features of up to 9 km or more, whereas images using our new orbits match the actual image, showing the improvements in geolocation.

The updated orbits are archived for general use, at NASA GSFC's Planetary Geodesy Data Archive <https://pgda.gsfc.nasa.gov/products/74> and at the JAXA archive <http://darts.isas.jaxa.jp/>. Our orbits cover the time span 2008-10-31 02:30:00 until 2009-06-10 19:30:00 UTC. Our orbit product uses altimetry with the variable grid resolution (Table 3), and the GRGM900C model at $I_{\max} = 660$ because this combination produced the best orbit overlaps. Gaps where no orbit is available are listed in Table 1. Finally, in future work we will use these orbits to create a pilot test mosaic ($\sim 10^\circ$ by 10° in size) from Kaguya TC data for the Hadley Rille region. This geodetically controlled mosaic will serve as a further validation of our methods, and as a starting point to possibly recalibrate the entire Kaguya XM data set.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The data used in this work are available at NASA's PDS (<http://pds-geosciences.wustl.edu/missions/lro/lola.htm>) and JAXA's DARTS website (<https://darts.isas.jaxa.jp/>). Our final orbit in SPK form is available at DARTS and NASA GSFC's Planetary Geodesy Data Archive website (<https://pgda.gsfc.nasa.gov/products/74>). We express our sincere thanks to JAXA in general and the entire SELENE project staff in particular for their work in successfully carrying out the SELENE mission and in collecting such a spectacular dataset. We thank two anonymous reviewers for their constructive comments. This project was funded through NASA's Planetary Data Archiving, Restoration, and Tools (PDART) program (LG and BA, IAA 80HQTR18T0053) and NASA/GSFC's ISFM "Planetary Geodesy" (SG and EM).

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Figure 1:

Amounts of acquired radio tracking and altimetry data for Kaguya. The altimetry data were acquired once per second (1 Hz) when LALT was turned on. The count interval of the Doppler data is 10 s.

Figure 2:

RMS of the fit per arc for the Doppler data (top, A) and the altimetry data (bottom, B). The Doppler fits are for the case where we used only Doppler data in the processing. The fits are with respect to two different gravity field models, the pre-GRAIL LP150Q model (degree and order 150 in spherical harmonics) that was used in the previously archived low-altitude Kaguya orbits, and the GRAIL model GRGM900C (expanded up to degree and order 270). Altimetry data were used in combination with GRGM900C exclusively. We include the periapsis altitude in the altimetry fit plot.

Figure 3:

The root-sum-square values per arc of orbit overlap differences, for different processing cases: using only Doppler data with either a pre-GRAIL model or a GRAIL model, or using Doppler and altimetry data (while using a GRAIL gravity field model). Note that the y-scale is logarithmic.

Figure 4:
The root-sum-square values of differences between our current best orbits, and the previously archived Kaguya XM orbits.

Figure 5: RMS of fit for Doppler data when using different expansions of the gravity field model (top, **A**), and the root-sum-square values per arc of orbit overlap differences when using different expansions of the gravity field model (bottom, **B**). In both cases we only used Doppler data in the processing.

Figure 6:
The root-sum-square values per arc of orbit overlap differences when using topography basemaps of different resolution.

Figure 7:

Lunar topography in polar stereographic projection covering 77° – 90° latitude for both the north pole (top) and south pole (bottom), using the previously archived orbits (left, **A,C**) and the new orbits (right, **B,D**). With the new orbits, there are no artifacts due to geolocation errors as there are with the old orbits. A close-up is shown in Figure 8.

Figure 8:

A close-up of the topography maps as shown in Figure 7, with topography now covering 88° -90° latitude for both the north pole (top) and south pole (bottom), using the previously archived orbits (left, **A,C**) and the new orbits (right, **B,D**). The projection is stereographic.

Figure 9:

Top: a typical 10m/pixel SP image (left, **A**; image SP_2B2_02_06256_S623_E1364, acquired on 2009-03-02 at 18:00 UTC), and the results of an image simulation using the new orbit (middle, **B**), and the previously archived orbits (right, **C**). The old orbits show a large mismatch of about 9 km, whereas the new orbits result in a near-perfect match of the image.

Bottom: orbit differences between the previously archived trajectory and our new orbit, during the time that the image below was acquired (**D**)

Table 1:

Gaps in our orbit time series due to orbit correction maneuvers or other events. Times are in UTC. Our final orbit product covers the period 2008-10-30 02:30:00 until 2009-06-10 19:30:00 UTC.

Start time	End time
2008-11-03 00:30:00	2008-11-03 09:00:00
2008-12-26 21:00:00	2008-12-27 05:30:00
2009-02-20 20:00:00	2009-02-20 23:45:00
2009-03-19 18:00:00	2009-03-19 22:00:00
2009-04-16 19:00:00	2009-04-16 21:30:00

Table 2:

Locations of the LALT instrument and the High-Gain Antenna (HGA), with respect to the center-of-mass of Kaguya, as used in our processing.

Instrument	X [mm]	Y [mm]	Z [mm]
HGA	1190.5	41.70	-3285.1
LALT	385.0	689.7	1439.50

Table 3:

Resolution of the tiles used in our processing of the LALT direct altimetry data for orbit determination. Between 60°S and 60°N we use SLDEM2015, and outside of that the tiles are derived from the 512 ppd LOLA topographic grid. Polar caps are stereographic projections and hence have a unit of [m] instead of pixel-per-degree [ppd] in longitude. The equivalent resolution in [m] is given for the other grids. The ppd values are adjusted with latitude in order to obtain an approximately uniform grid (in meters). The resolution of the tiles is symmetric, so no indication of north (N) or south (S) latitude is given, except for the tile around the equator.

Area	Resolution [ppd, or m]
85° to poles	20 m
80°–85°	64 ppd (40–80 m)
70°–80°	128 ppd (40–80 m)
50°–70°	256 ppd (40–80 m)
50°S–50°N	512 ppd (40–60 m)