Orbit determination for the Kaguya satellites: altimetry crossovers and extended mission data

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Orbit determination results for the Kaguya satellites are presented, with a special focus on the orbit determination performance of new gravity field models containing farside tracking data. The models are compared with pre-Kaguya models in terms of data fit and orbit overlap analysis, for both Kaguya satellites and the Lunar Prospector satellite, showing that the Kaguya models have a similar performance as the Lunar Prospector-based LP100K model, with an improved performance in cross-track direction. Orbit precision from overlaps is 50 m in a root-sum-square sense. Results for the Kaguya extended mission (that started from November 2008) are also discussed. During this phase, tracking data were fewer and for a large part the main satellite was in thruster-mode, making precise orbit determination especially difficult. The used orbit determination strategy is discussed, showing the possibility for regular levels of data fit, although overall orbit quality deteriorates. Altimetry data from the laser altimeter LALT have also been used in the orbit determination process, and it is shown that especially along-track and cross-track directions are improved.

I. Introduction

The Kaguya satellites were launched on September 14, 2007, from the Tanegashima Space Center. Kaguya consists of three satellites: a main orbiter in an initially 100 km circular polar orbit, a relay satellite named Rstar in an initially elliptical 100 km x 2400 km polar orbit, and a sub-satellite named Vstar in an initially elliptical 100 km x 800 km polar orbit. By employing 4-way Doppler data, constituting a link between Rstar and the main orbiter when it is over the farside, Kaguya has obtained the first precise map of lunar farside gravity.[1] Differential VLBI data furthermore complement the newly obtained data, and they help to improve the orbit precision of the two small sub-satellites.[2,3] Rstar crashed into the lunar surface on February 12, 2009 as foreseen, thus ending the collection of 4-way data. The main orbiter crashed into the Moon on June 10, 2009.

Historical tracking data (*i.e.*, tracking data from before SELENE, thus including the relatively recent Lunar Prospector (LP) mission) and tracking data from SELENE have been combined to derive models for the lunar gravity field.[1,4,5] With the 4-way data that covered the farside of the Moon these models show an improved view of the farside, for example in terms of correlation with topography. Here, further analysis of orbit determination for Kaguya is presented and the newly obtained lunar gravity field models are tested for their orbit determination performance in terms of data fit and orbit overlap characteristics.

The main orbiter entered its extended mission phase on November 1, 2008. From this time on, fewer tracking data were collected than before, so continuous coverage in time, as was the case during the nominal mission, was lost. On December 26, 2008, there was another reaction wheel failure onboard (there was one on July 23, 2008 as well, reducing the time between angular momentum desaturation manoeuvres from 12

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hours to 6 hours), leaving the main orbiter with only two reaction wheels. Attitude control was then switched to the thrusters. This means that there are induced accelerations acting on the spacecraft. If they are not taken care of in the orbit determination process, they will lead to spurious signals in the data residuals. By using empirical accelerations and estimating scaling coefficients, this problem has been largely mitigated as will be shown here, although it can not be avoided that orbit quality is reduced.

The laser altimeter onboard Kaguya called LALT[6] provides an additional constraint in the orbit determination process through crossover constraint equations:[7,8] at points where the groundtracks of the satellite intersect, the measured topography should be the same apart from time-varying effects (which are taken to be absent on the Moon). These data have been added and it will be shown that including them improves the orbit overlap quality, especially in along and cross-track directions.

This paper is structured as follows. In section II the model comparison results are presented. In section III the extended mission data processing and results are discussed, followed by results for using the laser altimetry crossovers in section IV. Conclusions and an outlook are given in section V.

II. Model comparison

Models incorporating historical as well as Kaguya tracking data have been created.[1,4,5] The GEODYN II[9] and SOLVE[10] software were used for determining these models. GEODYN II has been especially modified to incorporate both the interplanetary 4-way Doppler data and the differential VLBI data. Precise models for both the forces that act on the satellite and the measurements are applied in this software. The data are then reduced and partials with respect to the gravity field coefficients as well as a number of other parameters are written into normal matrices per arc (a continuous span for processing the data), which are then combined and solved for. The latest lunar ephemeris, DE-421,[11] were used in this solution. Further details on the processing can be found in the given references.

The resulting models are called SGM for Selene Gravity Model, followed by the degree and order of the spherical harmonics expansion and a version number. The latest version is called SGM100h.[5] This is a 100 degrees and order expansion, using all historical data (Lunar Orbiters I-IV, Apollo 15 and 16 subsatellites, Clementine, LP and some SMART-1 data) except for the data from the extended mission of LP. During the last 6 months of its mission (January-July 1999) LP flew at an extremely low altitude (on average 30 km) over the lunar surface. These data thus contain a wealth of information on the nearside high-resolution gravity field (models up to degree and order 165 have been created[12]), and they are indispensable for the study of the accuracy of low-lunar satellite orbits. However, they were excluded from the processing because it was felt that these data, covering the nearside only, would disrupt the gravity field solutions over the farside too much, for example in terms of loss of correlation with the topography. SGM100h is compared to the pre-Kaguya model LP100K,[12,13] which used all available tracking data at that time, including the LP extended mission data. This should be kept in mind when comparing these models.

Data fit for both models are very similar (not shown in this paper). Both models fit the Lunar Prospector nominal mission data (at an average of 100 km above lunar surface) to a level of 0.5 mm/s for the Doppler data. Another way of comparing the performance of different gravity field models is by computing orbit overlaps. Orbit differences between two overlapping arcs are computed, and the size of the differences allows one to check the orbit consistency and orbit determination setup/parametrisation. Here, LP is chosen because it constitutes a set of high quality continuous data, from which it is straightforward to compute overlaps between two arcs. For the Kaguya main orbiter, there were angular momentum desaturation (AMD) manoeuvres which break up the arcs, and thus it is much more difficult to create overlaps over a reasonably amount of time, without introducing the deteriorating effect of the AMD events. Here, LP data for one month in 1998 were chosen, since LP was then in a similar orbit (*i.e.* polar at an average of 100 km above lunar surface) as Kaguya. Arc length is chosen to be 2 days, the standard arc length for lunar satellites in the absence of farside tracking,[12] with overlaps of one day, constituting about 12 orbital revolutions of LP. Results for the three directions in the satellite local frame (radial, along- and cross-track) are shown in Figure 1.

This Figure shows that both models perform equally well, with a total orbit error (in the root-sum-square sense) of on average better than 50 m. Both LP100K and SGM100h perform similar in the radial direction, with LP100K showing less variations. However, the differences between both models for this direction are generally less than 1 m. For both along- and cross-track, LP100K shows one strong peak that is mostly absent in the results for SGM100h. This peak for LP100K was found to coincide with a so-called edge-on

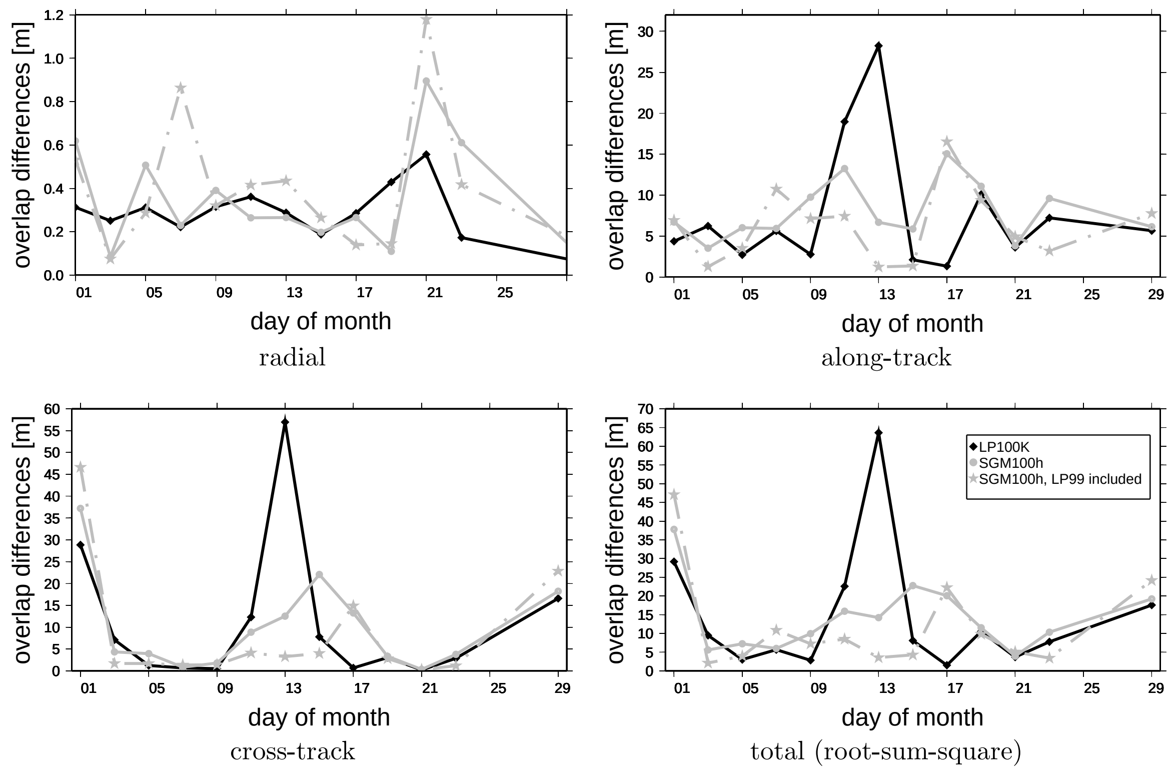


Figure 1. Orbit overlap results using the LP100K and SGM100h models and an enhanced version of SGM100h that also included LP extended mission data. Arcs are for LP in July, 1998, with a length of two days and an overlap of one day. The legend for each plot is the same, so it is only given once, in the plot with the root-sum-square results.

geometry, where the normal vector of the orbital plane is perpendicular to the Earth-Moon line, meaning that the satellite travels over the middle of the Moon, and thus also over the middle of the farside. During those arcs, LP travelled over the Dirichlet/Korolev basin on the farside of the Moon, which show up as strong anomalies in lunar gravity maps.[1,5,12] These anomalies were mapped particularly well with Kaguya data, since they are on the far side, showing their circular features that correlate well with topography.[1] Thus, it is to be expected that SGM100h captures the gravity force better in such a configuration, leading to an orbit that is more consistent.

In Figure 1 results for another model are also shown. This model is SGM100h where LP extended mission data were also included in the inversion. This model shows possible further improvements in orbit consistency, especially for the edge-on geometry in along- and cross-track. This also shows the strength of the extended mission data, which will be included in future SGM updates, especially those focusing on low-lunar satellite orbit determination. In the model shown in the Figure, the LP extended mission data were included only once in the gravity field determination iterations, meaning, further global iterations are expected to sort out the signals better (and possibly improve the radial overlaps since they are slightly higher for this ehanced SGM100h model).

III. Extended mission data analysis

The Kaguya mission consisted of several parts: the nominal mission lasted from October 2007 until October 31 2008, and the extended mission started on November 2008, and it ended when the mission ended with the main satellite crashing into the Moon as planned on June 10, 2009. The average altitude was 100 km throughout the nominal mission and the start of the extended mission. After that, it was lowered to an average of 50 km. During the nominal mission, the main satellite was continuously tracked using JAXA's ground network (GN). In the extended mission, most of the overseas (outside of Japan) stations were cut from the tracking, resulting in much sparser data coverage. Especially with the AMDs this severely disrupts the orbit quality: AMDs can be estimated from the tracking data, but they need to be covered by data.

If they are not, they induce spurious signal into the tracking data and the orbit quality deteriorates. This makes precise orbit determination in the extended mission of Kaguya a non-trivial matter.

On top of this, on December 26 a second reaction wheel had a failure, after the first one failed in July 2008. With two out of four wheels gone, this meant that the attitude could not be controlled anymore by the reaction wheels. The satellite went into thrustering mode, where the cold-gas thrusters are fired often to maintain the attitude within certain limits. However, this induces a lot of spurious signal on the tracking data that has to be accounted for in the orbit determination process. However, in general there is no accurate information available on the size and direction of the accelerations induced by the thrustering. Thus, like normal AMD events, the accelerations are described by so-called empirical accelerations. In the GEODYN II software, they can be in one of the three directions in the local satellite frame (radial, along- and cross-track), and they can be either constant, or periodic, with a period equal to the satellite orbital period. These latter accelerations are called once-per-revolution, or 1CPR. The total induced acceleration $a_i(t)$ in on of the directions ($i = 1, 2, 3$) is then described by:

$$a_i(t) = a_{i,0} + a_{i,11} * cos(n(t - t_0)) + a_{i,12} * sin(n(t - t_0)) \tag{1}$$

where n is the satellite orbital frequency ($n = \sqrt{GM/a^3}$), $t0$ the epoch reference time, and $a_{i,j}$ the constants that are determined from the data, with $a_{i,0}$ being the constant term and $a_{i,11}$ and $a_{i,12}$ the cosine and sine terms, respectively. Several of these sets can be estimated per arc, with different sets (and thus different values for the constants a_i per time-interval).

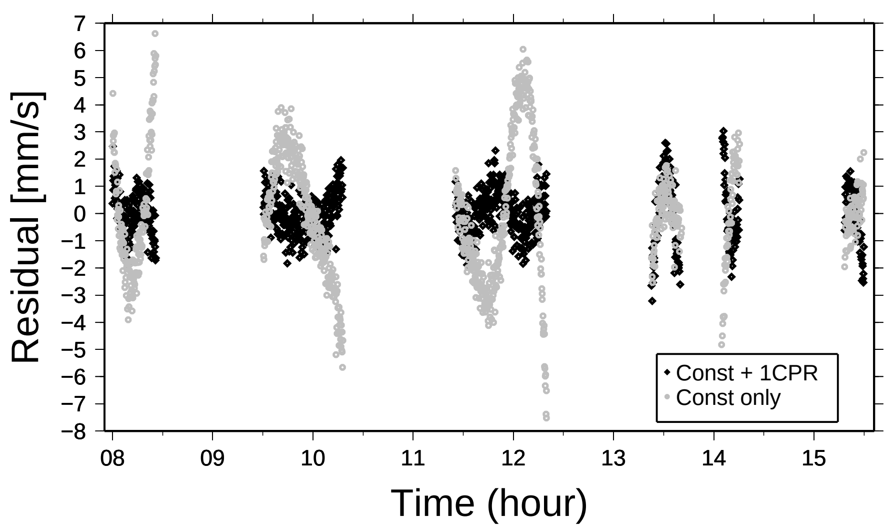


Figure 2. Residuals for one arc where different sets of empirical accelerations are tested. One uses constant accelerations only, and one uses 1CPR accelerations in along- and cross-track as well as constant accelerations in along-track and radial direction.

The influence of estimating empirical accelerations on the data fit is shown in Figure 2. This Figure shows Doppler residuals when different sets of empirical accelerations are used. One setup applies 1 CPR accelerations in along- and cross-track, and constant accelerations in along-track and radial direction, thus a total of 5 constants a_i following Equation (1), whereas the other setup uses only constant accelerations, in all three directions. In order to obtain a slightly better fit for this arc, there were two sets of these constant accelerations (one for the first, one of the second half of the arc, thus 6 constants a_i in total), whereas the setup with 1CPRs included only used one such set. The result is clear from the Figure: even if only constant accelerations are estimated, there is still a lot of signal left in the residuals. For comparison, the total RMS of the setup with 1CPRs included is 0.9 mm/s, whereas it is 2.3 mm/s for the setup with constant accelerations only. Accelerations with a 1CPR signature generally help to improve the data fit, since a lot of force mismodelling has it's largest power at the frequency of the orbital revolution (following linear perturbation theory[14]). Results for an arc without any empirical accelerations are not shown as the residuals were much larger for such an arc. The RMS of Doppler residuals was 0.1 m/s with a lot of signal left.

Since the satellite is in thruster-mode, and due to the configuration of the thrusters on the main bus of the satellite, it can be expected that most of the induced signal is in along-track. This makes the

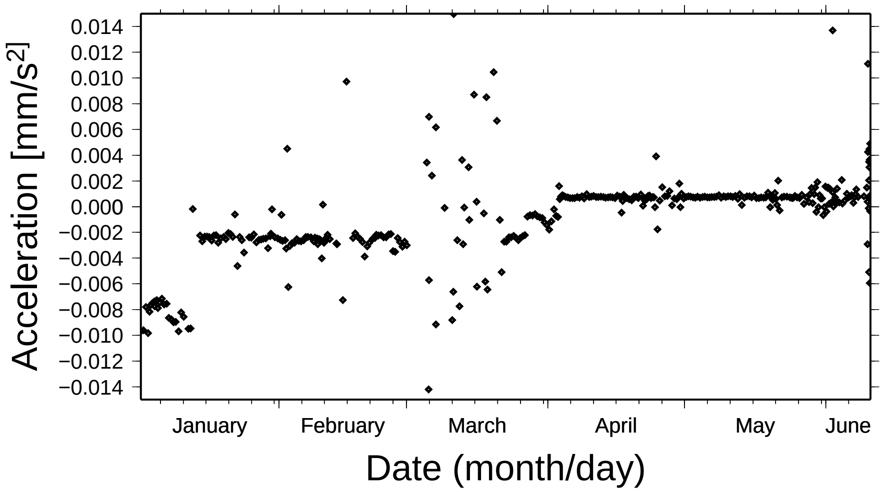


Figure 3. Values from orbit determination results for the constant acceleration in along-track during the extended mission of the main satellite of Kaguya.

constant acceleration in along-track especially interesting. Results for this constant as estimated in orbit determination are shown in Figure 3. This Figure shows that for long durations, the estimated constant along-track coefficient is essentially constant as well, meaning, it does not vary much with time. This was confirmed by Flight Operations, and the values presented here agreed very well with theirs [*H. Ikeda, JAXA, priv. comm., 2009*]. Figure 3 also shows distinct periods of constant accelerations, which also coincide with operations on the spacecraft, so it shows that at least a large part of the thruster-induced accelerations can be estimated. The varying results for the constant acceleration during March 2009 are due to there being periods where the main satellite switched from thrustering mode to control mode by (two) reaction wheels, with very short intervals for AMD events, typically once per revolution (~ 2 hours).

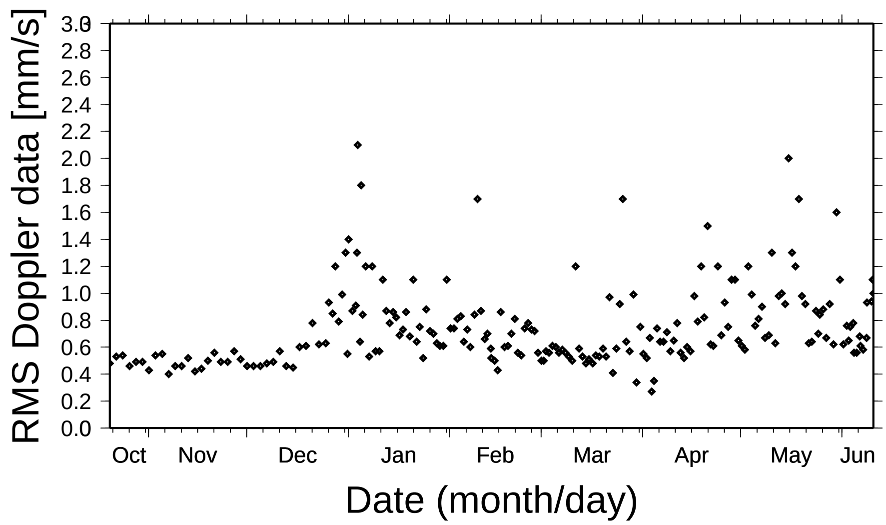


Figure 4. RMS of Doppler data fit during the complete extended mission, with some part of the nominal mission included as well for reference.

By employing these empirical accelerations in the orbit determination process, the whole extended mission data have been processed. The typical arclength was 1 day, where the arcs were chosen such that there was always data at both the start and end of the arc, to constrain the initial state vector. This often means that in between there are no tracking data, due to lack of coverage. Estimated acceleration parameters were 1 CPR along- and cross-track coefficients, and an along-track constant coefficient. In the case of tabulated AMD events (mostly during March 2009), per AMD event three constants were estimated. During the other arcs, the radial constant was left out. Multiple sets per arc were estimated: for most arcs, there were two sets of constants, but several arcs were difficult to fit with such a setup, and they generally had a better data fit with 3 or 4 sets. The used gravity model was SGM100h for data up to February 11 2009. After that, due to the lower altitude of the main satellite, the LP150Q[15] model was used, which is a 150x150 spherical harmonical model using all LP data extensively, and it is especially suited for low-altitude lunar satellite orbit determination as it contains a lot of high-frequency gravity information on the near side. Results for the RMS of data fit are shown in Figure 4.

This Figure shows that with the use of empirical acceleration parameters, the data fit level for the extended mission is not too different from that of the nominal mission, which is at roughlyn 0.5 mm/s or better.[3] Figure 4 shows an increase for the last part of the extended mission. This is due to lowering the altitude of the satellite.

With fewer tracking data, and thrustering, it is difficult to do orbit overlap analysis, because the lack of knowledge of the thrustering during parts without tracking data coverage deteriorates the orbit quality. However, all the arcs were connected in the sense that the start time of the next arc was the stop time of the previous one, so orbit comparisons at these connections can be done. Results for this is given in Section IV, where the usage of altimetry in the orbit determination process is discussed.

IV. Altimetry crossovers

One of the instruments onboard Kaguya was a laser altimeter, LALT, which measured the topography of the Moon.[6] In order to determine a high-accuracy map of the lunar topography, precise orbits are needed. Apart from that, the altimeter data themselves can also be used in the orbit determination process: at intersecting ground-tracks, essentially the same topography should be measured (assuming that for the Moon there are no temporal variations). This can be used as a constraint equation in the orbit determination process, where the distance between two ground-tracks is minimised.[7] For planetary orbiters, this has been used in the past on Mars using the Mars Orbiter Laser Altimeter MOLA, and it was shown that especially cross-track orbit consistency is improved.[7,8] Altimetry crossovers can also be used to calibrate the altimeter in terms of timing-biases and pointing biases.[7,16]

IV.A. Altimetry data and processing

LALT collected data continuously in both the nominal and extended mission, from the end of December 2007 until April 2008, and from February 12 2009 until the end of life of the main orbiter. LALT collected data at a frequency of 1 Hz, whereas MOLA collected data at 10 Hz. This means a vastly different data spacing in along-track direction, and fitting polynomials through 1 Hz data over the rough lunar surface will lead to substantial errors. Nevertheless, due to their inherent strength, employing the LALT crossovers in orbit determination is expected to lead to some improvements, which might then also lead to further improvements in the derived topography. And especially during the extended mission, with thrustering and few tracking data yet continuous LALT data, the crossovers might prove to be especially useful.

Since the GEODYN II software is used, crossovers are treated in the following way: around points where two ground-tracks intersect, a polynomial is fitted through each track. The shortest distance between the tracks is then computed, and this distance is minimised in the constraint equation that is fed back into the orbit determination iterations.[7] There are several criteria to choose that effect how the crossovers influence the final orbit: there is of course the data weight, and there are selection criteria for the RMS-of-fit of the polynomial, and the slope of the surface. The idea behind this is, if the fit to the polynomial is bad, that particular crossover might deteriorate the orbit. And over a rough surface, the crossover might also be not well-defined.

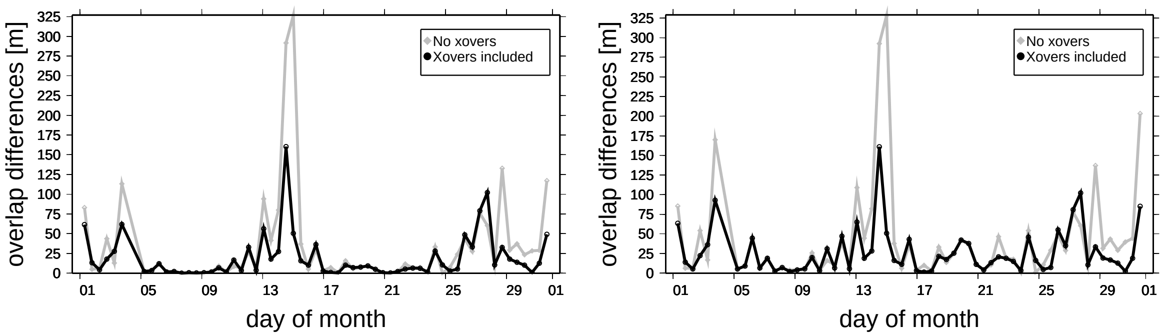
Kaguya is a polar orbiter, and this means that most ground-tracks are parallel and do not cross, except in the polar areas. This complicates the whole process, since a good data coverage over the whole of the Moon can not be achieved. Furthermore, due to the Moon's slow rotation, it takes about one month for a satellite to have a full coverage of the surface with crossings. This means that data are to be processed at one month at a time. Computationally, this means adding many arcs into one setup, and then having all these arcs interact with each other through crossovers. For Kaguya in particular, the 1 Hz data collection at the poles means an inherent handicap in terms of rougher areas where the data are collected and in terms of polynomial fit. Nevertheless, as a test setup, one month during the nominal mission and one month during the extended mission were processed to probe the effect of including crossovers on the orbit determination.

In the following two subsections, results for each are discussed.

IV.B. Nominal mission results

LALT data coverage in the nominal mission was from the end of December 2007 until April 2008. Here, one month of data, in January 2008, are processed. During this time, AMD events on the main satellite occured every 12 hours, so in total 65 arcs were selected that covered the month of January. Processing-wise this means that 65 separate (they are assigned different IDs internally, but of course they are the same satellite) main satellites were combined together in one setup, interacting through the altimetry crossovers. For January, a total of 22,056 crossover points were loaded. The actual number used in the final solution depends on edit criteria settings as discussed in the previous section.

In order to compute the influence of adding crossovers to the orbit determination process, orbit overlaps are computed. As pointed out earlier, for the main satellite this poses a problem due to the AMD events. When they are included in the arc, they disrupt the tracking data, and when they are not constrained by these data, the orbit quality deteriorates, and the orbit overlaps do not necessarily reflect the actual orbit quality that can be obtained by cutting the arcs around these events. So, here it was chosen to compute overlaps within a span of 12 hours, between AMD events, by choosing an arc length of 8 hours and thus creating a 4 hour overlap.



cross-track total root-sum-square

Figure 5. Overlap results for the main satellite for arcs in January 2008, comparing results with and without altimetry crossovers included. The label "xover" stands for crossover. Cross-track is the component that is affected the most, so that component along with the total root-sum-square RMS of orbit differences is shown.

Results for orbit overlaps created in this way in January 2008 are shown in Figure 5. Crossovers had a data weight of 40 m. The cross-track component is the one that is mostly affected, so that is shown together with the total root-sum-square of the RMS of the orbit differences per overlapping part. Along-track (not shown) also shows improvements, especially for some outliers that are present without the crossovers, and the radial direction (also not shown) shows only minor improvements. Compared to not including crossovers, Figure 5 shows great improvements for certain outlying peaks. From previous orbit overlap analysis and a comparison with results from the topography data it was found that these peaks correspond to arcs in an edge-on geometry, with sometimes some gaps in the tracking data.[3] Thus by including crossovers, the orbits for these particular parts are greatly improved.

These overlap results were created by deleting crossovers that had a polynomial RMS of fit higher than 25 m, or that had slope values larger than 0.1. This leads to about 4800 crossovers used in the solution, which is only about 20% of the total amount of 22,056 crossovers. Further inspection of the distribution of RMS of polynomial fit versus crossover discrepancy (the crossover residual so to say) did not produce a clear relationship between the two, suggesting that a higher RMS criterium can be used. This would lead to making use of more crossovers.

Figure 6 shows orbit overlap results as the total root-sum-square of the orbit differences for different slope and RMS of fit criteria. This Figure shows that the orbit overlaps can be further improved by changing the edit criteria, showing that indeed there is room for including data at higher slope values, or at a higher RMS of fit of the polynomial. From the point of view of orbit determination, this is fortuitous because the Moon is a rough body (high slope values) and at 1 Hz data collection the RMS of fit of a polynomial is expected to be high. Both Figures show the improvements to be had when altimeter data are included in the orbit determination.

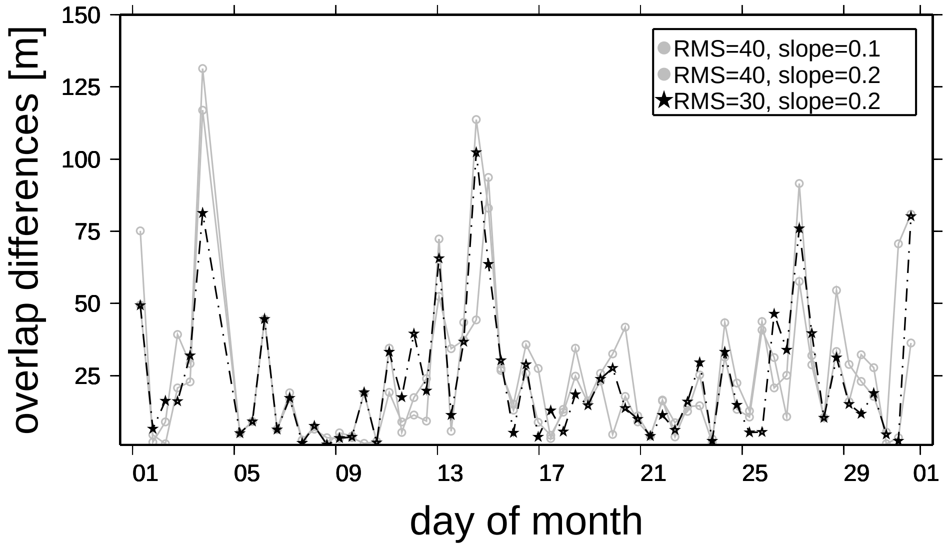


Figure 6. Total root-sum-square RMS of orbit differences for different slope and RMS criteria.

IV.C. Extended mission results

Extended mission data processing was discussed in Section III. Here, altimetry data are included next to the 2-way Doppler and range data to see their effect on the determined orbits. As mentioned earlier, due to the thrustering, doing orbit overlap analysis is difficult, because the effect of thrustering would be highly noticeable during the overlap. Instead, here it is chosen to inspect the connection at each subsequent arc. All included arcs are connected, so the orbit can be compared at the connection point. One should be warned not to infer too much from these results though, because that would be akin to doing statistical analysis on a sample set of one. Nevertheless, orbit differences at connection points can be instructive to get an overal feel for the orbit quality.

Data in April 2009 were processed. Arcs are now on average 1 day long, so a total of 30 satellites is processed at once. There again about 25,000 crossovers. The RMS edit criterium is turned off in this run, meaning, no points are edited out because of a bad polynomial fit. Slope data are edited out if the slope value is larger than 0.1. The crossover data weight is 40 m. Empirical accelerations that are estimated are one set per arc of 1 CPR along- and cross-track coefficients, and an along-track constant coefficient. The used gravity field is again LP150Q.

Figure 7 shows the orbit connection differences for this month with and without altimetry data. From this Figure it is immediately clear that the orbit consistency is vastly different from that in the nominal mission. Several km in along- and cross-track unfortunately are not rare, and the radial direction is also much worse at several tens of meters. It should again be noted that these are difference for only one point in time, but nevertheless, the size is remarkable. The Figure also shows that including the altimetry data drastically improves the orbit quality, again in mostly along- and cross-track, as expected. Several peaks in along-track direction are removed when crossovers are included, resulting in a much smoother connection-difference. So including the altimetry data definitely improves the orbit estimates for the extended mission. It remains to be seen however whether the orbits can be estimated precisely enough for the LALT data to be used in topography studies. Considering that there are almost 5 months of continuous data during the extended mission, taken at lower altitudes, this will certainly be pursued.

V. Conclusions and outlook

Results for orbit determination of the main satellite of Kaguya were discussed in this paper, by comparing Kaguya models with pre-Kaguya models, and by discussing particularities of processing the extended mission data. Special focus was put on using the altimetry data in the orbit determination process. Model comparisons show that the SGM100h model performs at a level very close to that of the LP100K model. SGM100h shows improved cross-track performance for arcs over the middle of the farside, owing to the use

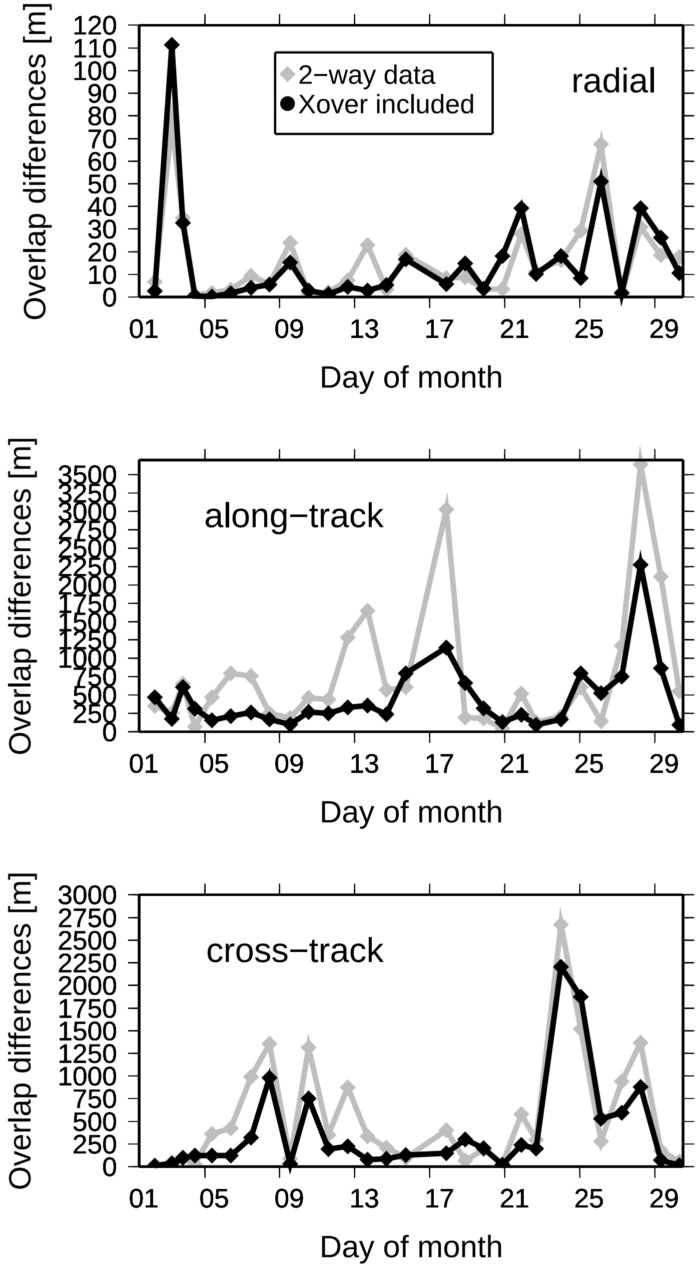


Figure 7. **Orbit differences at connecting points of adjacent arcs for April 2009 data, in all three directions. The label "xover" again stands for crossover.**

of 4-way data in that model. Despite not including the Lunar Prospector extended mission data in the official model, performance for polar orbits at 100 km is the same as that of LP100K, which does include these data (but obviously not the farside data). A preliminary test with an SGM model that did include these data shows further possible improvement in orbit overlap statistics. Future SGM models, especially those focusing on low-lunar orbit determination applications will include these data. Orbit overlaps show a precision level of typically better than 50 m at 100 km altitude.

The extended mission data are difficult to process due to a number of reasons: limited tracking data coverage, low altitude above lunar surface, and the satellite being in thruster-mode. By using empirical accelerations in the orbit determination setup, a good level of data fit (around 1 mm/s for the extended mission at low altitude) is possible. Estimated accelerations are coefficients for accelerations with a once-per-orbital-revolution signature (called 1CPR), in along- and cross-track, and a constant in along-track. If there were tabulated Angular Momentum Desaturation events, these were estimated with a constant coefficient in each of the three directions of the local satellite frame. Estimated along-track constant coefficients were shown to b mostly constant throughout the extended mission, showing that at least a large part of the thrustering is taken care off. Nevertheless, orbit overlap analysis remains difficult, which is why only connections at adjacent arcs were inspected. These connections showed discrepancies of up to several km in along-track and cross-track directions, showing that precise orbit determination for these data remains a challenge.

This challenge can be partly met by including data from the laser altimeter. Tests in the nominal mission phase showed improvements in especially along- and cross-track. Orbits that previously showed outlying orbit consistency due to orbit geometry (edge-on) and/or data sparcity are improved by including crossovers into the orbit determination. How to edit the crossover data remains an open issue, but tests showed possible improvements by adjusting several edit criteria, such as slope values and RMS of polynomial fit of the laser ground-track. For the extended mission data, the crossovers also improved the orbit consistency in both along- and cross-track.

In the future, applying crossovers in the orbit determination will be continued. In the nominal mission phase, they may be used to further improve gravity field determination, although computationally this is rather expensive. In the extended mission phase, they are a necessity if at least a reasonable level of orbit quality is to be used. Even then, it remains a question whether the derived topography data can be used in topography models, due to the inherent absence of quality of the orbit solutions. Finally, since altimetry data are also sensitive to adjustments in the attitude and to timing-biases on those data, this will also be further investigated, possible improving the results further, making the altimetry data even more useful.

Acknowledgments

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