Kaguya Orbit Determination from JPL

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Selene (re-named 'Kaguya' after launch) is an unmanned mission to the Moon navigated, in part, by JPL personnel. Launched by an H-IIA rocket on September 14, 2007 from Tanegashima Space Center, Kaguya entered a high, Earth-centered phasing orbit with apogee near the radius of the Moon's orbit. After 19 days and two orbits of Earth, Kaguya entered lunar orbit. Over the next 2 weeks the spacecraft decreased its apolune altitude until reaching a circular, 100 km altitude orbit. This paper describes NASA/JPL's participation in the JAXA/Kaguya mission during that 5 week period, wherein JPL provided tracking data and orbit determination support for Kaguya.

Nomenclature & Acronyms

critical maneuver = spacecraft ΔV that must occur at a scheduled time without incurring large penalties
delivery requirement = accuracy in state that a spacecraft must attain at a specific time

desat	=	momentum wheel de-saturation impulse
AMD	=	angular momentum dump (synonym to *desat*)
DCO	=	(tracking) data cutoff
DSN	=	Deep Space Network
DSS	=	Deep Space Station
HGA	=	high gain antenna (X-band)
JAXA	=	Japan Aerospace Exploration Agency
JPL	=	Jet Propulsion Laboratory
LOI	=	Lunar orbit insertion
OD	=	orbit determination
ODF	=	orbit data file (calibrated DSN tracking data file)
S-ANT-B	=	low gain antenna "B" (S-band)
SECO2	=	the second (and final) second stage engine cutoff
SRP	=	solar radiation pressure
TCA	=	time of closest approach
UTC	=	Universal Time, Coordinated

I. Introduction

SELENE (SELenological and ENgineering Explorer) is the first large, lunar, probe from Japan. The mission objectives are to acquire scientific data of the Moon's evolution and to test technology for future lunar exploration.

Selene (re-named 'Kaguya' after launch) was launched on September 14, 2007 by the H-IIA rocket from Tanegashima Space Center, Kagoshima Prefecture, Japan. (The launch had slipped one month from the first scheduled launch time (August 16) due to an electrical component failure.) The H-IIA placed Kaguya into a high Earth-centered phasing orbit with apogee near the radius of the Moon's orbit. After 19 days and two orbits of Earth, Kaguya was inserted into a polar, elliptic, lunar orbit. Over the next 2 weeks the spacecraft decreased its apolune altitude until reaching the final (approximately) circular orbit of 100 km altitude.

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II. Background

JAXA collaborated with NASA on this mission because of the DSN's worldwide network of large tracking antennas. With its network, the DSN was able to maintain around-the-clock contact with Kaguya, a capability that eluded JAXA because its large ground antennas are limited to a single longitude band (i.e. on Japanese soil). JAXA scheduled most critical events (e.g. spacecraft maneuvers) to occur within view of its tracking stations, but due to the latency of mission timelines and spacecraft delivery requirements, DSN coverage was still valuable.

NASA recruited JPL for launch acquisition and initial orbit determination since the DSN would acquire Kaguya tracking data first (at DSN's Madrid complex, ~1 hour after launch versus ~12 hours later for JAXA's initial acquisition of signal at its Usuda station). In addition to this initial acquisition support, two major OD deliveries to JAXA were needed within 12 hours of launch. Moreover, because of numerous spacecraft maneuvers throughout cruise phase (almost all of them critical), JPL was asked subsequently to lead the orbit determination task from low Earth orbit to low lunar orbit. The JAXA/Kaguya flight dynamics team performed back-up OD during this same time span; they were also responsible for all maneuver designs.

A. Spacecraft Description

A view of the Kaguya orbiter is given in Fig. 1. It is a large spacecraft, with 15 science instruments. The orbiter consists of a mission module, a propulsion module, and a single, solar panel. Science instruments are in the mission module; they are used for global mapping of the lunar surface. The lower third of the bus (the left end in the figure) is the propulsion module. The bus is 3-axis stabilized. Momentum wheels orient the vehicle and the accumulated momentum is dumped periodically using attitude control thrusters.

At the right end of the bus in Fig. 1 are two sub-satellites: a relay satellite ("Rstar") and a radio science satellite ("Vstar"), both released after arrival at the Moon. Rstar is released first, followed a few days later by Vstar. Rstar is used to measure the lunar gravity field using 4-way doppler between the bus and Earth, and the Vstar-Rstar pair are used to perform differential VLBI observations. Both sub-satellites are spin-stabilized after release.

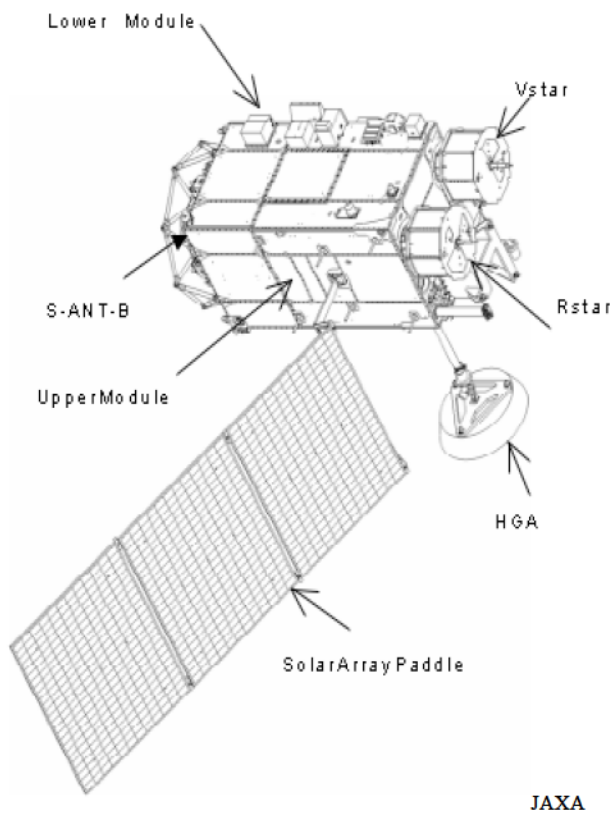


Figure 1. View of Kaguya Spacecraft

Dimensions:
- bus: length = 4.2 m,
  - end = 2.1 x 2.1 m
- sub-satellites: height = 0.66 m,
  - diameter = 1.0 m,
- solar array: length = 7.3 m,
  - width = 3.2 m
  - power = 3.5 kW

Mass: wet = 3020 kg (with sub-satellites),
dry = 2000 kg (no sub-satellites),
sub-satellites: 45 kg each,

Tracking subsystem: S-band (via one of four different low-gain antennas, *e.g.* S-ANT-B, shown in Fig. 1),

Telecom subsystem: X-band (via HGA, shown in Fig. 1),

Propulsion subsystem: main engine = 547 N (bi-propellant),
attitude control & maneuvering thrusters = 20 N each, total of 12 thrusters (hydrazine),
roll control thrusters = 1 N each, total of 8 thrusters (hydrazine)

B. Deliverable and Receivables

The JPL Navigation team deliverables to JAXA consisted of three products: a calibrated tracking data file

(ODF), a converged spacecraft trajectory, and two covariance files. The deliverables were placed on a secure NASA network server at scheduled times and JAXA retrieved those products from that server. (Raw, uncalibrated DSN tracking data with a latency of ~20 minutes were also available to JAXA from the same server.)

The start and end times of the delivered products were defined by JAXA, as were covariance times and formats. The delivery times were not expected to change as the mission progressed (and they did not) because the Kaguya flight dynamics team did not optimize the spacecraft trajectory. (Kaguya had significant propellant reserves.) Thus it was elementary for JPL to automate product deliveries.

In a reciprocal arrangement, JPL had access to JAXA range and range-rate tracking data (also via the network server). Calibrated tracking data from JAXA's tracking station (usually the Usuda station) were placed on the server ~3 hours after the end of each pass.

III. Launch and Early Operations

A. Pre-launch Predictions

Pre-launch analysis had already determined that early Madrid tracking could generate a satisfactory spacecraft ephemeris after launch, thereby facilitating secondary acquisition of the spacecraft at the DSN's next set of antennas. It was expected that approximately one hour of tracking data from DSN Madrid would suffice to locate Kaguya within the antenna beam width at Goldstone, when Kaguya rose above the horizon at Goldstone. See Figures 2 and 3 for the Earth ground track of Kaguya.

For conservative mission planning reasons, initial acquisition of signal was planned to occur at Madrid via specialized acquisition antennas (beam width = ±5°). For a nominal launch however, the 26-meter deep space antenna at Madrid would be able to acquire the signal immediately (beam width ±0.17°).

B. Initial Acquisition

Lift-off of the H-IIA occurred on schedule at 1:31:01 UTC, September 14 (6:31 pm PDT, Sept 13). The injection orbit elements provided by JAXA before and after launch are shown in Table 1, along with JPL's calculation of the same quantities from DSN tracking data. Spacecraft injection time was 2:15:03 UTC (i.e. the final, second stage engine cutoff) at an altitude of 290 km. Spacecraft separation occurred at 2:16:35 UTC (altitude = 375 km). The pre-launch JAXA elements were more accurate than the update from them shortly after launch (using the 5th column as "truth").

DSN's acquisition of signal occurred at 2:39:49 UTC from their two Madrid stations (DSS-54, DSS-66). The signal was acquired in the main beam of DSS-66 without need of any acquisition-aid antenna (i.e. the launch was very nearly nominal). Auto-track angle tracking data was gathered for 25 minutes followed by two-way doppler, starting at 3:04:00 UTC.

Table 1: H-IIA Injection Orbit, Altitude = 290 km, 3σ
EME2000

	JAXA pre-launch nominal	JAXA 2.5 hr after launch	JPL 2.5 hr tracking data	JPL 9 hr data, ΔVc1
a (km)	122885.152	123172.285	122983.015	122967.890 ± 5.52
e	0.9457998	0.9459339	0.9458331	0.9458307 ±3.6e-6
i (°)	29.9747	29.9382	29.9686	29.9654 ± 6.9e-3
Ω (°)	52.5306	52.5869	52.5365	52.5348 ± 8.1e-3
ω (°)	243.6264	243.5633	243.6287	243.6151 ± 6.9e-3
M (°)	0.1252	0.1252	0.7007	0.7008 ± 0.1200

Injection accuracy is shown in Table 2 -- it compares the nominal trajectory (column 2 in Table 1) with the launch reconstruction (column 5 in Table 1). The difference between the two columns is shown in Table 2 in terms of fractions of the H-IIA injection covariance (column 2 in Table 2). (The "P" in Table 2 denotes orbital period.) Table 2 shows that injection targetting was nearly nominal (all parameters are sub-sigma except for i – which was offset by less than 2σ).

The Earth ground track of the boost phase is shown in Fig. 2. The track in Fig. 2 ends where the spacecraft separated from the launch vehicle. Figure 3 shows the Earth track of the spacecraft on the first day, beginning at SECO2 near where Fig. 2 ends. Figure 3 also shows the tracking station coverage on the first day, as well as the

location of the first maneuver, ΔVc1.

Table 2: H-IIA Injection Accuracy, Altitude = 290 km
EME2000

	1σ *A priori* Uncertainty (Injection Covariance)	Injection Error multiples of "σ"
a	558.55 km	0.15
e	0.0002477	0.13
i	0.0055492°	1.68
Ω	0.1115133°	0.038
ω	0.0987950°	0.11
M	0.0035018°	0.97
P	2923 s	0.15

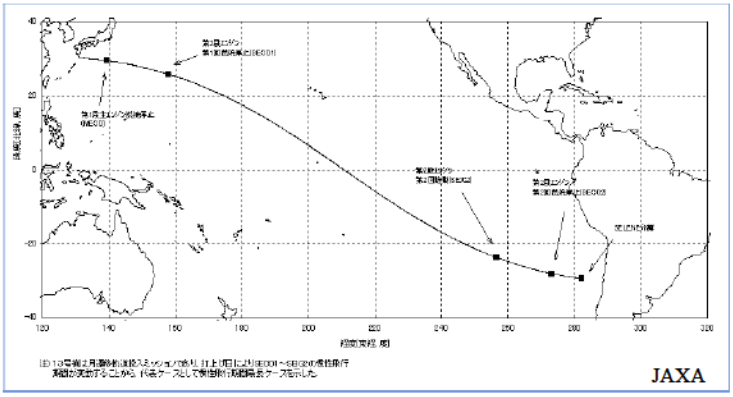


Figure 2. H-IIA Earth track

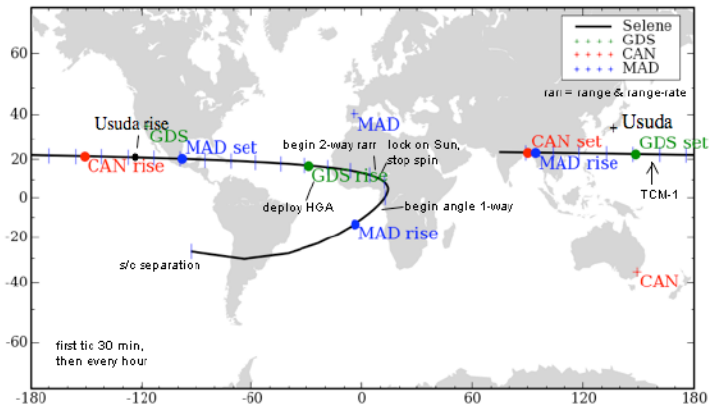


Figure 3. Kaguya Earth track on Launch Day

Shortly after spacecraft separation from the booster, Kaguya transitioned from a 4 revolution per hour spin-stabilized attitude to 3-axis control. The spin-stop event occurred at 04:18:30. The tracking data residuals for that event are shown in Fig. 4. Other spacecraft events are also shown in Fig. 4; those events are addressed in the following sub-section.

The near-nominal injection resulted in an easy tracking acquisition by DSS-66 (beam width = ±0.17°). Table 3 shows the results of this acquisition at Madrid, and Table 4 shows similar results for the secondary acquisition at Goldstone. Since the beam width at Goldstone's DSS-24 station is ±0.12°, the pre-launch spacecraft ephemeris also

exceeded requirements there (the offset of the trajectory from the center of the beam was only 0.005°).

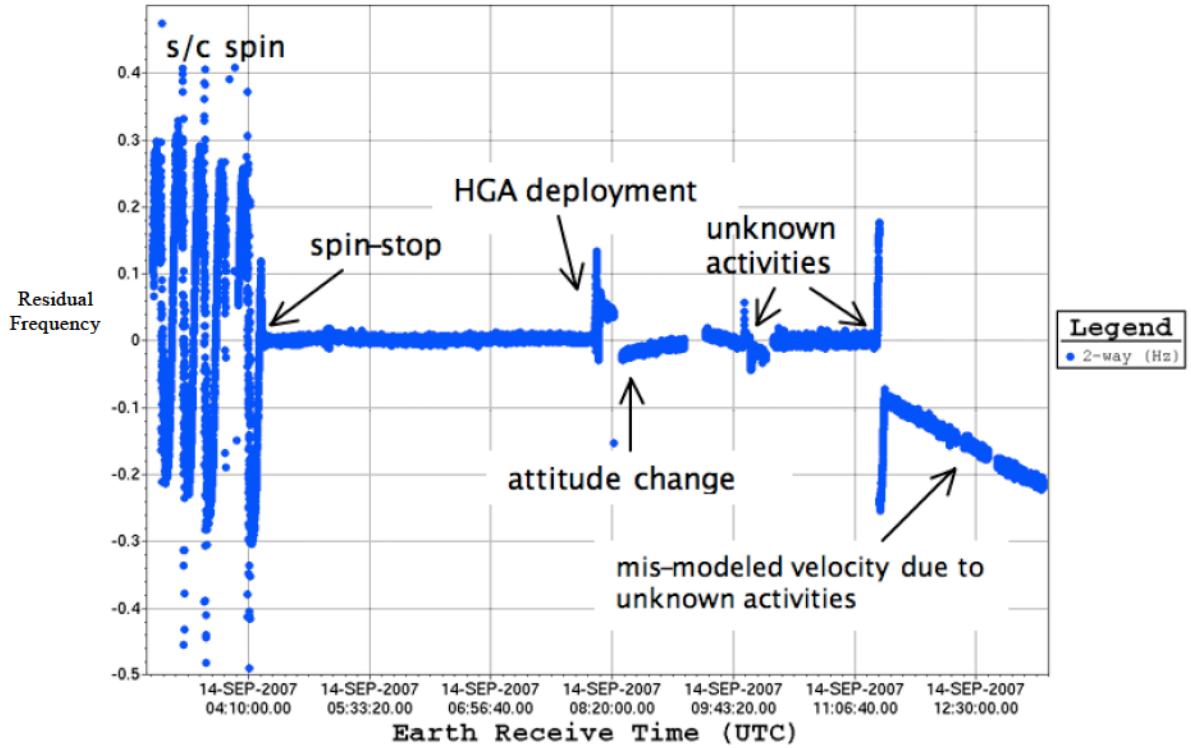


Figure 4. Transition from Spinning s/c to 3-axis Stabilized Attitude

Table 3: DSN Acquisition
Madrid DSS-66, Sept 14 (for 5° elevation)

	Prediction pre-launch nominal	Actual Reconstruction
Rise time (UTC)	02:39:08	02:39:12*
Azimuth (°)	181.36	181.39

* on launch day, acquisition of signal was reported at 02:39:49 (when elevation = 6°)

Table 4: DSN Acquisition
Goldstone DSS-24, Sept 14 (for 6° elevation)

	Prediction DSN Delivery	Actual Reconstruction
Rise time (UTC)	07:58:17.35	07:58:15.46
Azimuth (°)	76.75	76.76

C. Meeting the Goldstone Pointing Requirement

The spacecraft ephemeris was known well enough after 35 minutes of tracking to satisfy the secondary acquisition pointing criteria at DSN Goldstone. Yet the JPL team had difficulty converging those 35 minutes of tracking data. It turned out the spacecraft was very active during the first half-day of tracking (refer to Fig. 4 again). Doppler tracking data indicated more activities occurred than were listed on the official Schedule of Events (i.e. the schedule that was available to JPL), leading to mis-modelling. In order to accommodate the (inferred) activities, the tracking data was de-weighted, thereby inflating the spacecraft state uncertainty that in turn yielded larger uncertainties for the Goldstone delivery. Nevertheless despite the mis-modelling, spacecraft ephemeris knowledge still satisfied the Goldstone pointing requirements after only 35 minutes of tracking.

IV. Cruise Phase

A. Trajectory

The trajectory to the Moon is shown in Fig. 5 and Fig. 6. Those views represent the trajectory reconstruction determined from tracking data. Maneuver locations are indicated in the figures.

The fidelity of the trajectory is compared with the nominal, pre-launch, reference trajectory in Fig. 7. The significant difference between these two trajectories is a timing error, which was corrected at trajectory correction maneuver ΔVp1. (Perigee time changed by 15 minutes.) The plot indicates that the earlier correction burns ΔVc1 and ΔVa1 (neither shown in Fig. 7) did not correct all injection errors, leaving *period* to be corrected at perigee with ΔVp1. Another period correction occurred on the next orbit at ΔVp2. (ΔVc1 corrected H-IIA injection errors as well as correcting inclination. ΔVa1 adjusted perigee altitude in order for ΔVp1 to implement a period change.)

B. Tracking Data

In quiet cruise, the *a priori* metric accuracy of DSN S-band 2-way coherent range-rate tracking data was routinely set to 0.25 mm/s. Range data was routinely assigned 2 m uncertainty, and for some passes could be set to 1 m. Usuda station's 2-way range-rate data tended to be noisier than DSN's (but without any systematic bias) so the JAXA doppler uncertainty was set between 0.5 and 1.0 mm/s. We did not fit JAXA range data because it was inconsistent with DSN range.

C. OD Modelling

The JPL team provided only orbit determination support. With this interface we were obliged to align our models as closely as possible with the JAXA models, insofar as that was possible. For example, JAXA used a simple bus model for solar radiation force and so we used that too.

The following list briefly summarizes the models employed in the OD: spacecraft epoch state, SRP bus model, momentum wheel de-saturation impulses, and stochastic non-gravitational accelerations. The complete OD model is provided in Appendix 1.

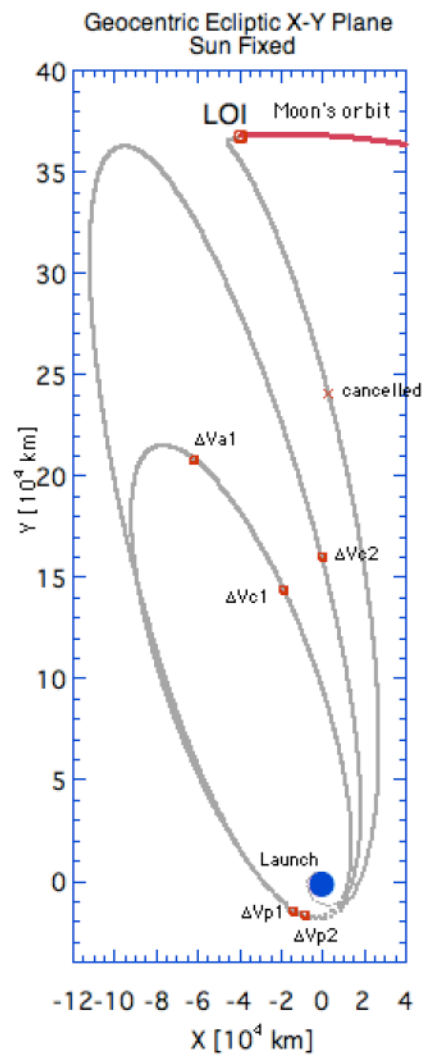


Figure 5. Transfer Orbit to Moon, Ecliptic View

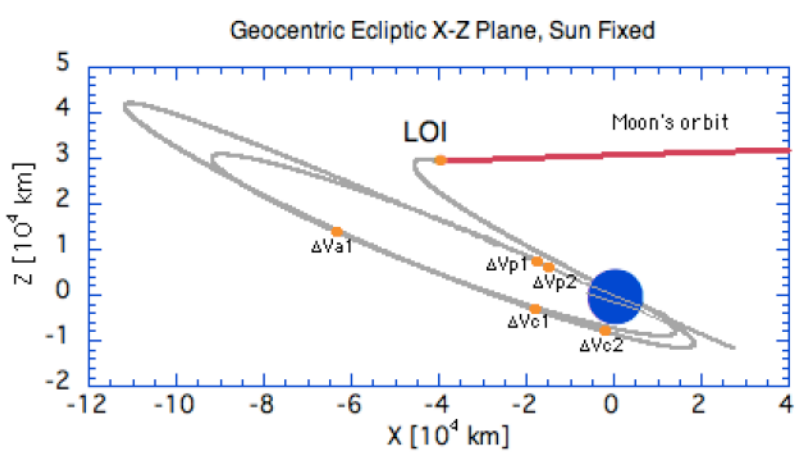


Figure 6. Transfer Orbit to Moon, Side View

D. Momentum Wheel De-saturation Impulses

Momentum wheel de-saturation ΔVs (desats) occurred daily, autonomously, with a typical duration of ~15 minutes, and imparted a net ΔV magnitude to the spacecraft on the order of 10 cm/s. (The thrusters performing the AMDs were unbalanced.) JAXA would notify JPL *a posteriori* of the begin and end times approximately 6-8 hours after each desat (since the AMDs were autonomous, their times were not scheduled and were not known in advance), and JPL would subsequently add that event to the dynamic model. No *a priori* AMD magnitudes were provided. Appendix 2 lists estimated AMD magnitudes during the cruise phase as well as showing a representative AMD residual plot.

Desaturation events continued after lunar orbit insertion. In the orbit phase they increased in frequency (about twice per day) but decreased in magnitude.

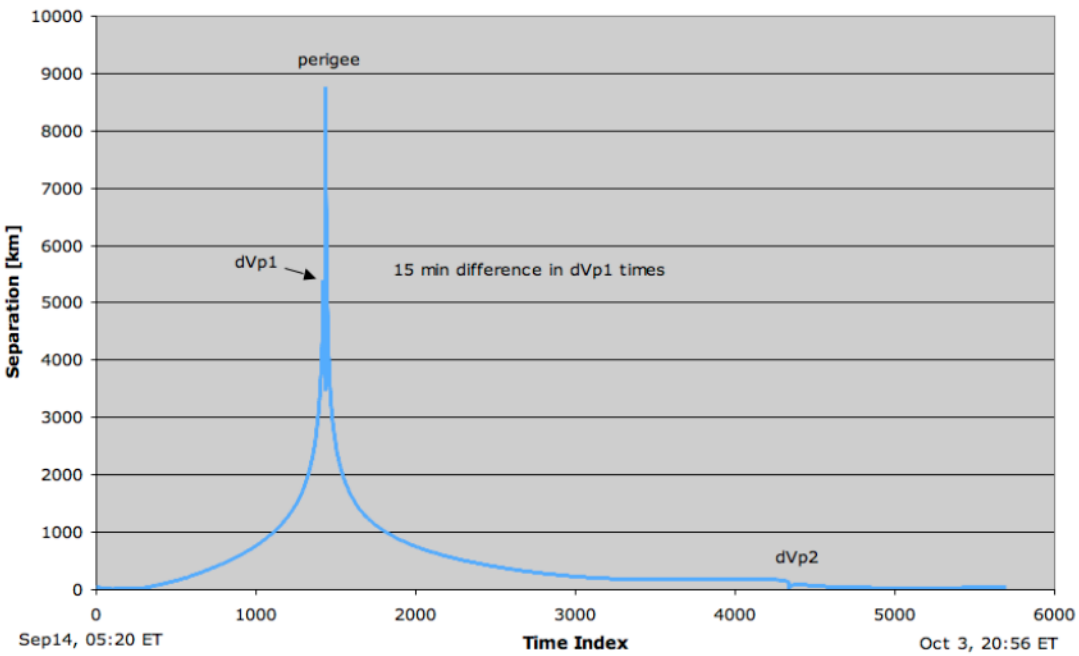


Figure 7. Difference Between Actual Trajectory & Pre-launch Ref. Trajectory

E. Maneuver Schedule

Trajectory correction maneuvers (both cruise and orbit) and sub-satellite release times are listed in Appendix 3. JPL did not normally reconstruct maneuvers because we did not have the resources to perform this function.

F. Maneuver Monitoring

Real-time monitoring of the downlink signal was performed during critical events. JAXA valued this feedback because it provided immediate confirmation of event activities e.g. spin-stop times and maneuver start/stop times. Since all maneuvers occurred over Usuda (which controlled the uplink), the monitoring activity used 3-way doppler between Usuda and DSS-34. Figure 4 is an example of this tool's output, as are the doppler residuals from the lunar orbit insertion burn shown in Fig. 8, and the figure shown in Appendix 2. The residual points are computed with respect to an *a priori* reference trajectory, and are displayed as they arrive, point by point.

We noticed that the display could be compromised while operating in a cross-agency mode (ordinate should be centered on zero if the reference trajectory is current). For the monitoring tool to generate zero-bias residuals, the DSN shift operators needed to query Usuda station for its uplink frequency (which varied slightly from pass to pass) and tune DSS-34 appropriately. If tuning was overlooked or ignored by the operators, then the resulting display showed an aesthetically undesirable bias (although this bias did not degrade the maneuver assessment function).

G. Earth Swing-bys

The results of the two Earth swing-bys are shown in Tables 5 and 6. JAXA provided nominal aim points before launch. The JPL team was not notified of any update to the aim points after launch, but we suspect the aim points

did change. Compare the Achieved column with the Target column in Tables 5 & 6. Both swing-bys were higher than the nominal targets by tens of kilometers. A 15-minute change in the time of closest approach was needed at the Earth-1 swing-by in order to return the spacecraft closer to the reference trajectory.

Table 5: Earth-1 Swing-by, 3σ

	Target pre-launch nominal	Achieved
Radius (km)	7381.6	7414.8 ± 0.039
Lat (°)	-26.533	-26.496 ± 3.3e-4
E. Long (°)	291.724	269.240 ± 1.62e-3
TCA (UTC)	Sept 19, 1:55:08	Sept 19, 1:40:01

Table 6: Earth-2 Swing-by, 3σ

	Target pre-launch nominal	Achieved
Radius (km)	8576.4	8622.4 ± 0.090
Lat (°)	-26.660	-26.647 ± 9.6e-4
E. Long (°)	291.550	228.258 ± 4.5e-3
TCA (UTC)	Sept 29, 3:43:41	Sept 29, 3:43:33

V. Orbit Insertion Phase

A. Lunar Approach

The results of the lunar approach are shown in Table 7. The achieved b-plane position was ~0.2σ from the delivery prediction. The delivery missed the B•T target by 7 km (due to AMDs), but this was insignificant and could be accommodated in the LOI design. For reference, the LOI burn began at 20:55 UTC on October 3.

Table 7: B-plane, 3σ
Moon-Mean-Equator on 2007/10/3 UTC

	Target pre-launch nominal	Revised Target after canceling ΔVc3	Delivery DCO Oct 3, 9:00	Achieved
B•T (km)	92.00	64.29	71.13	71.52
B•R (km)	-5540.13	-5533.39	-5533.95	-5534.25
SMA (km)	--	--	1.92	0.15
smi (km)	--	--	1.83	0.010
θ (°)	--	--	93.9	92.5
TCA	21:06:25	21:07:04.1	21:07:10.2 ± 1.2 s	21:07:10.5 ± 0.032 s

The performance requirement levied by JAXA before launch was to deliver Kaguya with a perilune altitude error less than ±10 km, 3σ. Pre-launch analysis indicated that this requirement would be satisfied by greater than a factor of 3. Table 8 shows that this requirement was exceeded at the Moon by almost an order of magnitude.

Table 8: LOI Delivery Uncertainty, 3σ

	Requirement	Prediction pre-launch nominal	Delivery DCO Oct 3, 9:00
Altitude (km)	99 ±10	98.9 ± 3.0	95.9 ±1.2
TCA (s)	none	±1.9	±1.2

B. Lunar Orbit Insertion

Lunar orbit insertion occurred on October 3 between 20:54:49 and 21:19:49 UTC. The maneuver began with a

"settling period" of 40 seconds, which was a warm-up activation interval. The hot burn started at 20:55:29 UTC. The spacecraft traveled through 95° of true anomaly while performing LOI. The plan for the spacecraft was to maintain a fixed attitude during the burn (i.e. no pitching).

Figure 8 shows doppler residuals for LOI. The expected line-of-sight frequency for a nominal burn with nominal pointing was ~320 hz. The burn signature shown in the figure confirms orbit insertion, since the observed frequency shift is ~318 hz. The observation indicates that the burn was probably slightly "cold" (under-burn) although it is difficult to determine with certainty because of all the uncertainties associated with this event. The residuals after the end of the burn are not horizontal because the resulting orbit period differs slightly from the targetted orbit.

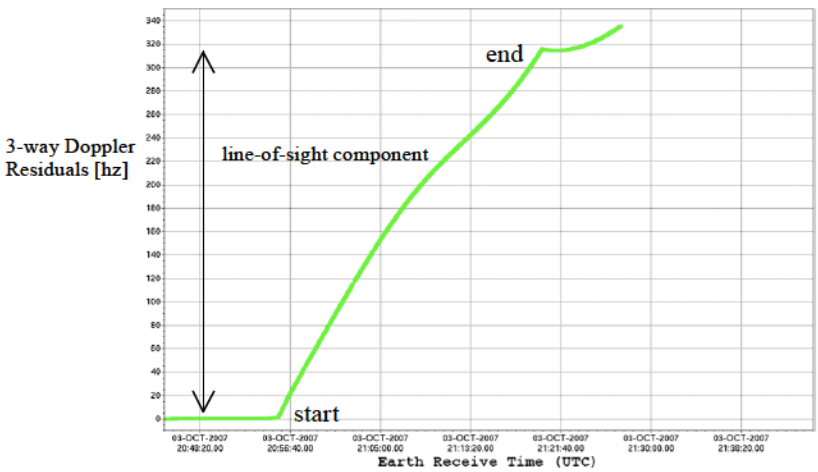


Figure 8. Lunar Orbit Insertion Burn

A preliminary LOI reconstruction from tracking data is given in Table 9. Orbit insertion occurred in view of Usuda, so 2-way tracking was not available to JPL at that time. Therefore for this reconstruction JPL used Usuda 2-way tracking data available from the file-server. Our solution yields a small over-burn (~0.05σ), with a pointing error of 0.3° (~0.3σ). Note: the *a priori* nominal maneuver profile specified constant thrust and attitude, although that is probably incorrect as integrating the burn with those nominal parameters will verify. Data residuals for the LOI reconstruction are shown in Fig. 9.

Table 9: LOI-1 Burn Estimate, 3σ
EME2000

	A priori Nominal	JPL Reconstruction
Duration (s)	1460	1460
Thrust (N)	547.0 ± 11	547.2 ± 0.2
Right Ascension (°)	211.9 ± 2.5	211.7 ± 0.1*
Declination (°)	35.5 ± 2.5	35.68 ± 0.05*
ΔV (m/s)	298.79 ± 6.0	298.9 ± 0.1

*at start of burn

We presume JAXA's reconstruction utilized spacecraft attitude and accelerometer data from telemetry to constrain their solution. They estimated LOI to equal 298.43 m/s ± 1.11 (3σ) (which is 0.1% low, or ~0.2σ) with a pointing error of 0.2° (~0.2σ) [2]. No reconstruction of pointing components has been published by JAXA.

Thirty minutes of 3-way tracking data from the Canberra station immediately after LOI provided initial orbit pointing parameters for the DSN antennas. That pointing prediction remained robust until the end of the Canberra pass. JAXA, which retained the uplink at that time, did not provide pointing predictions for the upcoming DSN Madrid and Goldstone stations. So sometime after the Canberra pass, the pointing prediction file became stale. The stale predictions eventually led to a degraded downlink at Goldstone, which wasn't rectified until ~1 hour after Goldstone rise, resulting in the loss of ~1 hour of tracking data to JAXA. (This was important because Kaguya's mission plan was set up with little schedule margin, with its first post-LOI maneuver planned for LOI + 50 hours.)

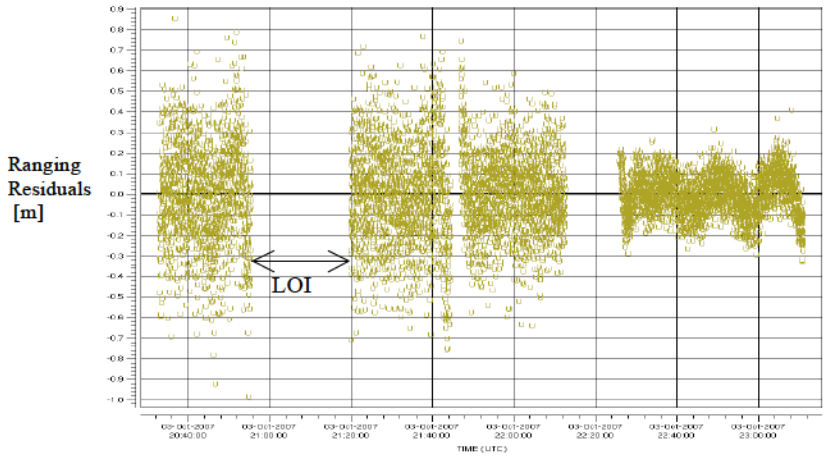


Figure 9. Tracking Data Around LOI

The initial Kaguya orbit determined 18 hours after LOI is shown in Table 10. These results verify that the target orbit was achieved for most parameters. The ascending node was missed by 83°, but this deviation may not be significant for this orbiter. It will affect the sequence of events and observations planned for the orbiter during the science phase.

Table 10: Post-LOI Lunar Orbit
Moon-centered MME, 3σ

	Pre-launch Nominal	Reconstructed DCO: Oct 4, 15:41 UT
a (km)	7688.7	7667.8 ± 0.72
e	0.76051	0.76037 ± 6.e-6
i (°)	89.065	89.342 ± 1.2e-4
Ω (°)	274.88	192.061 ± 9.0e-6
ω (°)	131.88	131.627 ± 9.0e-4
M (°)	4.8001	39.920 ± 3.0e-4
P (hr)	16.8	16.7 ± 0.03
h_a (km)	11,798.0	11,762 ± 72
h_p (km)	103.4	99.914 ± 17.442

VI. Circularization Phase

Seven circularization burns occurred in the 2 weeks following LOI. After completing these maneuvers the science orbit was achieved on October 18. All orbit correction maneuvers performed remarkably well, resulting in the cancellation of ΔVloi5d and ΔVloi5e. Appendix 3 tabulates the seven maneuvers. A Moon-centered view of the circularization phase is shown in Fig. 10.

The two sub-satellites were dropped off in intermediate orbits approximately three-quarters of the distance to the final orbit configuration. Rstar was placed in an orbit with about twice the apolune height as Vstar. Their orbits are shown in Fig. 11 and described in Table 11. Note that no tracking data from these sub-satellites were made available to JPL. The orbits established here were calculated from the state of the spacecraft bus at the time of release.

A data arc of 70 minutes was used for the Rstar solution and 300 minutes for Vstar. The arc lengths were defined (and limited) by adjacent spacecraft dynamics. The formal uncertainties for Rstar are larger than Vstar because of its shorter data arc. The inclination of Rstar is inconsistent with all other orbit solutions in this subsection, so its formal uncertainty is almost certainly too small.

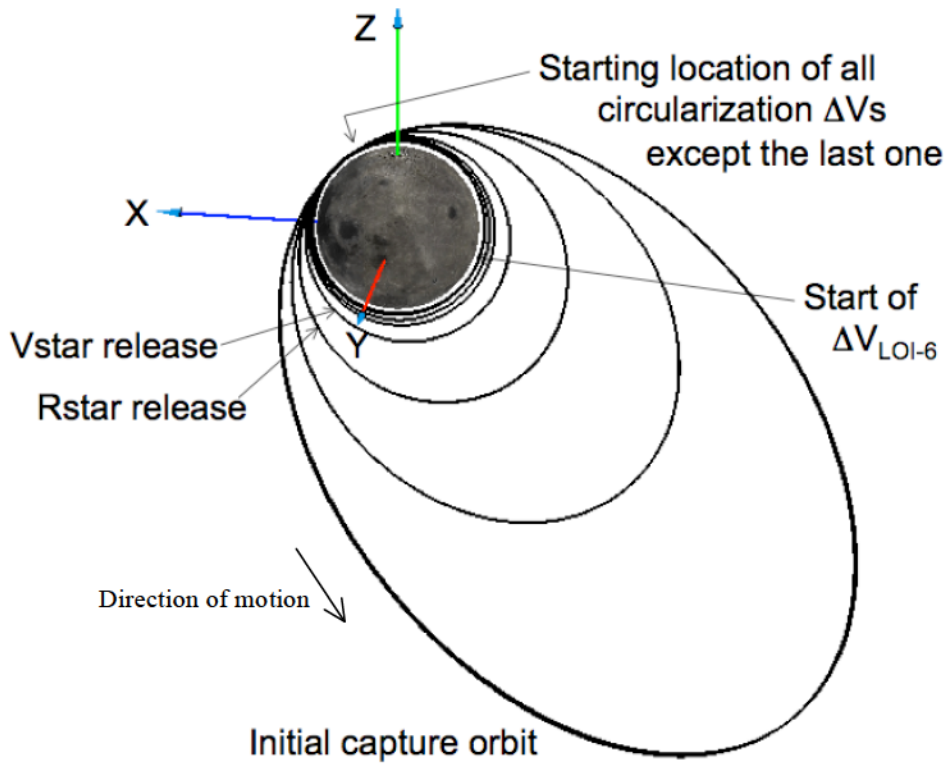


Figure 10. Circularization Orbits, Moon-centered J2000

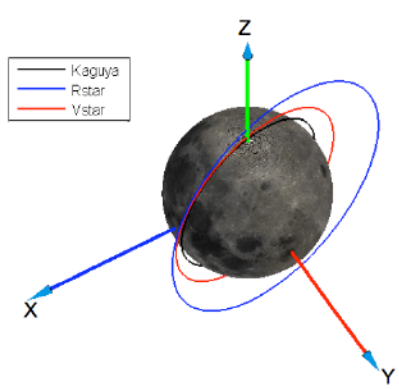


Figure 11. Mission Orbiters, Oct. 21 2007 Moon-centered MME

Table 11: Sub-satellite Orbits
Moon-centered MME, 3σ

	Rstar epoch: Oct 9 00:38	Vstar epoch: Oct 12 04:28
a (km)	3005 ± 10	2197 ± 2
e	0.379 ± 0.002	0.1519 ± 0.0004
i (°)	90.3 ± 0.2	91.88 ± 0.02
Ω (°)	196.8 ± 0.2	196.57 ± 0.02
ω (°)	136.9 ± 0.3	135.7 ± 0.2
M (°)	67.2 ± 0.2	93.4 ± 0.1
P	4.11 hr ± 84 s	2.568 hr ± 9 s
h_a (km)	2407 ± 18	794 ± 2
h_p (km)	130 ± 6	127 ± 2

VII. Science Phase

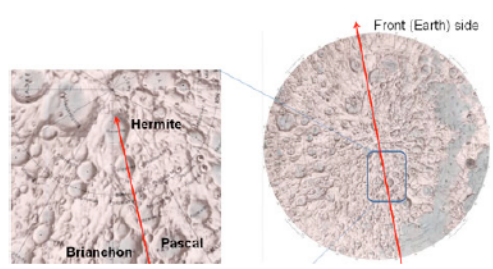
The science orbit achieved on October 18 is a 100 km high, nearly circular orbit. See Table 12.

Table 12: Science Phase Lunar Orbit
Moon-centered MME, 3σ

	JAXA pre-launch nominal	Achieved epoch: Oct 19, 23:26 UT
a (km)	1836.9	1839.6 ± 0.0006
e	0.01009	0.010645 ± 3.3e-6
i (°)	89.5061	91.2035 ± 2.6e-4
Ω (°)	69.554	196.439 ± 8.0e-5
ω (°)	200.03	217.52 ± 1.8e-2
M (°)	200.61	180.0 ± 0.015
P	1.96 hr	1.9667 hr ± 0.003 s
h_a (km)	117.4	121.7 ± 0.006
h_p (km)	80.40	82.90 ± 0.006

A photo of the lunar surface from the science orbit is shown in Fig. 12, and a corresponding map in Fig. 13 illustrates its Moon track at that time.

Figure 12. North Pole region of Moon
2007, Oct 30, 19:07 UTC



JAXA

Figure 13. North Pole Lunar Ground Track
2007, Oct 30, 19:07 UTC

The characteristics of the orbit after approximately two months are shown in Table 13. The maneuver schedule

followed to achieve this configuration (if any) is not known.

Table 13: Orbit Evolution after 2 Months
Moon-centered MME

	Propagated* as of: 2007, Dec 9	JAXA solution[1] as of: 2007, Dec 9
a (km)	1840	1834
e	0.00924	0.00058
i (°)	91.93	89.52
P (hr)	1.967	1.958
h_a (km)	119.6	98.1
h_p (km)	84.90	95.6

*using a 90x90 lunar gravity field

VIII. Summary

The total mission support duration for JPL was 35 days. Over that time JPL Navigation generated 21 OD solutions for the Project and 16 independent, internal DSN solutions. When JPL's support ended, Kaguya was in a stable, low lunar orbit, at the beginning of its science phase.

Many interfaces must be worked in an international collaboration like this. One of those interfaces was the provision for real-time doppler monitoring of critical events (as discussed in Section IV-F). The outcome of this endeavor was entirely satisfactory, although one particular detail of the process can be improved. JAXA controlled the uplink for these critical events and JPL monitored the downlink (3-way doppler). This arrangement required the DSN shift operators to query the JAXA station for its uplink frequency (which varied slightly from pass to pass) and tune the DSN receiver appropriately. This tuning did not occur on a regular basis. One suggestion for future cooperative missions is to include this reference frequency in data exchanges during station handovers and have the DSN act on that information in a timely manner (i.e. at beginning of track).

Another suggestion for improvement of future international collaborations is with respect to tracking. If the international partner and the DSN share the spacecraft tracking, as done with JAXA for Kaguya, the partner should have the capability to generate and upload pointing prediction files to the DSN. This would eliminate the coverage discontinuity that occurred after LOI as described in Section V-B.

Acknowledgements

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The Selene/Kaguya Flight Dynamics Team participated as equals during the cruise and circularization phases. They are fully capable practitioners of orbit determination. JPL's contribution to the mission was, mostly, an operation to manage and reduce risk.

References

1. Katoh, Takaaki et al, "Orbital Maneuver Plan and Operation Results of Kaguya during Lunar Transfer Orbit and Lunar Orbit Injection", *Proceedings of the 26th International Symposium on Space Technology and Science (ISTS)*, 2008-k-28, June 2008.
2. Ogawa, Mina et al, "Determination, Prediction and 3-D Graphical Display of Kaguya Orbit", *Proceedings of the 26th International Symposium on Space Technology and Science (ISTS)*, 2008-k-28, June 2008.

[1] *private communication*, Mina Ogawa, Kaguya Flight Dynamics team, JAXA, June 25 2008.

Appendix 1
Orbit Determination Models and Assumptions

Error Source	Estimated?	*A Priori* Uncertainty (1σ)	Correlation Time	Update Time	Comments/References
Angle tracking data (°)	–	0.02	–	–	only first 2.5 hours after launch
2-way doppler data (mm/s)	–	0.25	–	–	S-band (varied between 0.2 - 1.0)
Range (m)	–	2	–	–	S-band (varied from 1-3)
Epoch state					
Position (km)	√	1000	–	–	
Velocity (km/s)	√	1	–	–	
Range bias (m)	√	10	0	per pass	estimated per station
Doppler bias (mm/s)	√	0.15	–	–	only est'd on 1st day after launch
Angle bias (degree)	√	0.05	–	–	only est'd 1st 2.5 hrs after launch
Moon, Earth ephemerides & GMs	–	DE405	–	–	
Station locations (cm)	–	3	–	–	
Pole X, Y (cm)	–	10	–	–	~15 nradian for Pole, ~0.2 ms for UT
UT1 (cm)	–	10	–	–	
Ionosphere – day,night (cm)	–	75, 15	–	–	
Troposphere – wet,dry (cm)	–	4, 1	–	–	
Solar pressure					bus model, area = 30 m^2
SOLCOF	√	0.5	–	–	scale factor on total solar pressure
AMD event ΔV		~1 each day			angular momentum desaturation
X,Y,Z (cm/s)	√	10,10,10	–	–	
Non-gravitational accelerations (km/s^2)	√	3.0×10^{-11}	0	6 hours	spherical covariance. to correct apparent mismodelling.
Orbit maneuvers (N, °, °)					
LOI-2	√	3.7,0.71,0.71	–	–	estimated parameters: Thrust, R.A., Dec. The first four OTMs were performed with the main engine (547 N). The last three were performed using a cluster of 20 N thrusters (total axial thrust of 51.4 N).
Rstar separation	√	see footnote*	–	–	
Vstar separation	√	see footnote*	–	–	
LOI-5a	√	3.7,0.71,0.71	–	–	
LOI-5b	√	0.34,0.71,0.71	–	–	
LOI-5c	√	0.34,0.71,0.71	–	–	
LOI-6	√	0.34,0.71,0.71	–	–	
apolune ΔV		1 per orbit at apolune (orbit phase only)			to correct apparent mismodelling
X,Y,Z (cm/s)	√	10,10,10	–	–	
lunar gravity (2x2 field)	√	LP150Q	–	–	est'd in lower orbits (after LOI-5a)

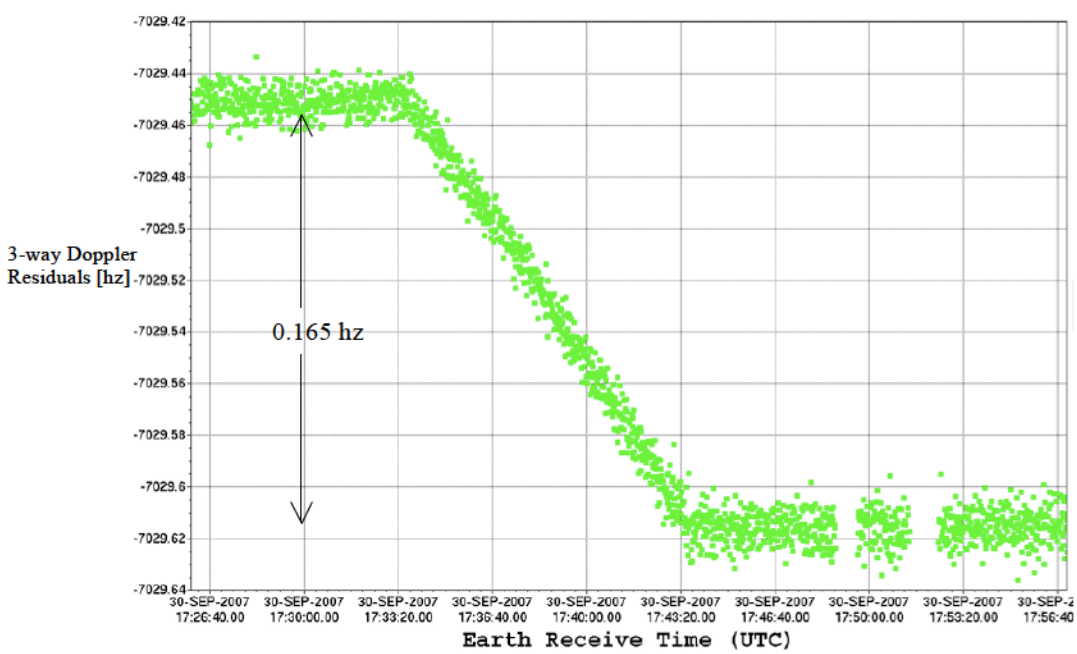
*sub-satellite release velocity uncertainty = (20, 20, 20) cm/s

Appendix 2

Estimated Angular Momentum De-saturation ΔV Impulses during Cruise, [cm/s]
EME2000

Midpoint of AMD (UTC)	X	Y	Z
15-SEP-2007 01:37:00	6.5	-5.0	1.7
16-SEP-2007 05:41:00	0.7	-1.2	-0.1
17-SEP-2007 07:48:00	-6.6	-5.7	2.0
19-SEP-2007 04:10:00	-1.6	-2.3	0.6
19-SEP-2007 21:22:30	-1.7	-2.4	0.6
21-SEP-2007 01:00:00	-10.2	-7.3	-3.9
22-SEP-2007 04:23:00	-8.4	-6.9	-2.7
23-SEP-2007 01:02:00	1.9	-0.3	-0.5
24-SEP-2007 07:16:00	-1.0	-5.0	-4.0
25-SEP-2007 13:13:00	-8.2	-7.5	-4.3
26-SEP-2007 18:11:30	-4.5	-5.6	-1.5
27-SEP-2007 16:44:00	-6.5	-5.7	-3.5
28-SEP-2007 20:27:00	-10.7	-9.3	-4.0
29-SEP-2007 14:36:00	6.1	-3.8	-8.3
30-SEP-2007 17:38:30	-11.9	-8.6	-5.7
01-OCT-2007 14:17:30	-7.9	-8.3	-1.1
02-OCT-2007 14:16:30	-8.2	-9.1	-1.7
03-OCT-2007 15:19:00	0.7	-1.8	3.9

An example of downlink monitoring is illustrated in the figure below, for the AMD occurring on Sept 30. The line-of-sight component measured in the figure represents a total ΔV imparted to the spacecraft equal to 15.8 cm/s.



Appendix 3

Maneuver Magnitudes and Sub-satellite Release Impulses

Mnvr/event	month	day	start time UT	Thrust	Planned	Actual	Mass Loss
			hr:min	*N*	*m/s*	*m/s*	*kg*
Launch	9	14	1:30				
ΔVc1	9	14	20:13	547	23.181	23.57	23
ΔVa1	9	15	23:00	51.4	0.577	0.766	1
ΔVp1	9	19	0:52	547	93.433	93.57	89
ΔVc2	9	19	20:00	51.4	1.254	1.23	1
ΔVp2	9	29	2:58	51.4	1.7	1.69	2
ΔVc3	9	30	19:00	--	statistical	cancelled	--
ΔVloi1	10	3	20:55	547	298.789	298.9	255
1st full day in orbit	10	4	0				
ΔVloi2	10	5	23:01	547	102.485	102.19	85
ΔVloi3	10	6	22:40	547	151.418	151.51	121
Rstar sep	10	9	0:36	--	--	-0.11	45
ΔVloi4a	10	10	0:18	547	164.948	164.68	123
Vstar sep	10	12	4:28	--	--	-0.35	45
ΔVloi5a	10	14	4:37	547	68.305	68.48	49
ΔVloi5b	10	15	4:51	51.4	25.627	25.74	25
ΔVloi5c	10	16	6:08	51.4	25.165	25.3	24
ΔVloi5d	10	17	7:28	--	contingency	cancelled	--
ΔVloi5e	10	18	8:41	--	contingency	cancelled	--
ΔVloi6*	10	18	7:54	51.4	12.98	12.82	12

*manv euv er mov ed 1 day ealier than baseline schedule after cancellation of ΔVloi5e

The entries in the table are from [1], except for the actual LOI magnitude & mass loss and the sub-satellite release velocities -- those were estimated by JPL. The magnitudes of the sub-satellite separation impulses are denoted as negative magnitudes to indicate that they represent reaction on the spacecraft.

Formally, the estimated impulses on the s/c due to the release of the sub-satellites are:

Rstar separation: 11 ±6 cm/s (1σ)
Vstar separation: 35 ±2 cm/s (1σ)

The separation ΔVs of the sub-satellites is inconsistent. It was not possible to determine which solution represents a better estimate, if either, since no *a priori* models for the separations were provided. The errors on Rstar are 3x larger than Vstar because the data arc for the Rstar solution is ~25% the length of the Vstar arc (data arcs were constrained by neighboring dynamics).