AAS 15-257

ORBIT DETERMINATION AND ACQUISITION FOR LADEE AND LLCD MISSION OPERATIONS

Lisa Policastri,[*] John P. Carrico Jr.,[†] Craig Nickel,[‡]
Arlen Kam,[§] Ryan Lebois[**] and Ryan Sherman[††]

This paper describes the orbit determination results for the Lunar Atmospheric Dust Environment Explorer (LADEE) from launch through the science operations. This paper also describes how the orbit determination and acquisition team supported the Lunar Laser Communications Demonstration (LLCD). Precise orbit determination was essential to all components in successful maneuver execution, properly correlated science collections, spacecraft situational awareness, and throughout the LLCD acquisition operations. We discuss the concurrent use of overlap analysis with the filter-smoother consistency test as quality-control methods.

INTRODUCTION

The LADEE mission operations team successfully flew the spacecraft in a retrograde, near-equatorial orbit around the Moon, and carried out the planned trajectory by precisely executing all maneuvers. LADEE exceeded all science collection goals. The LLCD was also successful in achieving its objectives. All of these mission goals were accomplished with the support of the LADEE orbit determination and acquisition team.

In this paper we will initially recap the orbit determination requirements and background for LADEE. The ground stations used throughout the LADEE mission, their allocations, and the acquisition process are described. Then we will present the initial orbit determination timeline after Stage 5 separation with initial acquisition and tracking. We will also refer to the Orbit Determination Plan[1,2] and describe how we followed the pre-launch processes to carry out flight dynamics operations.

ORBIT DETERMINATION REQUIREMENTS AND ACQUISISTION OVERVIEW

The LADEE mission collectively defined orbit determination requirements based on science instrument pointing requirements, activity planning needs, and simulated orbit accuracy

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[*] LADEE Orbit Determination Lead, Applied Defense Solutions Inc., 10440 Little Patuxent Parkway Suite 600, Columbia, MD 21044, lisa@applieddefense.com

[†] Technical Advisor, Google Inc., 1600 Amphitheatre Parkway, Mountain View, CA 94043, (former Applied Defense Solutions Inc.), JCarrico@Google.com

[‡] Astrodynamics Engineer, Applied Defense Solutions Inc., CNickel@applieddefense.com

[§] Orbit Analyst, OneWeb, (former Stinger Ghaffarian Technologies Inc. contractor at NASA ARC), akam@oneweb.net,

[**] Aerospace Engineer, Applied Defense Solutions Inc., RLebois@applieddefense.com

[††] Aerospace Engineer, Applied Defense Solutions Inc., RSherman@applieddefense.com

capabilities, which are listed in Table 1. Requirements were in terms of predict radial, predict in-track, definitive radial, definitive in-track, and definitive cross-track orbit accuracies. Requirements are also listed for definitive ephemeris deliveries during and after the mission. The mission operations cadence operated with a Tactical Planning Process, which updated the LADEE activity plan every-other day. Each plan included 3.5 days of activities, and was planned using the latest available predicted orbit ephemeris from that morning. The predict orbit accuracies are related to this 3.5 day activity span.

Table 1: LADEE Orbit Determination Requirements

Title	**Requirement ID**	**Requirement**	**Rationale**
Predict Radial	**MOS-26**	MOS shall predict satellite radial position covering commissioning and science phases to an accuracy of +/- 2 km (3-sigma) at least 84 hours in advance of the start of the prediction interval.	Science measurements rely heavily on the ability to predict the satellite altitude at the time of measurement. The 84 hours allows planning for science measurements 3.5 days in advance of the measurement itself, which supports the mission operations planning timelines.
Predict In-Track	**MOS-57**	MOS shall predict satellite in-track position with an accuracy of +/- 20 km (3-sigma) at least 84 hours in advance of the start of the prediction interval.	The UVS limb measurement relies heavily on the ability to predict the satellite in-track position at the time of measurement in order to point the instrument correctly. The 84 hours allows planning for science measurements 3.5 days in advance of the measurement itself, which supports the mission operations planning timelines. The 20-km figure is ~50% over the current estimate of FDS capability (1/25/2011).
Definitive Cross-Track	**MOS-55**	MOS shall provide definitive satellite cross-track position covering the commissioning and science phases to an accuracy of +/- 3 km (3-sigma) within 30 days of the end of the mission.	Provides information required for science data processing. Postevent satellite position knowledge is a more stringent requirement than orbit prediction accuracy.
Definitive In-Track	**MOS-56**	MOS shall provide definitive satellite in-track position covering the commissioning and science phases to an accuracy of +/- 3 km (3- sigma) within 30 days of the end of the mission.	Provides information required for science data processing. Postevent satellite position knowledge is a more stringent requirement than orbit prediction accuracy.
Definitive Radial	**MOS-25**	MOS shall provide definitive satellite radial position covering the commissioning and science phases to an accuracy of +/- 1 km (3-sigma) within 30 days of the end of the mission.	Provides information required for science data processing. Postevent satellite position knowledge is a more stringent requirement than orbit prediction accuracy. Resolution of measurements in the radial direction is of special importance as it will allow the science team to characterize how measurements vary with altitude from the surface.
Final Definitive Delivery	**MOS-58**	MOS shall provide a set of best available definitive ephemeris files including position and velocity covering the entire mission.	There is no accuracy requirement for position for mission phases outside commissioning and science phases. There never is an accuracy requirement for velocity. This one is sufficient for the NAIF delivery.
Interim Definitive Deliveries	**MOS-59**	MOS shall compute a set of preliminary spacecraft definitive ephemeris no later than 30 days after tracking data receipt.	The intent is for these to be the same products maneuver planning needs. These are intended to be every week or 10 days, but we use a looser requirement so as not to drive cost.

In addition to these requirements which supported the spacecraft and instrument activity planning, the orbit predictions had to be accurate enough to use for spacecraft acquisition to track LADEE from all specified ground stations. Ground stations from the NASA's Near Earth Network (NEN), the Universal Space Network (USN), and NASA's Deep Space Network (DSN) formed LADEE's ground network. LADEE was tracked by eleven antennas throughout the mission, which are listed in Table 2. We provided the acquisition data files to all of these stations to enable the antennas to accurately point to and track LADEE. The acquisition data was always created using the Ames Flight Dynamics System (FDS)[3], with the latest valid orbit determination solution.

Table 2: LADEE Operational Ground Stations

Antenna	Dish Size (m)	Measurement Types	Service Provider	Services Provided
AGO Santiago, Chile	9	Auto-track angles, 2-Way Doppler, Ranging	NEN	Tracking
WS1 White Sands, NM	18	Auto-track angles, 2-way Doppler, Ranging	NEN	Tracking
HBK/ZAHB Hartebeesthoek, South Africa	10	Auto-track angles, 2-way Doppler	USN	Tracking
AUWA01 Dongara, Western Australia	13	Auto-track angles, 2-way Doppler	USN	Tracking
Beam Wave Guide (BWG) Subnet **DSS-24, DSS-34, DSS-54** Goldstone, CA (GLD) Canberra, Australia (CAN) Madrid, Spain (MAD)	34	2-way Doppler, Sequential Ranging	DSN	TT&C
High Efficiency (HEF) Antennas **DSS-15, DSS-45, DSS-65** Goldstone, CA Canberra, Australia Madrid, Spain	34	2-way Doppler (all), Sequential Ranging (DSS-45, DSS-65)	DSN	TT&C
High Speed Beam Wave Guide (HSB) **DSS-27** Goldstone, CA	34	2-way Doppler, Sequential Ranging	DSN	TT&C

The DSN provided full telemetry, tracking, and commanding services (TT&C) and was our primary ground network. The USN and NEN antennas provided tracking only. All of these antennas were used throughout the entire mission, with the exception of DSS-15 and DSS-27; DSS-15 came online for initial testing in early November and it replaced DSS-27 by end of December. The pre-launch plan did not specify usage of all NEN and USN stations during Commissioning and Science operations, however, we commissioned those four stations for 2-way Doppler use with LADEE during the Commissioning phase. Although that was not part of the original plan, the operations team agreed it made sense to test all of our ground antennas for use for lunar orbit tracking while LADEE was in its Commissioning phase. We proceeded to rely on these four stations to provide tracking during Science phase when there were scheduling conflicts and antenna outages with DSN.

We also used the Tracking Data and Relay Satellite System (TDRSS) for monitoring LADEE during maneuvers at perigee during the cislunar phase. TDRSS was used for telemetry and commanding services only; it was not used for providing tracking service. We provided LADEE predicted ephemeris to NASA in order for TDRSS to track LADEE during these periods.

DSN, NEN, USN, and TDRSS required various formats of acquisition files (ephemeris and/or pointing data) to track the spacecraft. The LLCD operations required Lunar Laser Space Terminal (LLST) and Lunar Laser Ground Terminal (LLGT) pointing files, which are discussed in more detail in the "LLCD Operations" section. Each of these acquisition file types is listed in Table 3. Specifics about these products are detailed in the LADEE Products, Formats, and Exchanges (PFE) Interface Control Document[4].

Table 3: Acquisition data required by each ground station supporting LADEE

Acquisition Product	Station	Mission Phases
INP2	NEN/WS1,USN/AUWA	All
IIRV	NEN/AGO	All
SPK (.bsp and .xsp)	DSN	All
LLST	LLGT-1, 2, 3	Commissioning/Extended
LLGT	LLGT-1, 2, 3	Commissioning/Extended
STK (.e)	TDRSS	Launch, Phasing Loops
MCS Pointing File	USN/HBK	All

GROUND NETWORK ALLOCATIONS

LADEE was allocated time on each ground station for communications activities, often scheduled weeks in advance. For some ground networks, acquisition data was only created for stations during the actual allocations; while for others, such as DSN, one product was delivered for all stations and only the allocated station would utilize the posted data. The delivery and utilization of the acquisition data is detailed in the "Acquisition Data Delivery" section.

DSN Allocations

Acquisition products were created for DSN after each maneuver and spanned through the following maneuver regardless of allocation, as the DSN was the primary ground network for LADEE. The OA monitored the DSN allocation schedule to maintain situational awareness and use it a sanity check to verify the station views.

NEN and USN Allocations

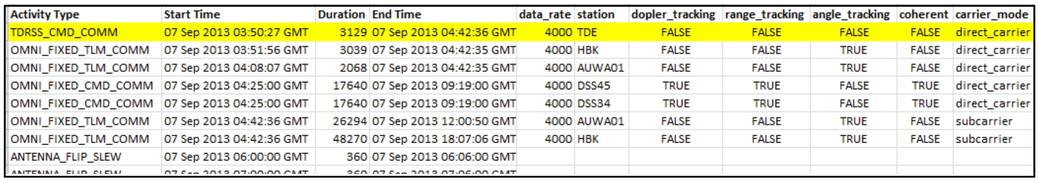
Acquisition products for each of the NEN and USN stations were only created for the span of each allocated pass with some margin added. The allocation requests were sent via email in the following form:

```
W1414-2569,LAD,SANTIAGO,2014090180500,2014090184000,TR2,1,S1
W1415-3841,LAD,WS1,2014099060000,2014099062500,TR2,1,S1
W1415-3842,LAD,HBK,2014102220000,2014102223500,TR2,1,S1
W1415-3843,LAD,AUWA01,2014103124500,2014103132000,TR2,1,S1
```

The "TR" codes listed near the end of each allocation request indicated the type of tracking to be taken (i.e. Doppler and angles, Doppler only, etc.).

TDRSS Allocations

The Tracking Activity Report (TAR) contained the spacecraft activities in the tactical plan, and this served to inform the OA of TDRSS activities near perigee during the Cislunar phase. A sample TAR is shown in Figure 1 with the TDRSS activity in yellow. The TDRSS acquisition product was generated only when there were allocated TDRSS activities.



Activity Type	Start Time	Duration	End Time	data_rate	station	dopler_tracking	range_tracking	angle_tracking	coherent	carrier_mode
TDRSS_CMD_COMM	07 Sep 2013 03:50:27 GMT	3129	07 Sep 2013 04:42:36 GMT	4000	TDE	FALSE	FALSE	FALSE	FALSE	direct_carrier
OMNI_FIXED_TLM_COMM	07 Sep 2013 03:51:56 GMT	3039	07 Sep 2013 04:42:35 GMT	4000	HBK	FALSE	FALSE	TRUE	FALSE	direct_carrier
OMNI_FIXED_TLM_COMM	07 Sep 2013 04:08:07 GMT	2068	07 Sep 2013 04:42:35 GMT	4000	AUWA01	FALSE	FALSE	TRUE	FALSE	direct_carrier
OMNI_FIXED_CMD_COMM	07 Sep 2013 04:25:00 GMT	17640	07 Sep 2013 09:19:00 GMT	4000	DSS45	TRUE	TRUE	FALSE	TRUE	direct_carrier
OMNI_FIXED_CMD_COMM	07 Sep 2013 04:25:00 GMT	17640	07 Sep 2013 09:19:00 GMT	4000	DSS34	TRUE	TRUE	FALSE	TRUE	direct_carrier
OMNI_FIXED_TLM_COMM	07 Sep 2013 04:42:36 GMT	26294	07 Sep 2013 12:00:50 GMT	4000	AUWA01	FALSE	FALSE	TRUE	FALSE	subcarrier
OMNI_FIXED_TLM_COMM	07 Sep 2013 04:42:36 GMT	48270	07 Sep 2013 18:07:06 GMT	4000	HBK	FALSE	FALSE	TRUE	FALSE	subcarrier
ANTENNA_FLIP_SLEW	07 Sep 2013 06:00:00 GMT	360	07 Sep 2013 06:06:00 GMT							

Figure 1: Portion of sample TAR file

ACQUISITION DATA GENERATION

To create the acquisition data and view periods, we used the latest valid predicted ephemeris and the ground station coordinates. The delivery schedule of this data mostly depended on the maneuver schedule and the activity planning processes. The Mission Operations System (MOS) tactical planning occurred every other day during Commissioning and Science phases where we had staff present to produce station view period updates for activity planning. We had staff present every day during Cislunar and LOA phases to update view periods for activity scheduling updates.

Acquisition data could become stale for several reasons: mission time was within one day of previous acquisition data running out, a significantly different OD solution may have invalidated previous data, or an updated trajectory design was created. Whenever any of these situations occurred, our team created new sets of view periods and/or acquisition data.

The acquisition products for DSN were created according to the maneuver schedule. Our team generated a SPICE file that did not contain any maneuvers—i.e. a “no burn” ephemeris—after each maneuver, or whenever necessary due to the previous acquisition data becoming stale. Figure 2 shows the timespan covered by a “no burn” ephemeris. During Commissioning and Science phases, in most cases the “no burn” data was still valid at the time of the next maneuver. This “no burn” file extended three days after the next maneuver in order to provide the stations with an ephemeris to fall back on in the case that the maneuver did not execute. The acquisition products that contained the maneuver were created and uploaded about 36 hours before the maneuver, and extended three days after the maneuver. The duration of the burn ephemeris was set at three days after the maneuver, however since the post-maneuver no burn products would be uploaded the day after the maneuver, this duration was largely arbitrary and used as a buffer to allow for delay in upload of the post-maneuver acquisition data or other operations issues.

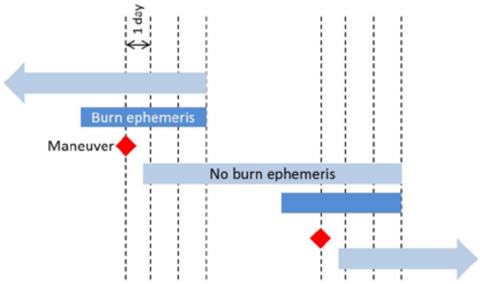


Figure 2: Schedule and duration of acquisition data for DSN during Science

The acquisition products for TDRSS, NEN, and USN were created per the station allocations, and typically covered spans as shown in Table 4: Acquisition Product Spans. Since the LLCD team scheduled operations in three to four day periods, our team provided LLST and LLGT pointing files on the planning day before the first LLCD operations day, in order to use the most up-to-date orbit solution.

Table 4: Acquisition Product Spans

Acquisition Product	Station	Product Span
INP2	NEN/WS1,AUWA	+/-8 hours from pass
IIRV	NEN/AGO	+/-8 hours from pass
LLST	LLGT-1, 2, 3	LLCD Ops (3-4 days)
LLGT	LLGT-1, 2, 3	LLCD Ops (3-4 days)
STK (.e)	TDRSS	+/-1 day from pass
MCS Pointing File	USN/HBK	+/-30 min from pass

Acquisition Data Comparison

To assess the need for new acquisition data we conducted ephemeris comparison analyses. This comparison occurred at different intervals depending on the mission phase. During the post-launch and Cislunar phase, due to potential launch and maneuver performance dispersions, nearly each new orbit determination solution prompted a comparison with the ephemeris most recently sent to the tracking station. As it turned out, launch and maneuver performances were very close to nominal, thus making unscheduled acquisition updates unnecessary during this mission phase.

An example of the comparison is shown below in Figure 3. In this example, the "LADEE_Previous" satellite in red represents the ephemeris that DSN was using, which did not contain a planned maneuver, while the "LADEE" satellite represents an ephemeris that had not yet been sent to DSN, which did contain the planned maneuver. If DSN continued to use the no burn ephemeris, the antenna would be pointed at the "LADEE_Previous" satellite while the more current "LADEE" satellite at the depicted time would no longer be within the DSS27 (blue) field of view. In this case DSN switched to the ephemeris containing the planned maneuver long before the time shown here. However, if our team observed this qualitatively with a new orbit solution, we would have recommended creating and sending new acquisition data to the ground station. Figure 3 also shows the WS1 (green) and AGO (red) antenna beams.

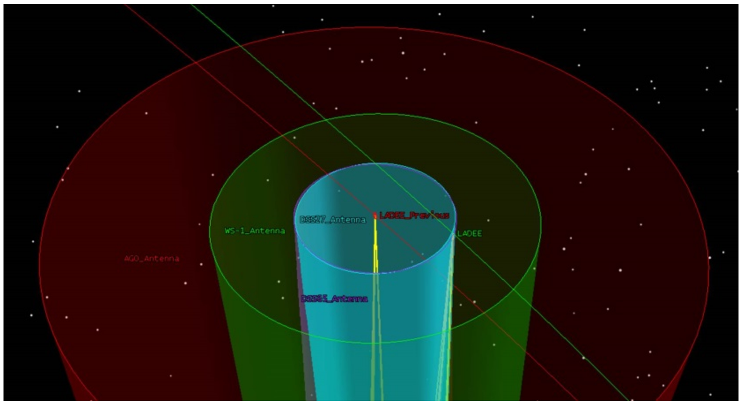


Figure 3: Qualitative comparison of ephemerides in STK

The lunar orbit achieved in Commissioning and Science phases did not require this qualitative comparison analysis as often, due to the size of the orbit relative to the ground station beam widths. As a result, comparisons were only carried out before and after each orbit maintenance maneuver (OMM). During these phases, the orbit determination solution remained valid for tracking purposes for that period of time (4 to 8 days). Figure 4 shows the relative size of the DSN, AGO, and HBK beam widths compared to LADEE's lunar orbit.

The comparison analysis also included reports such as the "Angle Between" report generated for WS1 shown in Figure 5. This allowed for a quantitative assessment of the staleness of acquisition data. In Figure 5, the "angle between" is the vector from WS1 to the previous LADEE ephemeris and the vector from WS1 to the latest LADEE ephemeris.

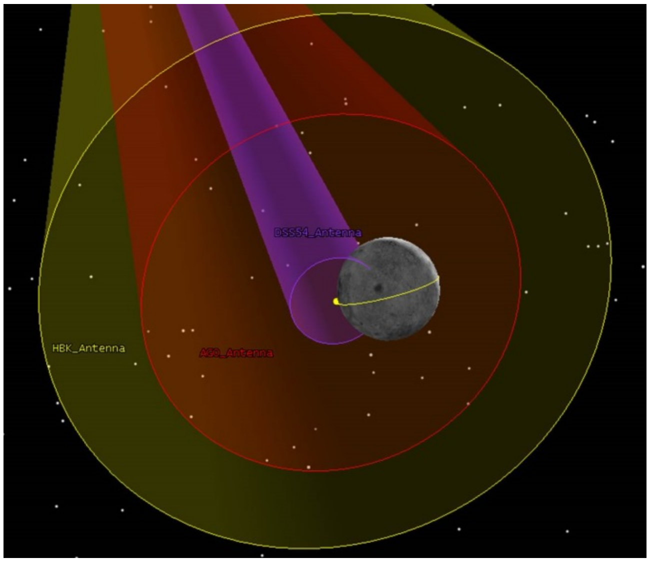


Figure 4: DSN, AGO, and HBK beams tracked on LADEE in lunar orbit

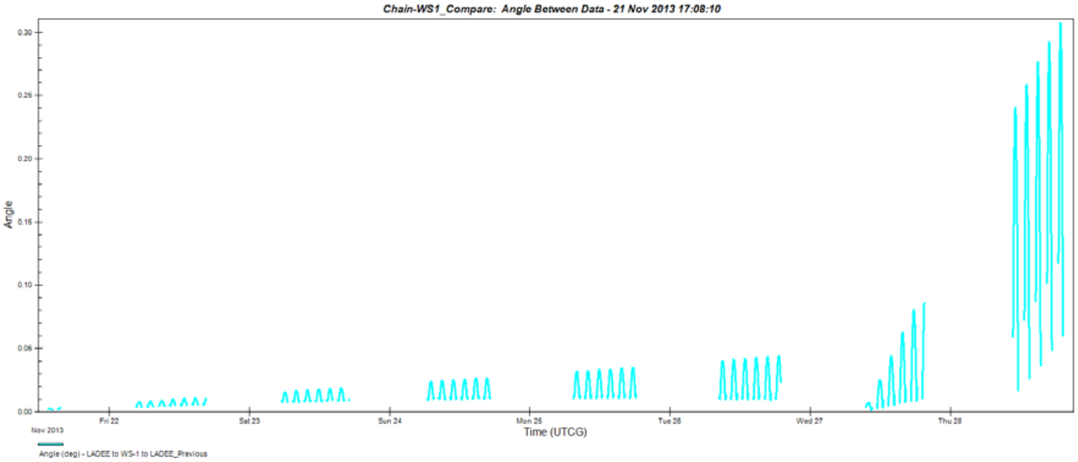


Figure 5: "Angle between" report comparing LADEE ephemerides from the White Sands tracking station

Table 5: Beam width half angles for ground stations

Ground station	Beam width half angle (degrees)
DSN	0.243
HBK	1.5
AGO	1.0
WS1	0.5
AUWA	0.6

Using the beam width half angles for each ground station in Table 5, and the graph in Figure 5, the OA could easily assess the need for updated acquisition data. In the example in Figure 5, the angle between does not increase above 0.5 degrees, which is the half angle threshold for WS-1; however, there is a large jump in the data on Wednesday, November 27. Regardless of this jump, the acquisition data is acceptable, i.e. WS1 will be able to track LADEE during the time period graphed. However, for accuracy, new acquisition data should be uploaded by the 27th if activities are planned on WS1.

The comparison analysis technique also provided an efficient method for processing launch dispersions from the Minotaur V fifth stage. By preparing a comparison ephemeris set representing possible launch dispersions (+/-10%), our team input each new initial orbit determination (IOD) solution as it became available, and then we qualitatively assessed launch performance. This process could be repeated until the dispersion ephemeris and the IOD solution converged to a reasonable match.

Acquisition Data Delivery

The acquisition product delivery method differed between ground networks. The DSN provides access to the "JPL SPS Portal" for all missions that use the DSN. "SPICE" files were uploaded to the Portal and automatically processed for use by the DSN antennas. We uploaded long-term and short-term SPICE files delivered to DSN throughout the mission. The long-term files were used only for allocation scheduling weeks in advance, while the short-term files were used by the stations for acquisition.

Acquisition data for all other assets had separate processes. NEN and USN station data were delivered through the Wallops Orbital Tracking Information Services (WOTIS) "Front End" SFTP using a local FTP Client. Acquisition data for TDRSS was delivered through the GSFC Flight Dynamics Facility (FDF) SFTP. LLCD pointing files were shared between teams over our internal shared File/Data Management system.

TRACKING DURING OPERATIONS

The tracking we received from each of the ground antennas throughout the mission that we used for orbit determination is shown in Figure 6: Tracking Time Used By Station, IOD and Cislunar Phases; Figure 7: Tracking Time Used By Station, Lunar Orbit Acquisition and Commissioning Phases; and Figure 8: Tracking Time Used By Station, Science Phase. In each of these graphs, the blue times show NEN and USN tracking; the black times show DSN tracking.

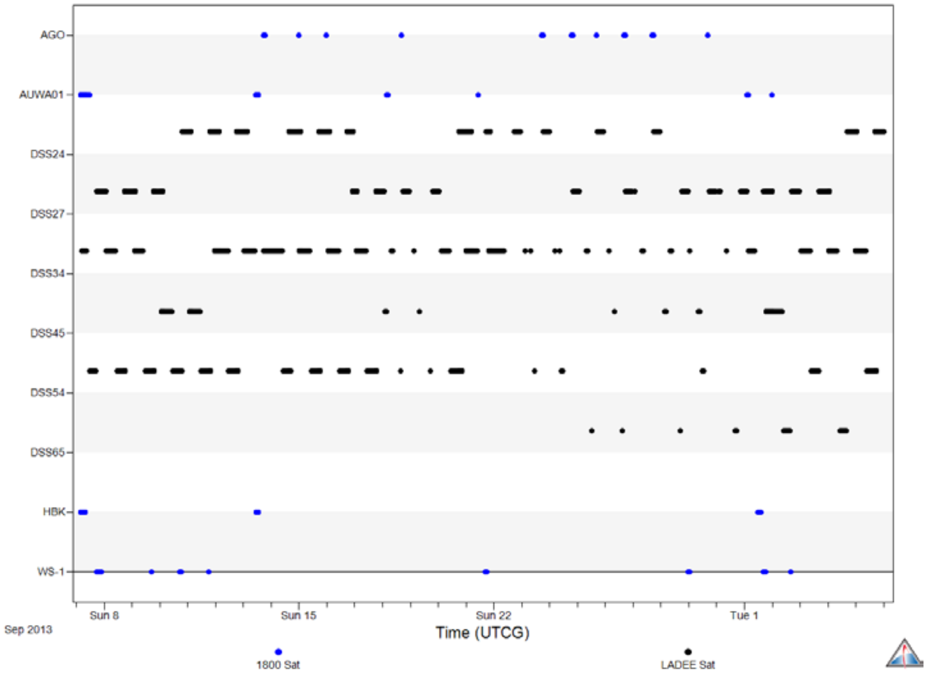


Figure 6: Tracking Time Used By Station, IOD and Cislunar Phases

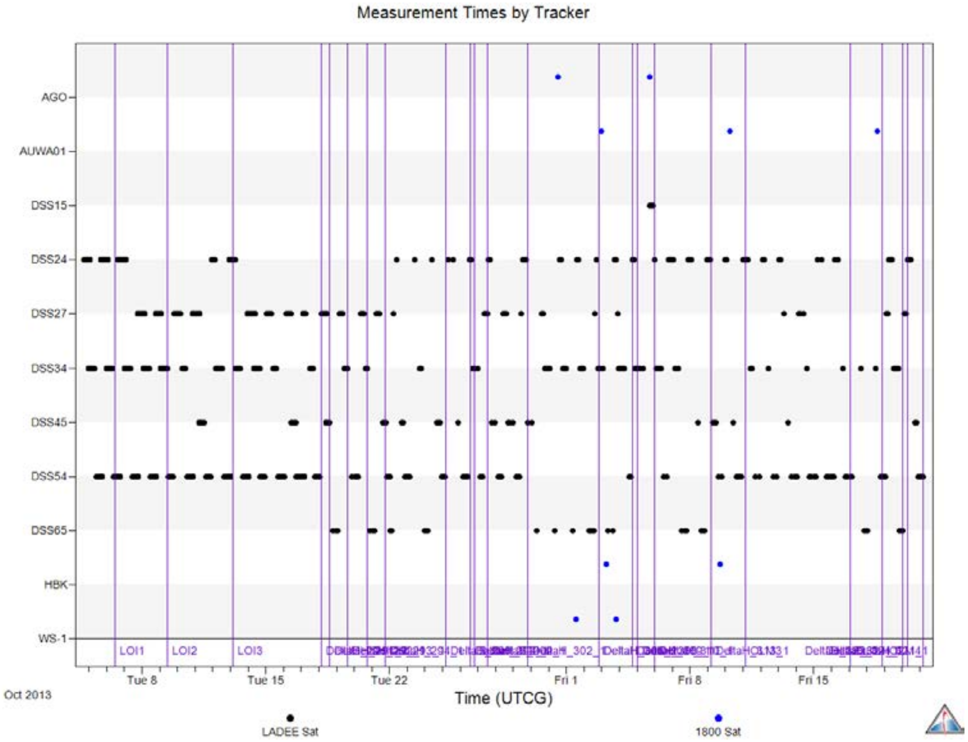


Figure 7: Tracking Time Used By Station, Lunar Orbit Acquisition and Commissioning Phases

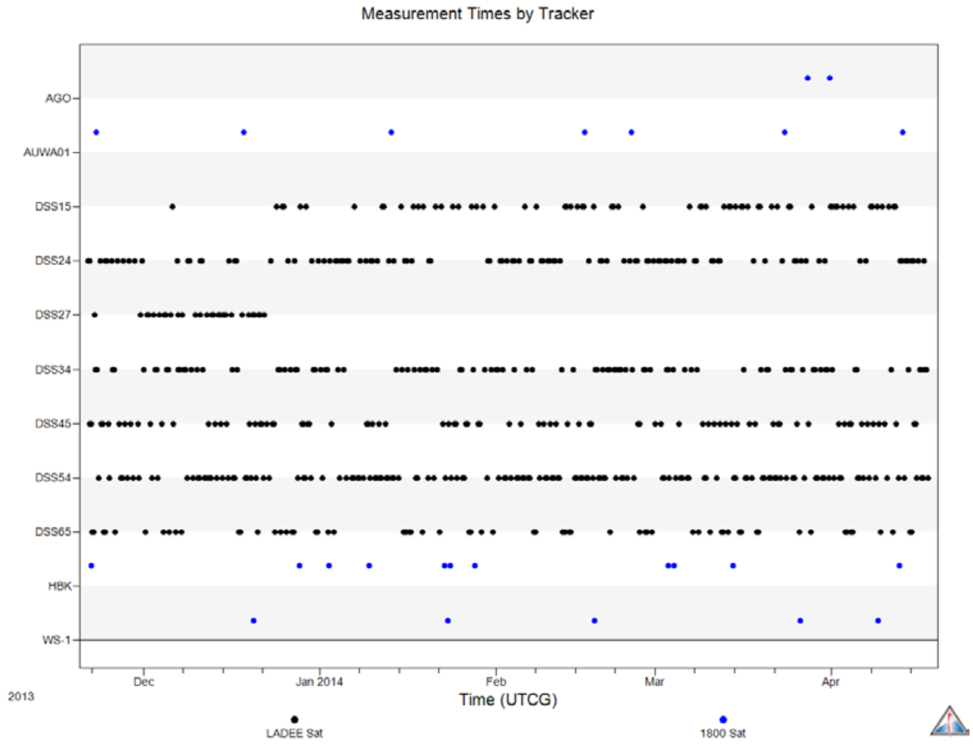


Figure 8: Tracking Time Used By Station, Science Phase

Tracking Data Files

We received the tracking from DSN in TRK-2-34 format and in Universal Tracking Data Format (UTDF) from all other NEN/USN antennas. The UTDF files were easy to manage; we typically received these files every 15 minutes for each track, and each file was uniquely named with a time tag in the file name. Tracks were scheduled anywhere from 25 minutes to several hours, depending on the phase, view period, and tracking type being collected. For example, during the Cislunar phase the track lengths were longer at times, when view periods were longer, and only angles were being collected where DSN was coherent simultaneous to an NEN or USN antenna auto-track pass. In lunar phases, the NEN/USN tracks were shorter and typically scheduled for 35 minutes, for two-way Doppler. No matter the pass length, our configuration was set to receive the UTDF files every 15 minutes. Each file contained new tracking measurements that were not contained in a previous file.

The TRK-2-34's were not as easy to manage. Historically, DSN only provides TRK-2-34 tracking files after the pass completes. If the operations center is configured to receive live tracking data streams from the DSN then you can control how you package the data, but the Ames MMOC is not configured to receive and package live tracking data streams. DSN defines a pass as the end of the scheduled station allocation. When LADEE orbited the Moon, it typically orbited four times during one DSN station allocation, with two-way tracking activities only during one or two of those orbits. Our team wanted to receive the tracking data before the end of the scheduled allocation, preferably after each tracking activity. This was unlike how DSN provided tracking files in the past, so our team worked with the DSN Tracking Data Team prior to launch to provide TRK-2-34 ".partial" files for LADEE. The DSN would send us an incomplete file, at requested intervals.

We requested DSN partial file deliveries at varying frequencies depending on the phase of the mission. During IOD, files were delivered three times per hour to allow for rapid turnaround of OD and Acquisition data products. This was subsequently reduced to one file every hour for most of the remainder of the mission – it was increased again to three files per hour during the Lunar Orbit Acquisition phase to enable a quicker turnaround on maneuver performance surrounding the lunar capture. It would have been advantageous for our team to adjust this frequency more often throughout the mission, for instance, to reduce unnecessary processing of many overlapping files when the pace was slower.

Partial files were named according to the time of the DSN track, and were appended with the extension *.partial; however, all partial files for a given track were given the exact same name by DSN, so re-naming and management of these files was done by LADEE MMOC scripts. These files were cumulative from the beginning of the DSN track, so only the most recent partial file was needed until the final file was delivered. This was much different than the UTDF files, where each file contained only new, unique tracking measurements. Our team processed whichever files were available at the time of each OD, but had to be sure that only the most recent partial file from the current track was validated in the FDS database. Once a final (complete) file was received from any track, all partial files from that track would be invalidated in the database.

INITIAL ORBIT DETERMINATION OPERATIONAL TIMELINE

LADEE launched on-time, right on schedule at the first launch opportunity on September 7, 2013 03:27 UTC. LADEE was in view right at Stage 5 separation, 03:50:19 UTC from the HBK station and shortly after from the AUWA01 antenna; both of these stations began auto-tracking LADEE immediately. LADEE was also in view from the CAN station right on schedule soon after Stage 5 separation.

We received a preliminary Stage 5 separation vector about 20 minutes after separation at 04:10 UTC. We received our first UTDF files from HBK at 04:14 UTC. Ranging was enabled at CAN at 04:53 UTC. We completed our ephemeris comparison against the preliminary Stage 5 burnout vector by 05:12 UTC, and determined that no acquisition data updates were needed. We received the official Stage 5 burnout state vector at 05:38 UTC, and by 06:11 UTC we completed our assessment that no acquisition data updates were needed based on the Stage 5 separation vector alone. In the meantime, we were collecting more UTDFs and TRK-2-34s to perform IOD with our Gooding Angles, Residuals vs Reference, and iGatorOD tools[1].

At 09:30 UTC both the DSS-54 station and USN confirmed that they had good signal, no issues maintain tracking using the pre-launch acquisition data, and did not need new acquisition data at that time. Since there was no urgency in tracking/acquiring earlier, at launch plus 7 hours, we provided our first official IOD solution to generate new products. Our team used this launch plus 7 hour solution to perform the first trajectory update, to run the Batch Least Squares to initialize the filter, and to create products.

We had several updates during the first 24 hours, as new tracking data was received from the variety of stations we had in our ground system. We began filter tuning during this time as well. Using the launch plus 27 hour OD solution, our team created the first new cislunar trajectory plan, predicted ephemeris, and maneuver command file.

ORBIT DETERMINATION OPERATIONAL PROCESS

From this point forward, the filter-smoother operational orbit determination process was completed almost daily. The operational orbit determination process included:

1. Tracking data preprocessor – input tracking activity report (TAR) to exclude tracking measurements during spacecraft slews; examine tracking files for containing expected data; validate tracking measurement files.
2. Orbit Determination & Maneuver Calibration – Run Filter & Smoother; iterate on solving for maneuver (if needed); produce standard set of graphs and reports including residual ratios (example Figure 9), residuals for each measurement type and/or tracker, measurement summary by altitude (Figure 10 and Figure 11), tracker biases, filter position uncertainty (Figure 12), smoother position uncertainty (Figure 13), maneuver reconstruction reports, filter-smoother consistency (Figure 14)
3. OD Trending – Compare previous several days' predicted radial, in-track, and cross-track position uncertainties with the difference between the definitive and predicted radial, in-track, and cross-track positions. (Example shown in Figure 15: Example OD Trending "Overlap" Analysis)
4. Database Update – Validate solution. Promote outputs.

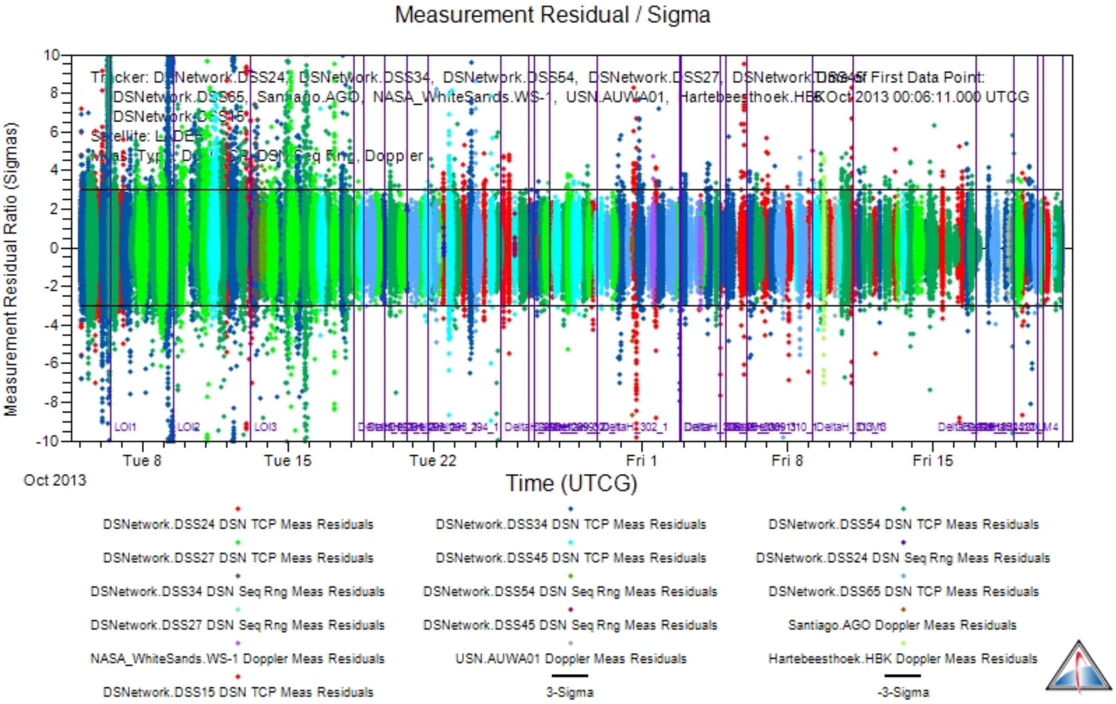


Figure 9: Example Residual Ratios Graph for an OD Run – LOA & Commissioning Phases

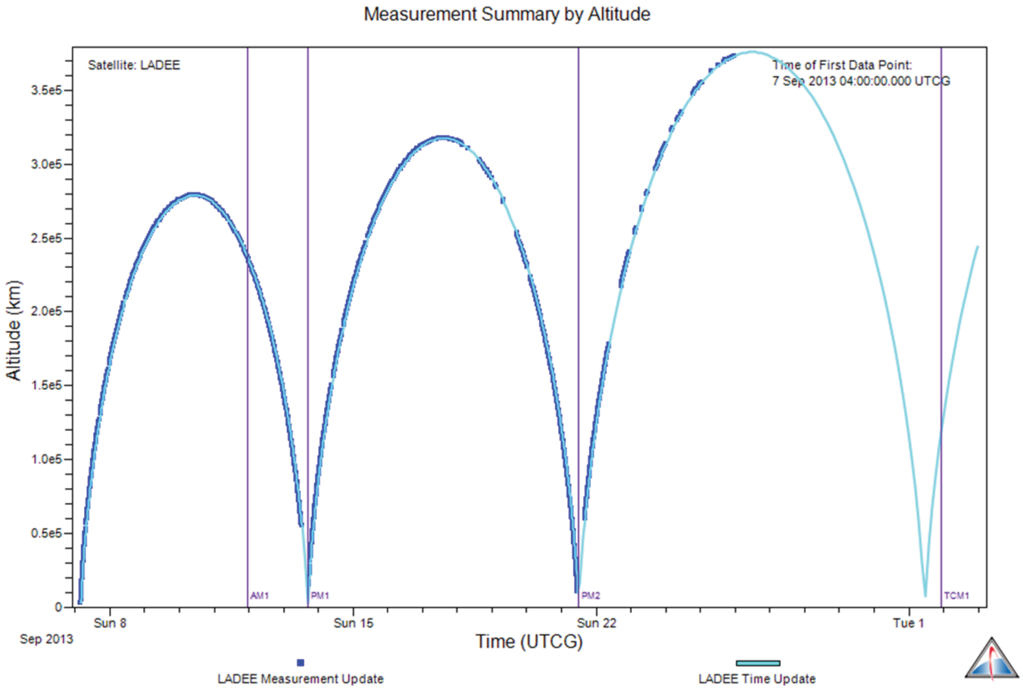


Figure 10: Example Tracking Measurements by Altitude Graph – Cislunar Phase

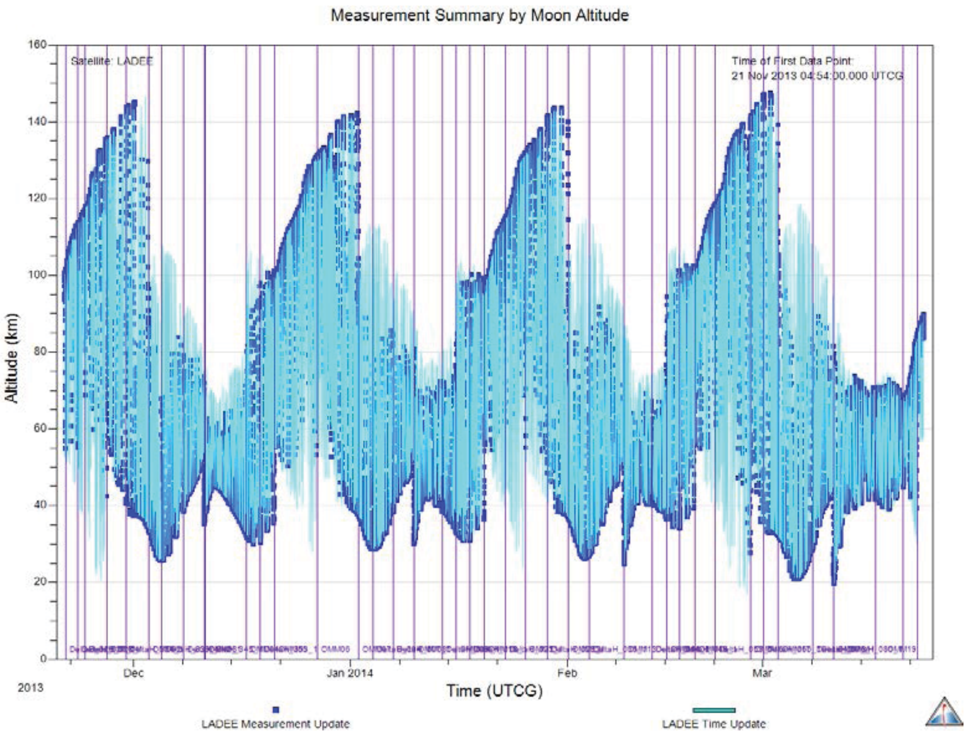


Figure 11: Example Tracking Measurements by Altitude Graph - Science Phase

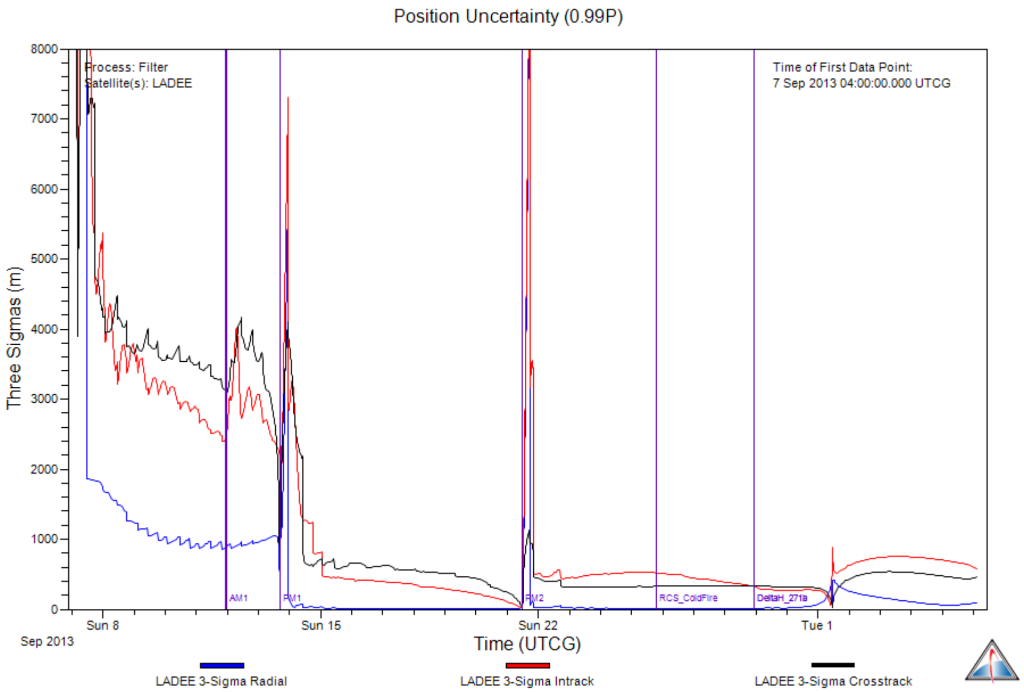


Figure 12: Example Filter Position Uncertainty Graph - Cislunar Phase

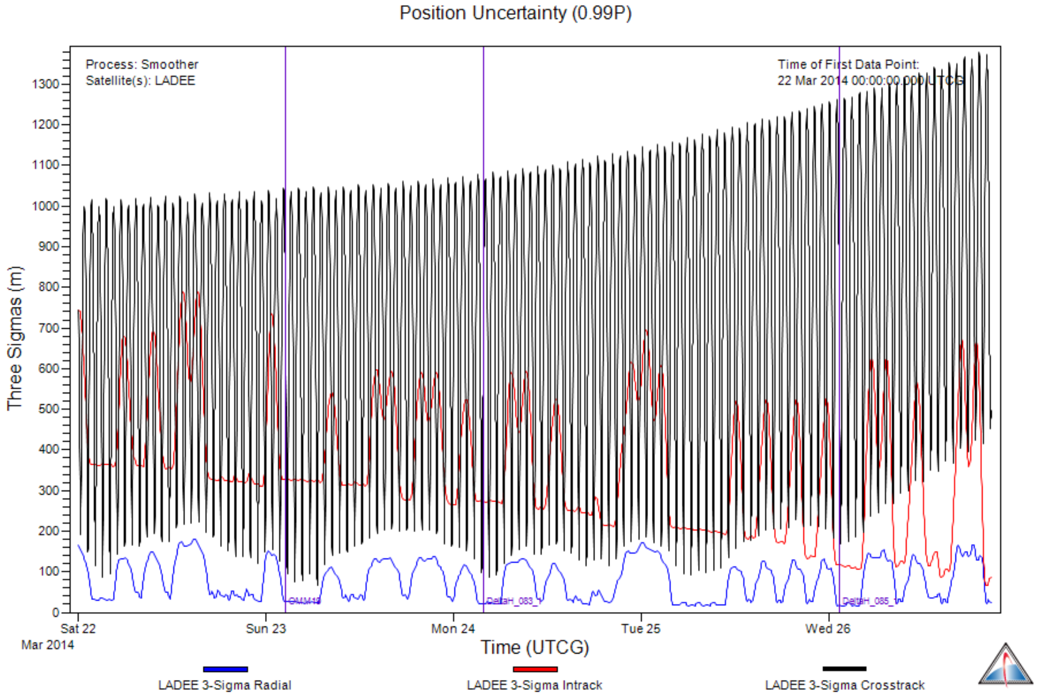


Figure 13: Example Smoother Position Uncertainty– Science Phase 5-Day OD Run

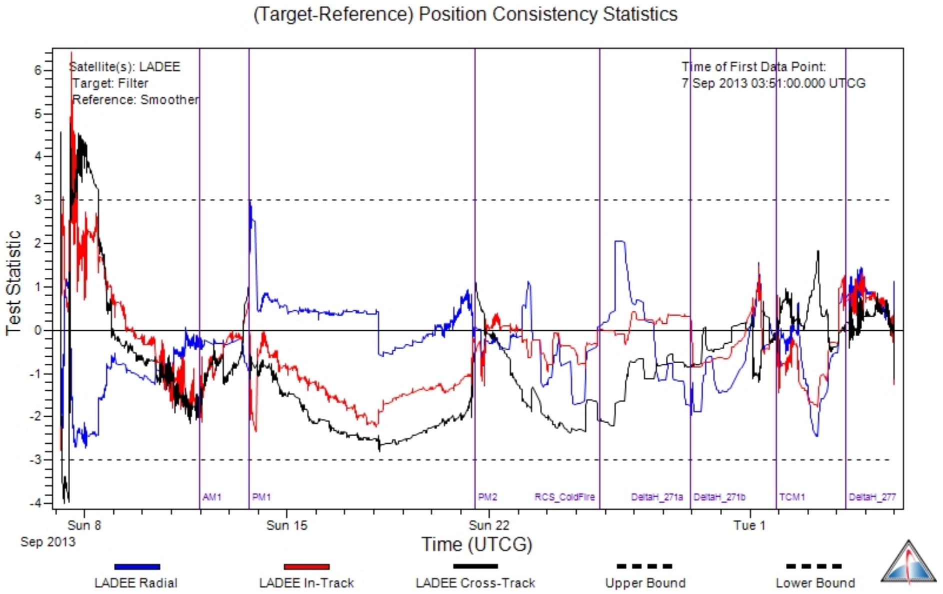
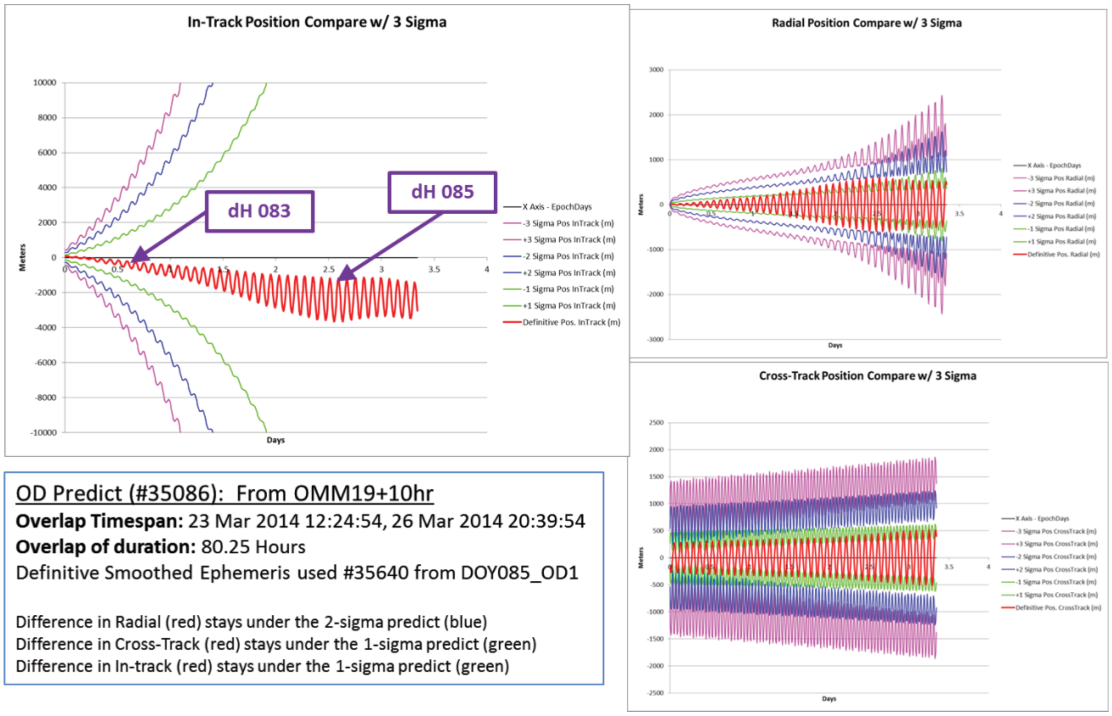


Figure 14: Example Filter-Smoother Position Consistency - Cislunar Phase

The OD process created new definitive ephemeris and new predicted ephemeris each time. All of our ephemeris products are in the STK .e format with 6 x 6 position and velocity covariance. Note that our process ended with "validating" a new solution set of a new OD solution, including "promoting" a predicted ephemeris and a definitive ephemeris for use by other flight dynamics team members. Uses of these ephemerides were for maneuver planning and for data product generation such as the previously-described acquisition data, as well as for attitude planning to create the activity plans.

Overall the orbit predictions we produced met and exceeded the prediction accuracy requirements: radial position accuracy of +/- 2 km (3-sigma) and in-track position accuracy +/- 20 km (3-sigma) at least 84 hours in advance of the start of the prediction interval. We used overlap analysis to monitor that our predicted ephemerides were accurate. An example of an overlap analysis is shown in Figure 15. In this example the difference between the predicted and the definitive (red) is less than 4 km in-track, less than 1 km radial, and around 0.5 km cross-track over a 3.5 day span. This span also included two momentum dumps which were not part of the predicted ephemeris. We successfully used this trending tool every-other day to monitor OD solution updates and to characterize the predict ephemeris uncertainty for the activity planning process.



OD Predict (#35086): From OMM19+10hr
Overlap Timespan: 23 Mar 2014 12:24:54, 26 Mar 2014 20:39:54
Overlap of duration: 80.25 Hours
Definitive Smoothed Ephemeris used #35640 from DOY085_OD1

Difference in Radial (red) stays under the 2-sigma predict (blue)
Difference in Cross-Track (red) stays under the 1-sigma predict (green)
Difference in In-track (red) stays under the 1-sigma predict (green)

Figure 15: Example OD Trending "Overlap" Analysis

We also applied our OD event trending tool to aide in maneuver planning since our orbit prediction results had to be accurate enough for the maneuver planning activities. For the orbits when a maneuver is planned, the predicted time of periapsis or apoapsis, and the uncertainty in that time was trended as each periapsis/apoapsis is approaching. An example of the event trending tool is shown in Figure 16. In this example, we were trending the time of the periapsis for orbit maintenance maneuver #14, which was planned for a periapsis on Feb 15, 2014 around 03:56 UTC. We began trending the uncertainty in the time of the periapsis five days in advance, and by Feb 13th the uncertainty in the time of the periapsis was under 5 seconds (1-sigma). This technique was used for trending every maneuver event, during all phases of the mission. By trending each new OD solution, our team was able to assess if the solution was converging quickly enough, and if not we could have requested additional tracking passes.

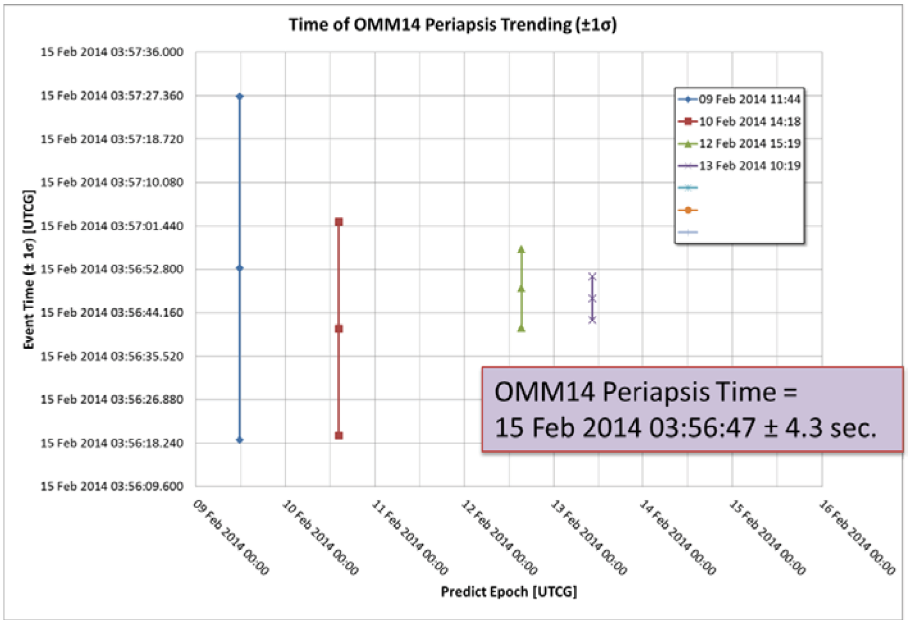


Figure 16: Event Prediction Trending Tool example

LLCD OPERATIONS

To support the LLCD during the LADEE commissioning phase, we needed to provide a predicted ephemeris accurate enough for planning purposes, and for pointing the Lunar Lasercom Ground Terminal (LLGT) at the Lunar Lasercom Space Terminal (LLST). To support planning, FDS created a product called the "LLCD Ephemeris File" which was to contain time; and the positions and velocities of both the LADEE spacecraft and the LLGT position, in Earth Centered Inertial (ECI) Mean Earth Equator and Mean Equinox of J2000 coordinates. The accuracy was required to be better than 30 km position (vector) 3-sigma, and better than 0.01 km/s velocity (vector) 3-sigma during the span of the product.

For commanding and pointing the LLGT to acquire LADEE during LLCD operations, the FDS created a product called the "LLGT Pointing Angle File," which contained the Range, Range-Rate, as well as the Azimuth and Elevation angles from the LLGT to the spacecraft, with accuracy better than 75 microradians (3-sigma). In addition, the file had to contain "point-ahead" azimuth and elevation angles, which were defined as the direction to point the uplink laser beam to hit the spacecraft accounting for round-trip light travel time. These point-ahead angles had an accuracy requirement of less than 0.5 microradians (3-sigma). The "point ahead" was defined as the difference between the received light and the transmitted light when both ground and space terminals are pointing at one another. These values had to include the velocity aberration effect due to the relative velocity between the moving spacecraft and the moving LLGT, which is, of course, on the rotating Earth.

It took a lot of coordination between the LLCD team at Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL) and our LADEE Flight Dynamics Team, ensuring that the coordinate systems and definitions were consistent. We also worked with Analytical Graphics to ensure that the correct settings were applied to Satellite Tool Kit, which was used to make the products. In particular, it was important to use the correct light-time delay and aberration settings. MIT/LL confirmed that these settings in STK created results that matched their development code.

In order to test the software systems prior to launch, the MIT/LL LLCD team suggested that the Flight Dynamics Team produce files for a phantom spacecraft that would match the observed positions of the stars Betelgeuse and Arcturus. (Using the observed stellar positions directly from the Hipparcos 2 catalog would not be a sufficient test, since the Flight Dynamics workflow was to use a predicted spacecraft ephemeris from orbit determination, and create the LLCD & LLGT products from that.) The Flight Dynamics Team created an artificial ephemeris for each star representing a phantom spacecraft 10^9 km from Earth, and used these to create the products. MIT/LL used these products to point their telescopes and were able to verify the accuracy by observing the appropriate star in the field of view.

Our team's support of the LLCD allowed for the successful operations of the LLCD, which met all of its objectives. LLCD used a pulsed laser beam and transmitted data from the Moon to Earth at 622 Mb/s download rate; it also demonstrated data upload rates of 20 Mb/s on a laser beam transmitted across 400,000 km[5].

ORBIT ACCURACY RESULTS

Additionally we were required to provide definitive satellite ephemeris to an accuracy of +/- 1 km radial, +/- 3 km in-track, and +/- 3 km cross-track (3-sigma) position, covering the commissioning and science phases. The definitive ephemeris is required for processing the science collections. We provided the long term definitive ephemeris updates throughout the mission by posting an update to the LADEE Project twice a week going back to the beginning of commissioning (November 21, 2013) through the most recent tracking pass. Figure 17 and Figure 18 are examples of the definitive uncertainty results from the Science Phase; these graphs also include the April timeframe which is extended mission.

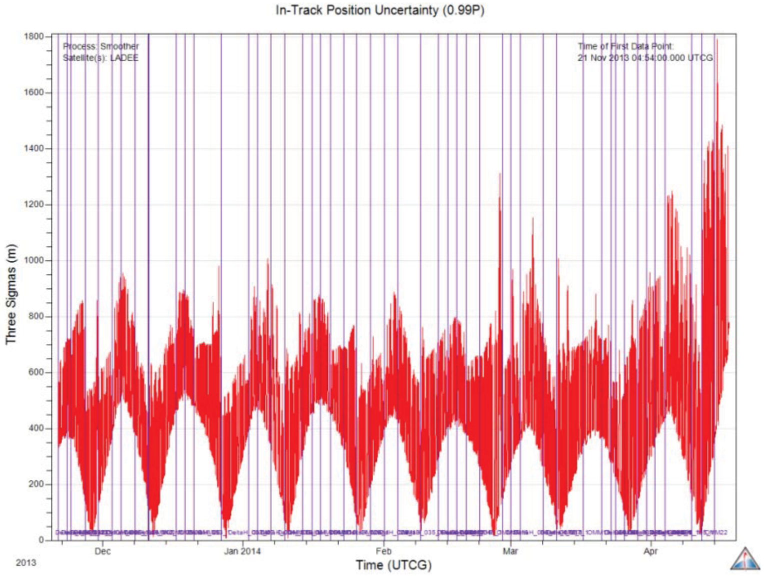


Figure 17: Smoothed 3-Sigma In-Track Position Uncertainty for Science Phase

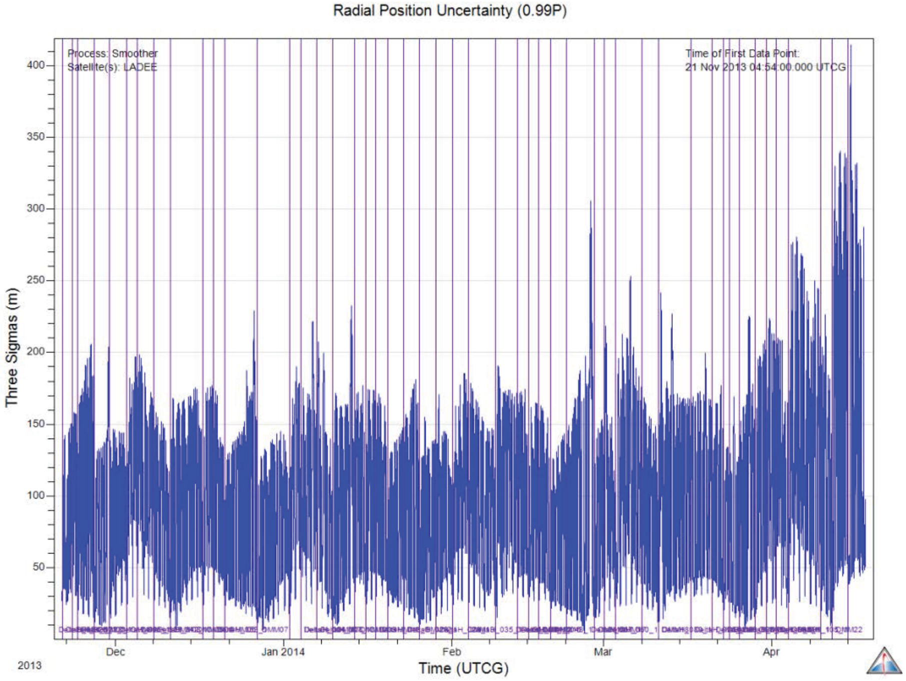


Figure 18: Smoothed 3-Sigma Radial Position Uncertainty for Science Phase

Table 6 lists the orbit accuracy requirements from Table 1 along with the achieved worst case results throughout the nominal science mission. These results were taken from the overlap tests that were completed between each OMM. For example, take the post-OMM15 to pre-OMM16 overlap analysis; the radial, in-track, and cross-track position differences were taken between the predicted post-OMM15 ephemeris and the pre-OMM16 definitive ephemeris throughout the 3.5 days after the post-OMM solution. The maximum difference during that timespan was logged for each direction. (This was computed for each of the OMM-to-OMM spans.) Then the worst case for each direction (radial and in-track) was taken from those calculations and logged.

The actual definitive accuracies were taken from the complete science smoother run, which is also shown in Figure 17 for in-track and Figure 18 for radial. The extended mission (April timeframe) is not included or held against these requirements.

Table 6: Orbit Accuracy Requirements & Performance During Nominal Science Mission

	Requirement (3-σ)	**Achieved Worst Case**
Predict Radial @ 84-hr	+/- 2 km	0.64 km
Predict In-Track @ 84-hr	+/- 20 km	<5 km
Definitive Radial	+/- 1 km	0.31 km
Definitive In-Track	+/- 3 km	1.31 km
Definitive Cross-Track	+/- 3 km	1.38 km

CONCLUSION

Our pre-launch orbit determination plan and acquisition strategies were successful in LADEE mission operations. The IOD tools and methods, with the acquisition update plan, and the ground stations we had scheduled, provided us with the necessary data and procedures to inform the mission management of trajectory status in a timely manner. The orbit determination process that we planned for and followed throughout the mission allowed us to meet mission requirements for the activity planning process, maneuver planning, and science data processing. The LLCD products that we generated allowed for successful mission operations for the technology demonstration. We had all of the tools, products, processes, and procedures in place, which were automated by the FDS, to do our jobs to carry out a successful LADEE mission, and take it into extended mission.

ACKNOWLEDGEMENTS

This work was done under prime contracts to Applied Defense Solutions Inc and to SGT Inc by direction from the NASA Ames Research Center at Moffett Field in Mountain View, CA. We could not have done our jobs in LADEE orbit determination and acquisition operations without the talents and contributions from our additional flight dynamics team members: Laura Plice (Metis Technology Solutions), lunar trajectory design lead and team lead; Michel Loucks (Space Exploration Engineering Corp), cislunar and LOA trajectory design lead; Alisa Hawkins (Google Inc/The Aerospace Corp) maneuver planner; and Ken Galal (NASA Ames), attitude design lead. We must especially acknowledge Matthew D'Ortenzio, LADEE Mission Operations Manager and Dr. John Bresina, LADEE Mission Planning & Sequencing Lead (both NASA Ames) who appreciated the technical details and the approach to flight dynamics operations which our flight dynamics team brought to the LADEE mission. We also thank the entire Flight Dynamics System Team and Ames Multi-Mission Operations Center Team who put together the software and infrastructure which enabled our team to perform the LADEE flight dynamics mission operations.

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[2] L. Policastri and J. Carrico "LADEE Orbit Determination Plan", NASA Ames Research Center, Moffett Field, CA, Document No. C77.LADEE.ODP. June 19, 2013

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