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PRE-LAUNCH ORBIT DETERMINATION DESIGN AND ANALYSIS FOR THE LADEE MISSION

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The Lunar Atmospheric Dust Environment Explorer (LADEE) successfully launched on September 7, 2013. The LADEE mission requirements relevant to orbit determination are listed. The orbit determination plan for each mission phase is described. Ground station assumptions, tracking schedule assumptions, timelines, goals, methods, and analysis results including gravity modeling approaches are discussed. The authors also present how testing with other operational spacecraft was used to verify the tracking plans and configurations prior to launch. Details are given on the analysis for the launch and early orbit phase as well as the nominal operations.

INTRODUCTION

The Lunar Atmosphere and Dust Environment (LADEE) mission was a NASA mission that orbited the Moon's equator with the goals of characterizing the atmosphere and dust environment of the Moon. LADEE launched on a Minotaur V from the Wallops Flight Facility in Virginia in September 2013, and used a phasing loop strategy to accommodate launch dispersions and raise apogee to lunar distance. Then through a series of lunar orbit insertion (LOI) maneuvers, LADEE captured into lunar orbit where it was commissioned and its science mission was executed. Due to LADEE's science requirements, planning for orbit determination operations was a critical activity. The purpose of this paper is to summarize the results of our analyses, prior to mission execution, which created the Orbit Determination Plan[1]. Mission and science activity planning; lunar gravity analysis and modeling; tracking schedules and measurement types; tools and techniques; and system verification are all components that comprised and influenced the LADEE Orbit Determination Plan. Results from this plan drove LADEE Mission Operations System (MOS)–wide planning, and they contributed to the development of the concept of operations.

The entire mission planning timeline heavily influenced the Orbit Determination Plan, and vice versa. To design and meet LADEE mission activity planning goals, our LADEE Flight Dynamics Team had to provide orbit ephemeris with uncertainty predictions that met specific accuracy requirements up to 3.5 days in advance of when the science activity would take place. No orbit ephemeris would be stored on board the spacecraft and no orbit propagation would take place on-board. Mission timelines, on board automated time sequences (ATS), science collections, orbit uncertainty predictability, and attitude planning all played a role in the accuracies and operations cadence.

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The science goals of this mission required that the LADEE science mission orbit was to be low, near-equatorial, and retrograde. Due to this orbit design, and Earth-based tracking geometries, LADEE is only ever observable from Earth during half of each lunar orbit, which greatly impacted the tracking opportunities, and therefore influenced the Orbit Determination Plan. Based on simulations, we created a tracking schedule that would provide enough tracking data to guarantee we would meet orbit accuracy needs, while minimizing interruption to science collections.

In addition to studying the tracking schedule, we considered tracking measurement types and tracking system accuracies in our design approach. We considered the tracking types and stations most suitable for post-launch initial orbit determination and phasing loops operations, which differed from what was needed for critical lunar orbit capture, and also differed for routine operations at the Moon. Therefore, the Orbit Determination Plan varied based on LADEE's orbit regime.

The uncertainty in lunar gravity modeling was also considered a major design driver for our Orbit Determination Plan. Our team performed studies which revealed that LADEE's low, lunar equatorial orbit would be affected by the lunar gravity model and its uncertainty more heavily than lunar polar orbiters. We then prepared a plan on how operationally we would handle the effects from the uncertainty in the lunar gravity modeling in our orbit uncertainty predictions.

LADEE mission operations was to be performed at the NASA Ames Research Center's Multi-Mission Ops Center (MMOC) facility. Flight dynamics processing is a component of the mission operations segment which includes flight dynamics personnel and a flight dynamics system. The flight dynamics roles at Ames include maneuver planning, maneuver reconstruction/calibration, attitude planning, and orbit determination for all mission phases. The Orbit Determination Plan takes all of the software into account needed for these functions.

Trained orbit determination analysts use the Ames Flight Dynamics System (FDS) for LADEE orbit determination operations. The FDS implements procedures and methods as sets of scripts that drive commercial-off-the-shelf (COTS) software, which is the basis for the FDS. The COTS software being utilized by LADEE Flight Dynamics is Analytical Graphics, Inc.'s Orbit Determination Tool Kit (ODTK) and Satellite Tool Kit (STK).

Verification for the entire end-to-end system was also part of our team's strategy to prepare for LADEE orbit determination operations. Our team worked with two operational spacecraft mission teams and with two ground stations to verify the acquisition and tracking process with the new FDS. The entire verification included FDS acquisition data generation processing, sending those files out to the ground stations, the ground antennas tracking real operational spacecraft in auto-track mode, and receipt of tracking measurement files at the Ames MMOC.

ORBIT DETERMINATION REQUIREMENTS

The mission and science activities specified the predictive and definitive orbit ephemeris accuracies. From these accuracies, the LADEE Project defined orbit determination requirements, which are listed in Table 1.

Table 1: LADEE Orbit Determination Requirements

Requirement ID	Requirement	Rationale
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.
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). COMMENT: From the orbits being considered for LADEE, the worst case in-track prediction uncertainty at 84 hours is approximately 12 km (see LADEE Lunar Orbit Prediction and Gravity Analysis[2] document, p. 47). Previously, 50-km by 50-km orbits were analyzed which produced worse results with an in-track prediction uncertainty at 84 hours of 26-km (p. 44), but that orbit is no longer being considered. Other orbit states were examined which produced even worse in-track predictions, but this investigation is on-going.
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.
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.
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.
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.
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. COMMENT: This requirement refers to distribution of these products outside of flight dynamics.

Predictive Orbit Uncertainty Requirements

The most stringent accuracies from all three of the science instruments were used to define the predicted accuracies in MOS-26 and MOS-57, listed in Table 1. Figure 1 is a graphic that portrays how the spacecraft's UV Spectrometer (UVS) instrument's pointing requirements are related to in-track error. (In this diagram the spacecraft is represented as blue boxes). Here the depiction shows that if the orbit in-track error is too great, the spacecraft attitude will be wrong at the time of the science measurement, because the UVS boresight will be pointed incorrectly.

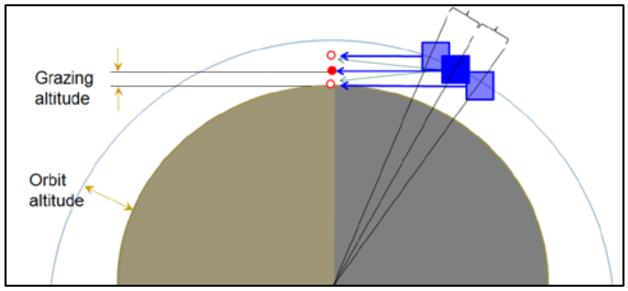


Figure 1: In-Track Position Error Derives from the Spacecraft Pointing Error Requirement

The mission operations cadence was planned such that a new activity plan would be generated every other day during the Tactical Planning Process, and the resulting activity plan would be of 3.5 days duration. The first 2 days of the plan would be a primary plan, and the next 1.5 days is considered a "Roll Out" or back up, since it would be re-planned during the next session. Nonetheless, in the event that the next plan was unable to be uploaded on schedule, the ATS would contain a full 3.5 days of activities, and the orbit ephemeris used for that entire plan had to meet accuracy requirements. Figure 2 shows an example of the Tactical Planning Process, where each group of three days is a full ATS of activities. In each group of three days, the yellow-color days are intended for execution, and the grey day is considered the "Roll Out" plan. This process is where the "84 hours" (or 3.5 days) duration for the orbit determination prediction requirement originates, for requirements MOS-26 and MOS-57. For simplification, the graphic shows the plan in blocks of 3 days instead of 3.5 days.

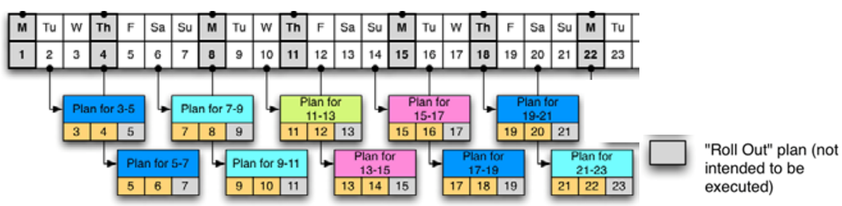


Figure 2: Example of Tactical Planning Process

This short 3.5 day tactical planning process was initially driven by results from early orbit determination simulation analysis from when the science orbit trajectory designs were still undergoing trade studies. We examined results from various trajectories to determine worst case orbit uncertainty predictions, and agreed with the science team and mission planning team that a 3.5 day prediction was achievable for worst case conditions.

Additionally, although not specifically called out in the official requirements list, the OD Plan accounted for the acquisition requirements from the ground stations. The orbit prediction must be accurate enough to use for spacecraft acquisition for tracking the satellite from all specified ground stations. The ground station pointing errors are specified at 36 hours prior to track start in Table 2. These criteria were derived from LADEE communication system assumptions.

Table 2 Ground Station Acquisition Orbit Accuracy Requirements by Orbit Regime

LADEE Orbit Regime	Required Accuracy for Acquisition
Cislunar below 50,000 km	< 0.2 degrees prediction error
Cislunar above 50,000 km	< 0.09 degrees prediction error
Commissioning and Science Phase	< 0.09 degrees prediction error

Orbit prediction results also needed be accurate enough for supporting trajectory maneuver planning activities. For the orbits when a maneuver is planned, the predicted time of periapsis or apoapsis, and the uncertainty in that time is trended as each periapsis/apoapsis is approaching. Our team provides this data as input to the maneuver planning process so that the mission operations team can understand the uncertainty in:

- Time of periapsis/apoapsis - and how this directly affects calculating the ignition times for maneuvers
- Velocity vector direction at periapsis/apoapsis - which is then used as the thrust vector for maneuvers
- Trajectory resulting from the planned maneuver – is it accurate enough to meet mission requirements

The orbit determination process for analyzing predicted orbit accuracy actively supports the maneuver planning process. By trending the solutions as they are processed, our team can be proactive to assess if the solution is converging quickly enough, and if needed, plan additional tracking supports to collapse the uncertainty for accurate maneuver planning.

Definitive Orbit Uncertainty Requirements

The definitive orbit ephemeris accuracy requirements are described in MOS-55, MOS-56, and MOS-25, listed in Table 1. Those “definitive” requirements were strictly driven by the accuracies needed to correlate the science measurement collections. The definitive accuracy requirements were what primarily drove tracking schedules, ground station considerations, and maneuver recovery schedules. We needed to be certain that the orbit would be known well enough for the science processing, therefore we performed a series of simulations to prove it would. Ground stations, tracking schedules, and tracking measurement types were all varied in the simulations. Our team had to answer the question: “What is the maximum time between tracking contacts?” during LADEE’s science mission, and still meet the definitive orbit accuracy. This analysis is described in the Science Phase Orbit Determination section.

GROUND NETWORK

Our flight dynamics team was a key stakeholder in the ground networks chosen for the LADEE mission. We understood the tracking challenges for the LADEE mission from the flight dynamics perspective, looking at orbit determination requirements, maneuver recovery needs, and the acquisition process, for example. We worked with the MOS Lead and ground network representatives to create a set of ground stations necessary to support the LADEE mission fully for telemetry, tracking, and commanding (TT&C). The list of ground stations and their general properties are shown in Table 3 and the antenna locations are shown in Figure 3.

Tracking Stations Selection

Ground stations from the NASA’s Near Earth Network (NEN), the Universal Space Network (USN), and NASA’s Deep Space Network (DSN) comprise LADEE’s ground network. The selected NEN and

USN antennas all provide auto-track angle measurements and two-way Doppler. The DSN is the primary network for LADEE, and provides two-way Doppler and sequential ranging tracking types.

Table 3 LADEE Ground Stations (Pre-Launch Plan)

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-45, DSS-65 Canberra, Australia Madrid, Spain	34	2-way Doppler, Sequential Ranging	DSN	TT&C
High Speed Beam Wave Guide (HSB) DSS-27 Goldstone, CA	34	2-way Doppler, Sequential Ranging	DSN	TT&C

Figure 3 LADEE Ground Station Antenna Locations

Tracking Measurement Files

The NEN and USN stations provide tracking measurement files in Universal Tracking Data File (UTDF) format. The DSN provides tracking measurement files in the TRK-2-34 format. All tracking file formats, acquisition data file formats, tracking sample frequencies, file delivery methods, and delivery frequencies for each station were documented in the LADEE Products, Formats, and Exchanges Interface Control Document[3] and in the LADEE DSN Operational Interface Control Document[4].

Even when we received the tracking files as planned, we knew that the information within the files would not always be perfect. Some of the reasons that tracking measurement files contain invalid information or unusable tracking measurements are:

- Software configuration problems at the ground station antenna, at the ground station control center, or on the spacecraft transponder

- Hardware problems at the ground station antenna, at the ground station control center, or on the spacecraft transponder
- Unknown or unanticipated interference on the ground or on the spacecraft
- Spacecraft spin rate or other attitude causes tracking data drop outs which may create invalid points near the drop out and re-acquire times

We designed a tracking data preprocessor procedure to screen for invalid and abnormal data as soon as we receive the UTDF and TRK-2-34 files. This enables the orbit analyst to detect and diagnose problems before ingesting undesirable measurements into any orbit estimation process.

ASTRODYNAMICS MODELING

Our flight dynamics team chose early on to use consistent settings for force model parameters, propagators, coordinate system definitions, and reference files during design and analysis, and we needed to solidify that moving forward for LADEE mission operations. The models planned for LADEE mission operations were coordinated between the Orbit Determination Plan and the LADEE Trajectory Design Plan for each Earth and Moon phase. The two gravity models chosen for LADEE are EGM2008 and LP150Q. (New lunar gravity modeling results from the lunar GRAIL mission were not available in time for LADEE analysis or operations.) The positions of the Sun, Moon, and planets are based on the JPL DE421 definitions. The details of all force model settings and propagator assumptions are completely documented in the LADEE Astrodynamics Modeling document[5]. Another document, LADEE Flight Dynamics: Coordinate Systems and Time Reference Systems[6], contains all details about time and coordinate systems to be used as standards for the LADEE mission. It is important that we researched and specified all of these definitions in advance so that any errors found between orbit estimations and trajectory designs could not be ascribed to modeling differences.

ORBIT DETERMINATION BY PHASE

Table 4: Phase Descriptions for Orbit Determination Purposes

Phase	Phase Start	Phase End	Duration (days)
Initial Acquisition & Initial Orbit Determination	Launch	Apogee 1 (worst case)	1 to 3
Cislunar Trajectory & Lunar Transfer	Prior to Apogee 1	LOI Maneuver 1	26 to 28
Lunar Orbit Acquisition	LOI Maneuver 1	Lunar staging orbit (250 km x 250 km)	3 to 6
Commissioning Orbit	Lunar staging orbit (250 km x 250 km)	Commissioning activities complete	40 to 60
Mission Orbit	Based on commissioning end	Science complete	100+

Each phase of the LADEE mission had a specific plan for orbit determination which was designed to meet the requirements for that phase. Each phase of the LADEE mission correlates to either a different orbit regime or different purpose of the mission, therefore we specified separate tracking needs by phase. The phases defined for the Orbit Determination Plan are listed in Table 4.

Initial Acquisition & Initial Orbit Determination

Because of the Minotaur V's potentially wide range of launch dispersions[7], we created an initial tracking and initial-orbit determination (IOD) strategy that included ground stations with auto-track capability. This strategy was important so that a ground station antenna could lock onto the spacecraft in auto-track tracking mode, essentially providing physical measurements and information to mission control. During this initial phase, the auto-track NEN and USN antennas were to operate in parallel to the DSN antennas, auto-tracking without going coherent. Meanwhile the DSN antennas (which are only programtrack capable) can attempt to go coherent providing telemetry and commanding services, as well as two-way Doppler and ranging.

For the initial state, the Minotaur V's Stage 5 burnout vector was to be delivered via e-mail by Orbital Sciences (the launch provider) to the MMOC within an hour of burnout. The spacecraft enters Safe Mode or Rate Reduction Mode after burnout and activation. In either of these modes, the spacecraft is spinning, and will continue for several minutes or hours until the spacecraft exits Safe Mode/Rate Reduction Mode. The first ground contact opportunities with HBK and with CAN occur when the spacecraft is still spinning at higher rates, therefore the ground station may only be capable of intermittent tracking. Table 5 describes a high level IOD timeline with spacecraft events relevant to tracking.

Table 5: Spacecraft Activation Events and IOD Timeline

Event	Approximate Minutes Past Launch	Comments
Stage 5 Burnout	27	
Spacecraft Activation		Receiver & Transmitter On, S/C in Idle Mode
HBKView	27	Auto-track attempts begin with nominal acquisition files
Reaction Wheels Enabled		S/C enters Safe Mode or Rate Reduction Mode
Canberra View	56	Canberra initially attempts acquisition in 1-way; commanded into 2-way
Receive first HBK UTDF	57	Begin receiving UTDFs from HBK in 15 min blocks
Begin assessing tracking measurements & begin IOD		
Receive Stage 5 Burnout Vector	90	E-mail from Orbital Sciences
Received first CAN TRK-2-34	90	Placeholder for nominal launch of when we would receive first TRK-2-34 from CAN
Assess/process Stage 5 Vector	120	Distribute new acquisition files based on Stage 5 vector
Provide first acquisition update based on tracking data		Approximately Launch plus 4 to 6 hours, deliver first acquisition file update based on IOD results

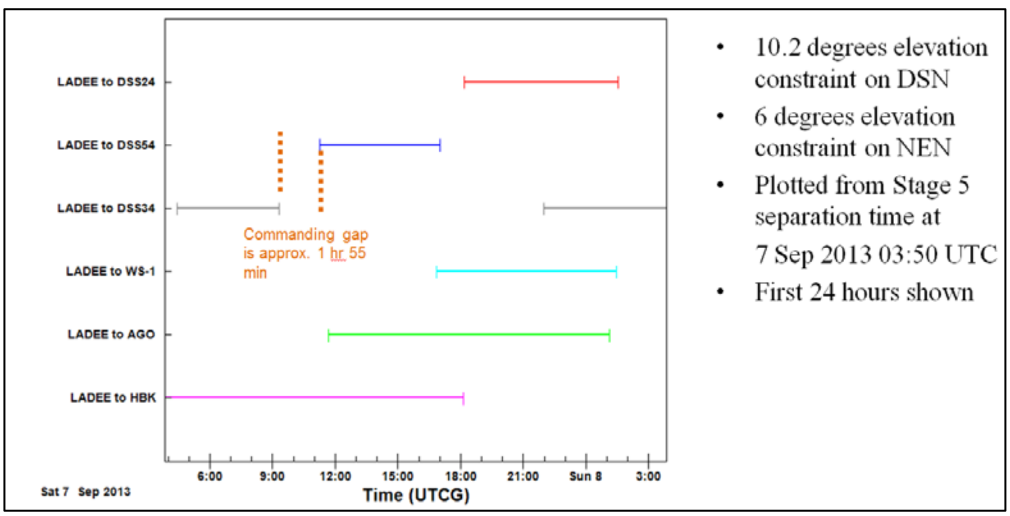


Figure 4: LADEE Ground Station Views Sept 7, 2013 Nominal Launch

Figure 4 represents the view periods on launch day for a nominal launch for the first 24 hours from six of the tracking locations. (AUWA01 not shown but has a similar view period to CAN/DSS34.) Several IOD methods could be used throughout this timeline. The IOD methods serve two purposes: 1) to generate products such as updated ephemeris files and acquisition data files, and 2) to produce initial states to seed the orbit determination filter. These methods do not require an *a priori* state, but they do require *a priori* information. The IOD methods can accommodate intermittent tracking, if received. This is important because the spacecraft is not expected to exit rate reduction mode (or safe mode) for up to 6 hours after Stage 5 separation. Many of the IOD methods require reference ephemeris files as an input. Prior to launch, injection ephemeris files for the nominal launch as well as the +/- 1, 2, and 3 sigma dispersions were to be cataloged and available as references.

The IOD methods and tools available in the FDS for LADEE are:

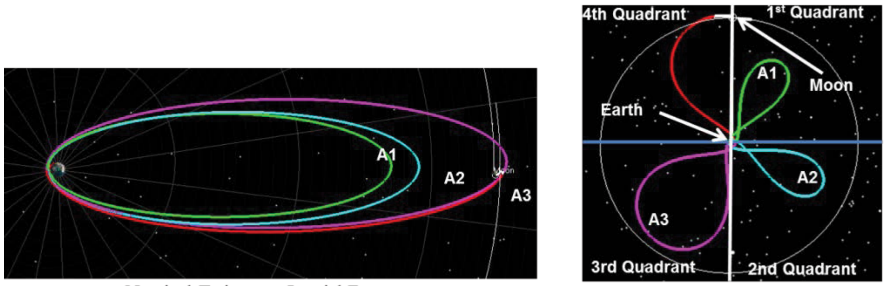
- Gooding Angles Only
    - Description: analytical, angles-only technique that is part of the ODTK software package
    - Input: Three pairs of Azimuth and Elevation (or X-Y) auto-track angle measurements, as well as and range estimates for the first and third measurement times
    - Output: orbit state
    - Initial use: 2 to 4 hours after tracking collection from HBK
    - Final expected use: 16 hours after launch
- Residuals versus Reference
    - Description: graphical assessment of measurement residuals; this is part of the ODTK software package; this provides a qualitative assessment of the observations in comparison to the predicted trajectories
    - Input: reference ephemeris files, and tracking data
    - Output: assessment of ephemeris files and selection of which to use for acquisition data
    - Initial use: immediately when tracking data is received
    - Final expected use: Filter initialization (approximately 12 hours after launch)
- iGatorOD
    - Description: Least squares technique which adjusts the Stage 5 burnout model to best match the collected tracking data
    - Input: Tracking measurements (angles, range, and range-rate); *a priori* launch burnout vector
    - Output: ephemeris files beginning at launch burnout, through a future point in time; updated burnout state vector
    - Initial use: immediately when tracking measurements are received
    - Final use: Filter initialization (approximately 12 hours after launch)

For IOD, we planned to have two OD analysts on staff per 12 hour shift. We can run these methods in parallel on separate FDS instances to compare, assess, and quality check IOD solutions. Within 6 hours of separation, new LADEE acquisition data will be delivered to the ground stations based on the results of the IOD solutions.

In addition to the IOD methods listed above, we can employ the ODTK Batch Least Squares (BLS) tool to calculate a state vector. It requires tracking measurements and an a priori state vector. The orbit state vector could be the result from any of the IOD methods or from a reference ephemeris. The BLS outputs a state vector which is used to test Filter initialization for orbit estimation. There was no plan to generate product deliverables from the BLS.

Cislunar Trajectory and Lunar Transfer Orbit Determination

Cislunar orbit determination begins after the IOD procedures yield a consistent estimate of LADEE's orbit state. This is expected to occur prior to the first apogee, within 24 hours after separation. This state will be used to initialize the filter. Figure 5 shows the LADEE cislunar trajectory plan for a nominal launch performance, with the three apogees labeled A1, A2, and A3; the Moon's position is also noted. We chose a phasing loop trajectory design strategy for this phase, which would raise the apogee over three orbits to lunar distance, aligning LADEE for a critical LOI maneuver[7].



Nominal Trajectory, Inertial Frame — Nominal Trajectory, Earth-Moon Rotating Frame

Figure 5: LADEE Phasing Loop Trajectory Plan Example

The tracking schedule assumptions from launch through lunar transfer are listed in Table 6. Events in this table are in reference to launch (L), a perigee (P), or a perigee maneuver (PM). This schedule is what is planned with agreement from the ground networks, as well as with the Tracking and Data Relay Satellite System (TDRSS). TDRSS is only used for monitoring the PMs.

Table 6: Tracking Schedule Assumptions from Launch through Lunar Transfer

Start Event	End Event	Track Length	Track Quantity	Stations	Events/Services
L+30 minutes	L + 1 day	Continuous	Continuous	DSN/CAN 34-m BWG DSN/CAN 34-m HEF DSN/GLD 34-m BWG DSN/MAD 34-m BWG NEN/USN	Initial acquisition TT&C (DSN) Tracking (NEN/USN)
L+24 hours	L + 10 days	Continuous	Continuous	DSN/GLD 34-m BWG DSN/CAN 34-m BWG DSN/MAD 34-m BWG	TT&C
L+24 hours	L + 10 days	30 minutes	1/day	NEN (AGO or WS1)	Tracking
L + 10 days	L + 22 days (post P3)	6 hours *	1/day	DSN/GLD 34-m BWG DSN/CAN 34-m BWG DSN/MAD 34-m BWG	TT&C
L + 10 days	L + 22 days (post P3)	1 hour (Every 3 hours)	5–6/day	DSN/GLD 34-M BWG DSN/CAN 34-m BWG DSN/MAD 34-m BWG NEN/USN	TT&C (DSN) Tracking (All)
PM1 – 1 hour	PM1 + 1 hour	2 hours **	1	TDRSS NEN/USN ***	PM1: Telemetry Commanding (TDRSS) Angle Tracking (NEN/USN)
PM2 – 1 hour	PM2 + 1 hour	2 hours **	1	TDRSS NEN/USN ***	PM2: Telemetry Commanding (TDRSS) Angle Tracking (NEN/USN)
PM3 – 1 hours	PM3 + 1 hour	2 hours **	1	TDRSS NEN/USN***	PM3: Telemetry

					Commanding (TDRSS) Angle Tracking (NEN/USN)
P3	P3 + 24 hours	Continuous	Continuous	DSN/GLD 34-m DSN/CAN 34-m DSN/MAD 34-m	TT&C
P3 + 24 hours	LOI-1 – 36 hours	6 hours *	1/day	DSN/GLD 34-m DSN/CAN 34-m DSN/MAD 34-m	TT&C
P3 + 24 hours	LOI-1 – 36 hours	1 hour (every 3 hours) *includes set up time*	5-6/day	DSN/GLD 34-m DSN/CAN 34-m DSN/MAD 34-m NEN/USN****	Telemetry (DSN) Tracking (All)

* Local time-of-day will be the priority in scheduling this track. The track should be scheduled during working hours in the Pacific Time Zone. Second priority in choosing station would be whether the full six hours could be supported on the same station without interruption.
** For pre-launch planning there will be a large uncertainty on the absolute placement of the 2-hour TDRSS track
*** 30-min angle tracking will be performed by whichever NEN/USN station is in view before and after the perigee.
**** NEN/USN antennas to be used for collecting two-way coherent Doppler when DSN is not available.

Beginning in the cislunar phase, the optimal sequential filter (and smoother)[8] becomes the primary orbit estimation technique for the remainder of the mission. We will use predicted-definitive overlap tools and filter-smoother consistency tests throughout as quality control metrics. Our team defined a set of routine reports and graphs for the FDS to produce for us to qualify and assess the tracking measurements and the orbit solutions. This routine set of products includes:

- Overlap comparisons between predicted ephemeris and definitive solutions
- Histograms of normalized residuals
- Realistic tracker bias values and trending behavior
- Position and velocity filter-smoother consistency tests
- Residual ratios and white noise assessment
- Realistic SRP correction
- Realistic transponder biases
- Rejected measurements vs. expected
- Absolute uncertainty in radial, in-track, and cross track directions, and in orbit period
- Realistic maneuver estimates and corrections
- Evolution and response of orbit uncertainty in position and in velocity
- 3-D graphical covariance trending for comparing predicted covariance to definitive

In the overlap comparison, the predicted and definitive ephemeris estimates are differenced, in radial, in-track, and cross-track directions. The differences are plotted against the predicted orbit uncertainty in each direction. Our orbit determination analysts are able to trend the predicted orbit uncertainty with the difference in predicted vs actual. This is an important tool, considering the uncertainty in the lunar gravity model and its effects in orbit covariance propagation.

The consistency tests and residual ratios products, for example, allow the analysts to trend tracking system information and perform knowledgeable filter tuning with the FDS. All of these products in some way aid the analysts in trending, tuning, and calibrating, in order to distribute the best estimated state to the mission operations team. These orbit determination products and tools are used throughout the mission for LADEE. These tools, along with maintaining a calibrated filter, are especially important for detecting unreported configuration changes at ground stations and potential spacecraft anomalies.

These tools are also important, qualified for, and useful for maneuver reconstruction. The plan, as described in Table 6, is to collect tracking measurements before and after all perigee regions, to solve for the perigee maneuvers using tracking measurements (as opposed to a separate, independent process to solve for the burns using telemetry). Due to the uncertainty in maneuver execution, orbit uncertainty grows during a maneuver, and we need the tracking data after the maneuver to collapse the orbit knowledge back down. We also need tracking data prior to the burn to have an accurate pre-burn best estimated trajectory for maneuver reconstruction.

The transition from Earth-centered orbit to a Moon-centered orbit has a special filter technique which is only planned for use for a short time, starting up to 2 days prior to LOI. We created a plan to transition the filter from an Earth-centered state to a Moon-centered state without the need to re-initialize the filter, or in other words without losing any built-up orbit knowledge. Both Earth-centered and Moon-centered filters are planned to be run in parallel for about a day until the Moon-centered filter is in steady-state, at which time the Earth-centered solution will be archived and abandoned, and the Moon-centered solution will be promoted to primary.

Lunar Orbit Acquisition Orbit Determination Plan

The Lunar Orbit Acquisition (LOA) phase uses the same orbit determination strategies as the cislunar phase, with a few modeling differences; this phase is modeled as Moon-centered. There are three LOI maneuvers in this phase, and a possible lunar apogee maneuver (LAM) depending on LOI-1 performance[7]. Figure 6 is an example of the planned LOA phase, showing three orbits resulting from three LOI maneuvers. The first orbit in yellow and white is a staging orbit with an orbit period of 24 hours. The blue orbit has an orbit period of 4 hours. The LOA phase ends with LOI-3 which is designed to place LADEE into its 250 km by 250 km (2.2 hour period) Commissioning orbit, which is shown in green in Figure 6. The tracking plan for the lunar orbit acquisition phase is listed in Table 7.

Since the LOI-1 maneuver is deemed critical, LADEE must be in view of ground stations during the maneuver. Additionally since the LOI-1 maneuver is critical, we are allowed to schedule a redundant DSN station before, during, and after the burn for back up TT&C, which is noted in Table 7.

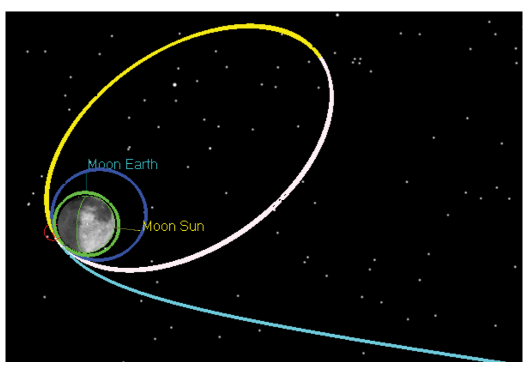


Figure 6 LADEE Moon Inertial Lunar Orbit Acquisition Phase Trajectory

Table 7: Tracking Schedule Assumptions for Lunar Orbit Acquisition Phase

Start Event	End Event	Track Length	Track Quantity	Stations	Events/Services
LOI-1 – 36 hours	End of Phase	Continuous	Continuous	DSN/GLD 34-m DSN/CAN 34-m DSN/MAD 34-m	TT&C
LOI-1 – 3 hours	LOI-1 + 3 hours	6 hours	1	Redundant DSN station	TT&C

It is the goal of the LOA orbit determination strategy to obtain sufficient tracking before and after each LOI maneuver in order to solve for each maneuver and collapse the orbit uncertainty as soon as possible after each maneuver. The quick recovery of each LOI maneuver is also needed to help rapidly plan subsequent activities and shift schedules. We are prepared to monitor specific orbit uncertainty parameters and trajectory properties at the periselene for each LOI, including:

- Cartesian uncertainty (X, Y, Z) in meters and (Vx, Vy, Vz) in meters/sec
- Velocity magnitude (meters/sec) and velocity azimuth (degrees)
- Horizontal flight path angle (degrees)
- Radial, in-track, and cross-track uncertainty in meters
- Time past periapsis in seconds

The same orbit determination trending metrics and filter-smoother techniques, as were described for the cislunar phase, are used for this phase and for the remainder of the mission. During the LOA phase we only plan to use the DSN for tracking, and have no intentions to use the NEN or USN. This LOA phase commences when LADEE completes its LOI-3 maneuver and it is in its 250 km circular orbit for Commissioning activities.

Commissioning Orbit Determination

One purpose of the this mission phase is for each of LADEE's three science instruments to undergo full testing and check-out activities. The additional purpose is for LADEE's Lunar Laser Communications Demonstration to compete its mission during this phase. This phase would last 40 days nominally, or up to 60 days if contingencies occurred. The tracking schedule assumptions for the Commissioning phase are shown in Table 8. The DSN is primarily planned to be used throughout this phase for tracking. If there were to be a scheduling conflict, our activity planners could add AGO or WS1 to augment the DSN availability.

During this phase, the orbit determination analysts planned to experience a similar cadence to science operations and will need to begin to use the tools to monitor the predicted and definitive orbit uncertainty and compare the results with the requirements. This Commissioning phase allows the team to exercise the processes tools in a similar pace for science operations. The effects of the uncertainty in the lunar gravity field in orbit predictions is expected to be of less significance in this higher lunar orbit than in the science orbit. This phase ends after two Orbit Lowering Maneuvers (OLM) are performed to bring LADEE down to its science mission orbit.

Table 8: Tracking Schedule Assumptions for Commissioning Phase

Start Event	End Event	Track Length	Track Quantity	Stations	Events/Services
Start of Phase	End of Phase (Orbit Lowering Maneuver)	65 min	12/day *	DSN/GLD 34-m DSN/CAN 34-m DSN/MAD 34-m NENAGO ** NEN/WS1 **	TT&C (DSN) Tracking (All)

* The time between tracks is driven by the period of LADEE's lunar orbit during the Commissioning Phase, estimated to be 135 minutes on average. Therefore the time between tracks is approximately 100 minutes.
** AGO and WS1 to be used when DSN not available.

To perform maneuver reconstruction after each OLM, first an orbit determination analyst uses all tracking up to prior to the OLM to create the pre-maneuver best estimated trajectory. Then the analyst uses the maneuver plan model with uncertainty, along with four to five orbits of post-maneuver tracking measurements to produce the post-burn orbit estimate. Both of these states are needed for the maneuver reconstruction and engine calibration process.

Science Phase Orbit Determination

The LADEE science mission orbit period averages approximately 113 minutes, yielding 12 to 13 orbits each day. Minimizing the tracking schedule is desirable to the LADEE mission operations team for scheduling ground station antennas and for simplifying mission timeline activities. A driving goal is to operate with a minimum tracking schedule that still meets all mission requirements for definitive ephemeris accuracy, predictive ephemeris accuracy, and allows for eight consecutive hours per day without interruptions to science.

Several tracking schedule variations were considered and analyzed, but we wanted something that was simple for scheduling if at all possible. The resulting minimum tracking schedule that meets both the definitive accuracy requirements and the science cadence needs consists of 30 minutes of two-way Doppler every four orbits, nominally. Then, when orbit maintenance maneuvers (OMM) are planned, an increased tracking schedule begins five orbits before each maneuver through five orbits after each maneuver; this OMM tracking scheme is outlined as follows:

- Maneuver minus 5 orbits: track 30 minutes
- Maneuver minus 4 orbits: track 30 minutes
- Maneuver minus 3 orbits: no tracking (tracking optional during operations)
- Maneuver minus 2 orbits: track 30 minutes
- Maneuver minus 1 orbit (or Maneuver Orbit): track 30 minutes
- Maneuver plus 1 orbit: track 30 minutes
- Maneuver plus 2 orbits: track 30 minutes
- Maneuver plus 3 orbits: no tracking (tracking optional during operations)
- Maneuver plus 4 orbits: track 30 minutes
- Maneuver plus 5 orbits: track 30 minutes
- Resume tracking 30 minutes every four orbits until 5 orbits prior to next OMM

Two tracking station groups, with each antenna's expected noise models included, were simulated for this analysis:

Group 1) DSN/MAD, DSN/CAN, DSN/GLD

Group 2) DSN/MAD, DSN/CAN, NEN/WS1

Both combinations provided sufficient tracking accuracies for meeting definitive orbit knowledge requirements. All DSN and NEN ground station measurement biases and sigmas were modeled based on simulations and real-data processing[1]. The LADEE Orbit Determination Plan uses these same statistics initially in operations, until more applicable, operationally-based statistics for the actual LADEE system are determined.

An example smoothed definitive position covariance graph for the tracking scheme is shown in Figure 7 where two months of lunar orbits were simulated containing 17 individual orbit maintenance maneuvers. This graph displays the smoothed definitive three-sigma radial (blue), in-track (red), and cross-track (black) orbit uncertainties. The vertical purple lines indicate the time of each maneuver. These results show that the planned tracking schedule meets all definitive requirements.

We also considered adding ranging tracking instead of Doppler-only during this phase[9]. The simulations showed that ranging provided no noticeable value in decreasing orbit uncertainty. We decided that operationally we would only request ranging for one track after each OMM in the event that it aided the team in performing maneuver reconstruction more quickly.

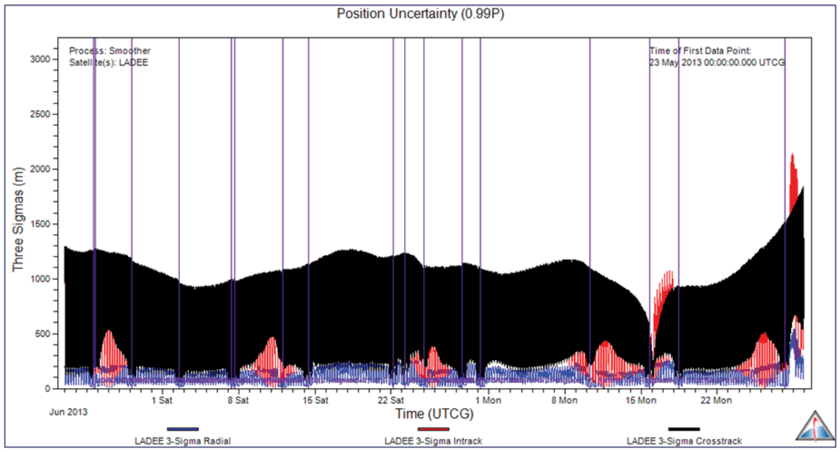


Figure 7: Science Phase Simulation Definitive Smoothed 3-Sigma Radial, In-Track, and Cross-Track Position Uncertainty

LUNAR GRAVITY MODELING EFFECTS

Early on when we performed the science phase simulations to begin defining our tracking schedules, we examined the resulting definitive and the predicted orbit uncertainties[2]. The predicted orbit uncertainties were not as we expected and grew very rapidly, as shown in Figure 8 and Figure 9. The results did not seem like they could be correct so we began an investigation into looking at real tracking data with the Lunar Reconnaissance Orbiter (LRO) [10] and working with the Chief Scientist for AGI's ODTK[11].

Prior to the LADEE mission, ODTK was only used for Earth missions, and had only recently been updated for lunar missions in 2009. In that year, our LADEE flight dynamics team was working closely with AGI to test and prepare ODTK for lunar mission operations. Our LADEE team had an agreement with NASA's LRO team to receive the LRO tracking files to process and test ODTK for a lunar mission.

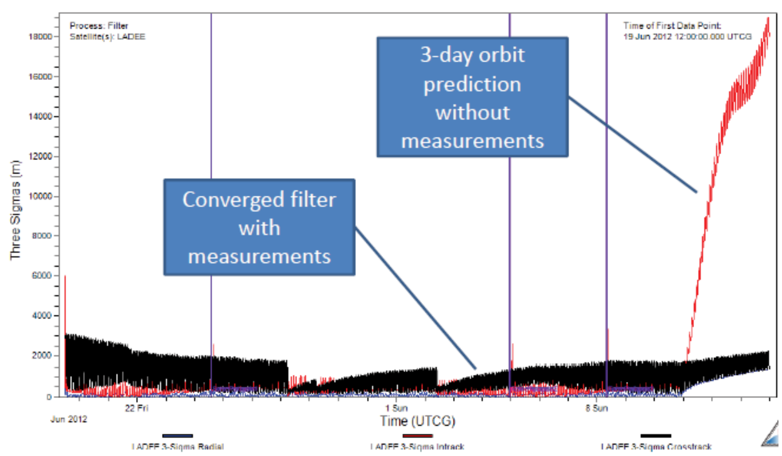


Figure 8: Simulation Results Showing Definitive and Predicted (Propagated) Orbit Covariance

ODTK is a commercial product used for orbit determination, error analysis, and as a tracking data simulator[8]. It has an optimal sequential filter, with physics-based process noise computed automatically, derived from force model selections, Gauss-Markov measurement model sections, uncertainty statistics and it outputs state estimations with realistic covariance. It uses physics based gravity process noise models for errors of commission and omission. The process noise model allows the orbit uncertainty to increase in a realistic way based on the actual uncertainties in the gravity field. The process noise model in ODTK was developed for Earth's gravity field, where some assumptions that are reasonable for Earth are not transferrable to the Moon, such as assuming that the planetary body is axial symmetric.

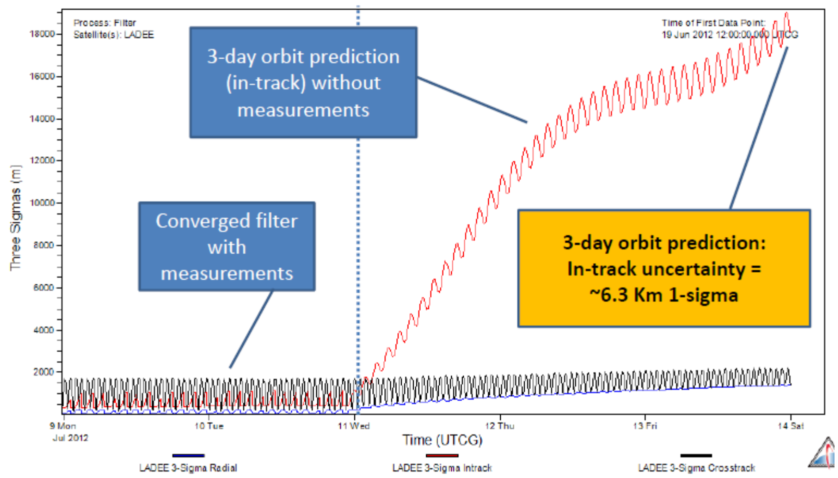


Figure 9: Zoomed in Graph of Predicted Covariance

The LRO orbit is different than LADEE's for two reasons: it is in a polar orbit and sometimes its entire orbit is observable from Earth. Tracking stations used by LRO were very similar to ones being considered for LADEE, and included ground stations from DSN, USN, and NEN.

We proceeded with our testing by first producing a set of simulated tracking measurements identical to the actual tracking data we received from the LRO team for a two week period, in order to test the ODTK simulator for a lunar mission orbit. We then filtered both the real data and the simulated data, and compared the two orbits and orbit uncertainties. The simulated orbit uncertainty was nearly identical to the actual as processed by ODTK, which gave us confidence that the simulator and moon-centered filter were functioning correctly.

Next we examined the two "observability conditions" for LRO, which are the "Face On" and the "Edge On" (Figure 10). With less observability than polar orbiters, LADEE may have larger orbit knowledge errors than polar orbiting spacecraft. However, the Edge On condition is a similar tracking condition to LADEE's equatorial orbiting tracking condition, only being observable from Earth half of the orbit. The next analysis was to take a converged state from when LRO is in an Edge On condition and propagate the state and covariance for three days, then repeat this for when LRO is a Face On condition and see if there are difference in propagated covariance. The results showed that after three days of prediction, the 3-sigma in-track position uncertainty reaches approximately 11 km in the Edge On case (Figure 11). Cross-track and radial uncertainties do not increase as rapidly as in-track. In the Face On case, the in-track grew to only 5.5 km (Figure 12).

Both LRO's Edge On orbits and LADEE's science orbits experience significant time flying at low altitudes on the far side of the Moon, where the lunar gravity field has large uncertainties. At the time of these analyses, the lunar gravity field was poorly understood on the far side of the Moon. We performed several more analyses and research tasks specifically to characterize and fully understand this problem[2,11]. Ultimately prior to launch we decided to handle the problem operationally by performing overlaps in operations to see how over-inflated the covariance is on-orbit, and then apply a scaling factor named Mean Motion Uncertainty Scaling [12]. By the time we finished these analyses, we were confident that our team was ready to fly LADEE with our orbit determination tools and techniques for all phases of the mission.

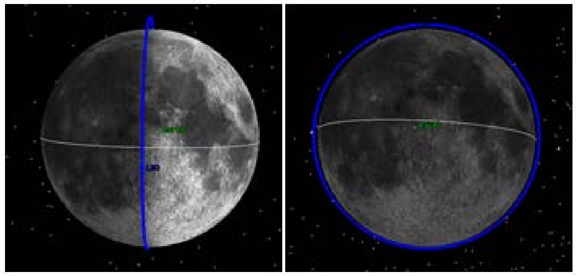


Figure 10: LRO "Edge On" Observability (Left); "Face On" Observability (Right)

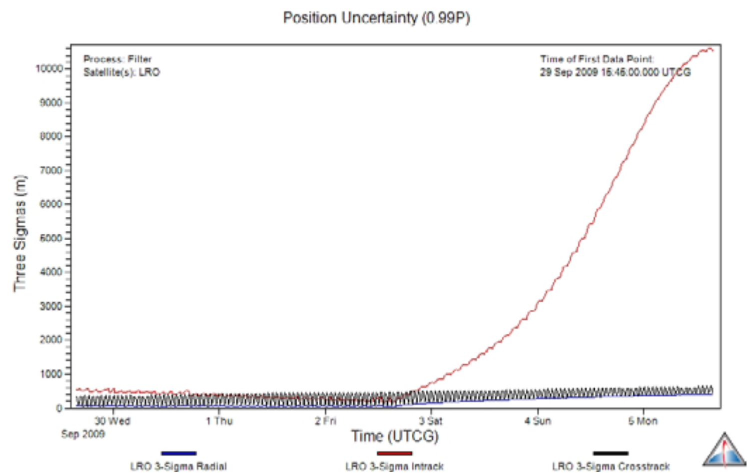


Figure 11: Filtered 3-Sigma Position Uncertainty with 3 Day Predict for Edge On Condition

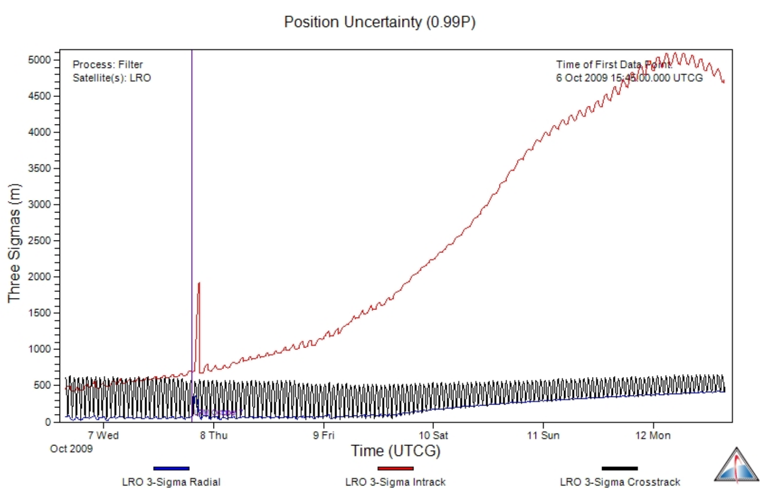


Figure 12: Filtered 3-Sigma Position Uncertainty with 3 Day Predict for Face On Condition

GROUND SYSTEM TESTS

Prior to launch we executed thread tests and end-to-end tests using the FDS to demonstrate the full process from 1) acquisition file delivery to the ground station, 2) ground station antenna use of acquisition file to point the antenna to track operational satellites, and 3) ground station delivery of valid tracking measurement files to the MMOC. All of this testing was necessary to demonstrate that the new NASA Ames FDS was ready for LADEE operations and could fully support orbit determination needs.

HBK had some equipment replacement and configuration changes in months leading up to LADEE launch and needed to be tested. HBK is the first antenna to view LADEE after launch and will auto-track to provide angle tracking. The HBK antenna is typically used to provide telemetry-only services, not tracking. All of these reasons combined created a need for us to propose a test plan. Our LADEE flight dynamics team includes team members that are on the Interstellar Boundary Explorer (IBEX) flight dynamics team and has relationships with the THEMIS mission team. Both Mission Operations Managers for those missions agreed to allow us use their satellites for testing HBK with the Ames FDS to help our LADEE team prepare for operations.

THEMIS-D HBK Testing

The LADEE project first worked with the THEMIS team because the scheduling opportunity allowed for a THEMIS-D test to take place on August 23, 2013. The LADEE project worked with the THEMIS-D Mission Operations Manager to allow for a test with the HBK station to track the spacecraft using auto-track with the HBK antenna. The concept was to have HBK shadow an already-scheduled THEMIS-D pass which would have an overlapping view period with HBK. The AUWA01 ground station was an excellent candidate. The THEMIS-D team gave our team their predicted ephemeris so that we could create acquisition data for HBK. The antenna used our pointing file to perform a passive, auto-track pass during the existing AUWA01 pass when the spacecraft transmitter was on.

The test was successful, where HBK tracked THEMIS the entire time in auto-track mode using our acquisition data, on August 23, 2013 22:16 through 22:46 UTC. Using the LADEE FDS, we preprocessed the UTDF tracking measurement files to check for valid data. Upon the assessment we noticed some configuration problems. The records were not being written in time order and the angles were being tagged a day late (August 24). The one-way Doppler had the correct date of August 23. There was also a 5 minute time tagging issue between when the Doppler was written and when the Angles were written. We reported all of these detailed issues back to USN, so that they could address them. We scheduled a subsequent test on August 27 and all issues were completely resolved.

IBEX HBK Testing

Since IBEX is in a similar orbit regime as the LADEE's cislunar phase where LADEE was to be using the HBK asset, we were especially interested in the antenna's performance at this higher orbit than THEMIS-D. Furthermore, with IBEX's tracking measurements from HBK, our team can process that data with the IBEX FDS since we have overlapping team members also in the IBEX flight dynamics group. The concept was to have HBK shadow an IBEX pass during an existing contact with one of their primary stations (AUWA01). Our LADEE team provided IBEX acquisition data in the HBK custom pointing format to the station. HBK used our pointing file to perform the auto-track pass when the spacecraft transmitter was on and coherent with AUWA01.

The test was completely successful, where HBK tracked IBEX the entire time in auto-track mode, on August 28, 2013 07:24:20 through 08:24:00 UTC. Using the LADEE FDS, we preprocessed the tracking measurement file to check for valid data and assessed the tracking data quality. We received four correctly configured UTDF files from HBK, containing 15 minutes of tracking each, as expected. We found no issues with the UTDF configuration or quality of the data.

Then the HBK angles tracking data was also included with the standard tracking data for IBEX orbit determination back in the IBEX flight dynamics system to perform a full quality assessment on the performance of the HBK antenna, compared to data from typical IBEX ground stations. All measurements were accepted by the filter, and the angles were included in IBEX's orbit determination solution. We were pleased to have identified and resolved the time tagging issues in the initial THEMIS-D test, and then successfully performed an end-to-end test with generating acquisition data using the LADEE FDS, tracking IBEX from the HBK antenna, receiving valid tracking files from HBK, and using the tracking data for orbit determination.

CONCLUSION

We created an orbit determination plan to operate LADEE in its completely unique, never flown before trajectory. Years of research, analysis, tool development, testing, verification, documentation, and training thoroughly prepared the team for LADEE orbit determination operations. The orbit determination plan addressed all requirements and the mission planning cadence. It included a variety of ground stations and tracking measurements, with a tracking schedule that supports meeting requirements and mission scheduling. We carefully constructed a plan for each mission phase to consider unique characteristics and needs for each phase, including astrodynamics modeling, propagator settings, and filter transitions. Results from realistic tracking simulations and detailed orbit determination error analyses from real lunar mission data revealed specific features which allowed us to perform additional research when necessary. Finally, tests with real operational spacecraft and ground stations allowed us to exercise aspects of our ground system to further validate it for orbit determination operations. All of these steps created a complete and prepared orbit determination plan for the LADEE mission.

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