AAS 15-381

GENERATION OF SIMULATED TRACKING DATA FOR LADEE OPERATIONAL READINESS TESTING

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Operational Readiness Tests were an important part of the pre-launch preparation for the LADEE mission. The generation of simulated tracking data to stress the Flight Dynamics System and the Flight Dynamics Team was important for satisfying the testing goal of demonstrating that the software and the team were ready to fly the operational mission. The simulated tracking was generated in a manner to incorporate the effects of errors in the baseline dynamical model, errors in maneuver execution and phenomenology associated with various tracking system based components. The ability of the mission team to overcome these challenges in a realistic flight dynamics scenario indicated that the team and Flight Dynamics System were ready to fly the LADEE mission.

INTRODUCTION

The Lunar Atmosphere and Dust Environment (LADEE) mission[1,2,3] was a lunar science and technology demonstration mission that launched in September of 2013 and operated for approximately 7 months. Operational Readiness Tests (ORTs) were an important part of the pre-launch preparation for the LADEE mission.[4,5] The goal of the ORTs was to demonstrate that the Mission Operations System--including the operations team--was prepared to conduct the planned mission. These tests were designed to support an evaluation of the level of preparedness of the operations system and team under normal and stressing conditions through the introduction of anomalies into a simulation of the nominal mission plan. Results of the ORTs were scrutinized at the Operations Readiness Review and passage of the ORTs was a requirement for the verification of launch readiness.

The ORTs were designed to exercise operational personnel, software, and procedures across selected portions of the complete mission timeline. Each ORT test period focused on evaluating the system and team performance across a significant event in the LADEE mission timeline. In this paper, we provide an overview of the LADEE mission trajectory to provide context for the events and anomalies included in the ORTs. We describe the design of the trajectory perturbations and tracking data anomalies which presented challenges to the operations team. We then outline procedures that were developed to allow the generation of the desired anomalies using the operational navigation software in a manner that maintained continuity of the spacecraft trajectory across each ORT. Finally, we discuss the effectiveness of the tests in familiarizing the team

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with potential anomaly scenarios and in identifying improvements to planned operational procedures.

TRAJECTORY OVERVIEW

The LADEE mission trajectory[6,7], though continuous over the duration of the mission, can be viewed as a concatenated set of trajectory segments beginning with the near Earth initial acquisition period, transitioning to the lunar transfer phase through cis-lunar space, entering a commissioning orbit at the Moon via a Lunar Orbit Insertion (LOI) maneuver, and finally descending into the lunar science orbit. LADEE was to be the first mission to launch on the all-solids five stage Minotaur V. To accommodate the launch dispersions, a phasing loop strategy, as shown in Figure 1, was chosen where two to three apogee-raising maneuvers were planned in order for LADEE to arrive at the Moon on the same day, regardless of the launch achieved. The progression of the trajectory from capture into lunar orbit to the final science orbit also followed a series of maneuvers that gradually decreased the altitude above the lunar surface as depicted in Figure 2. The red segments of the trajectory in Figure 2 denote where the Moon blocks view of LADEE from any Deep Space Network (DSN) station and the purple cone depicts the viewing geometry from the Earth for the LOI-1 maneuver.

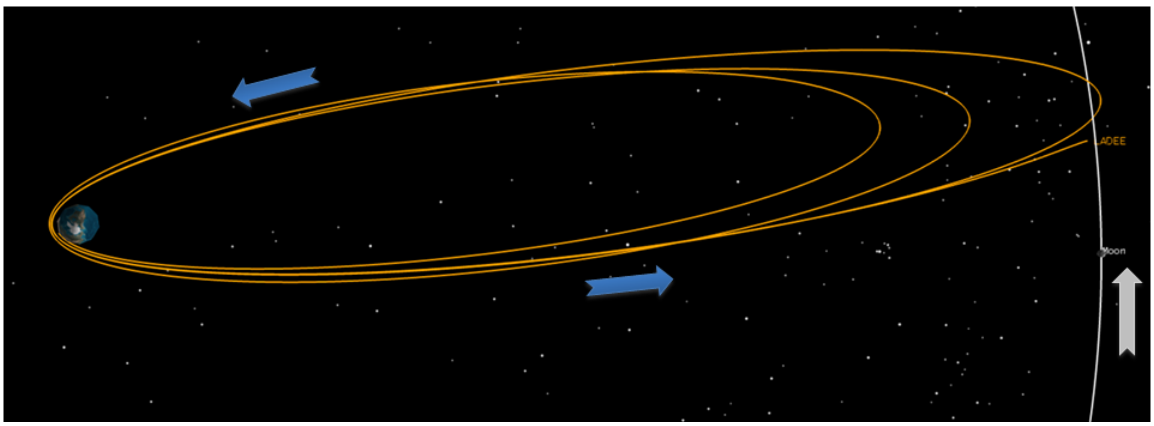

Figure 1. Phasing Loop Trajectory, Earth-Inertial Frame

Table 1 provides a subset of the overall maneuver plan for the LADEE mission. It is noteworthy that the maneuver plan contained a number of statistical maneuvers, which nominally have either zero or a very small effect on the trajectory, to correct for unexpected deviations from the nominal trajectory. During the ORTs, trajectory deviations resulted from intentionally inserted anomalies. In the case where a nominal or near nominal trajectory has been maintained leading up to the planned time for a statistical maneuver, the operations team often decides to waive (not perform) the maneuver. Table 1 also describes the thrusters, pressure modes, and minimum and maximum delta-v for each maneuver. The propulsion subsystem has an orbital control system (OCS) thruster for larger size orbit control maneuvers and four small 22N reaction control (RCS) thrusters. Pressure modes are either pressure regulated or blowdown. Because the phasing loop maneuvers will be planned after launch occurs, the minimum and maximum expected Delta-V are listed for each of those perigee and apogee maneuvers.

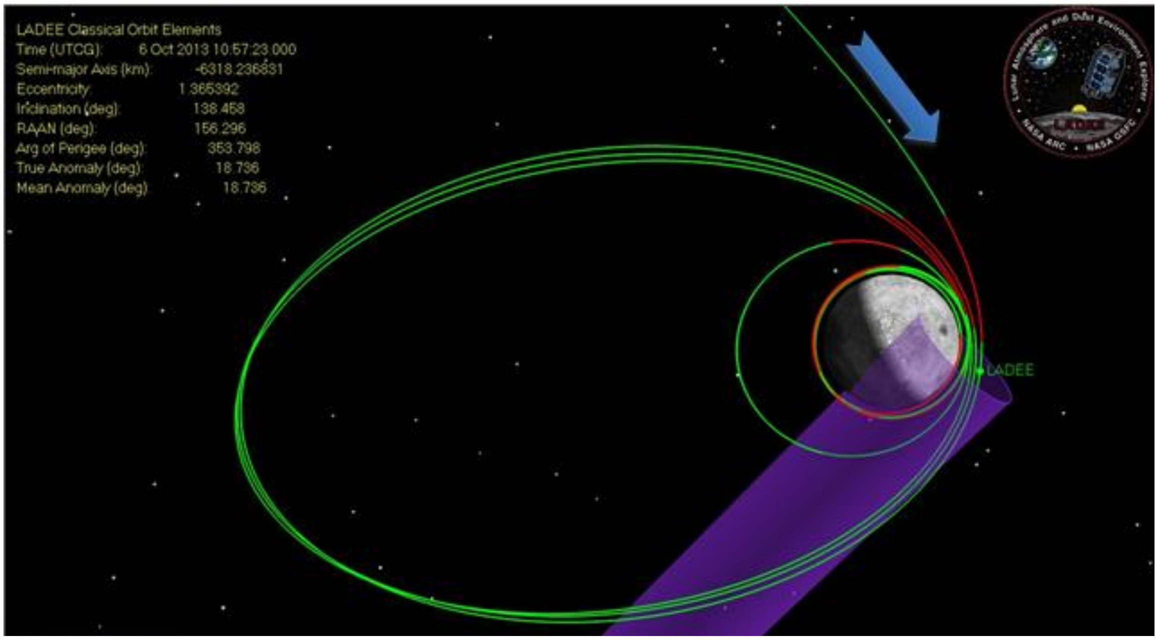

Figure 2. Trajectory During Lunar Orbit Insertion Maneuvers, and Orbit Lowering Maneuvers, Moon-Inertial Frame

Table 1. Example of LADEE Maneuver Plan Used for Planning ORTs

Mission Phase	Mnvr	Maneuver Name	Thruster Used	Pressure Mode	Baseline Min Expected DV (m/s)	Baseline Max Expected DV (m/s)
Phasing Loop	AM1	Apogee Maneuver 1	OCS or RCS	Pressure R	0.00	7.00
	PM1	Perigee Maneuver 1	OCS or RCS	Pressure R	3.57	34.95
	AM2	Apogee Maneuver 2	OCS or RCS	Pressure R	0.00	0.00
	PM2	Perigee Maneuver 2	OCS or RCS	Pressure R	2.11	26.95
	OPM	Out-of-Plane Maneuver	OCS or RCS	Pressure R	0.00	1.63
	PM3	Perigee Maneuver 3	OCS or RCS	Pressure R	0.26	19.90
	TCM1	Trajectory Correction Maneuver 1	RCS	Pressure R	0.00	0.00
	TCM2	Trajectory Correction Maneuver 2	RCS	Pressure R	0.00	0.00
	TCM3	Trajectory Correction Maneuver 3	RCS	Pressure R	0.00	0.00
LOA	LOI1	Lunar Orbit Insertion 1	OCS	Pressure R	302.74	318.32
	LAM1	Lunar Apogee Maneuver 1	RCS	Pressure R	0.00	0.00
	LOI2	Lunar Orbit Insertion 2	OCS	Pressure R	295.94	296.01
	LOI3	Lunar Orbit Insertion 3	OCS	Pressure R	237.94	238.25
Commissioning	OLM1	Orbit Lowering Maneuver 1	RCS	Pressure R	-	-
	OLM2	Orbit Lowering Maneuver 2	OCS	Pressure R	40.00	40.00
	OLM3	Orbit Lowering Maneuver 3	OCS	Pressure R	31.88	31.88
	OLM4	Orbit Lowering Maneuver 4	RCS	Pressure R	6.84	6.84
Science	OMM01	Orbit Maintenance Maneuver 1	RCS	Blowdown	2.76	2.76
	OMM02	Orbit Maintenance Maneuver 2	RCS	Blowdown	5.00	5.00
	OMM03	Orbit Maintenance Maneuver 3	RCS	Blowdown	4.90	4.90
	OMM04	Orbit Maintenance Maneuver 4	RCS	Blowdown	3.38	3.38
	OMM05	Orbit Maintenance Maneuver 5	RCS	Blowdown	4.50	4.50
	OMM06	Orbit Maintenance Maneuver 6	RCS	Blowdown	6.79	6.79
	OMM07	Orbit Maintenance Maneuver 7	RCS	Blowdown	4.71	4.71
	OMM08	Orbit Maintenance Maneuver 8	RCS	Blowdown	6.00	6.00
	OMM09	Orbit Maintenance Maneuver 9	RCS	Blowdown	4.94	4.94
	OMM10	Orbit Maintenance Maneuver 10	RCS	Blowdown	7.39	7.39
	OMM11	Orbit Maintenance Maneuver 11	RCS	Blowdown	4.76	4.76
	OMM12	Orbit Maintenance Maneuver 12	RCS	Blowdown	3.27	3.27

LADEE Tracking Resources

The LADEE spacecraft was tracked by a combination of three tracking systems: NASA's Near Earth Network (NEN), the Universal Space Network (USN), and NASA's Deep Space

Network (DSN), each of which was simulated during the ORTs. The set of stations used for the generation of simulated tracking data during the ORTs is given in Table 2. This set of stations was augmented by the addition of the USN/Western Australia station AUWA01 during operations. Not all measurement types associated with a station were generated for each tracking pass supported by that station. Measurements were reported on a pass by pass basis with a unique file containing the measurements from each pass. File naming conventions varied between DSN and non-DSN stations.

Table 2: LADEE Tracking Stations Simulated in ORTs

Station	Observation Types	Observation Spacing	Simulated Accuracy
DSN 27	TCP Sequential Range	10 sec 60 sec	0.003 cycles 0.5 m
DSN 24	TCP Sequential Range	10 sec 60 sec	0.003 cycles 0.5 m
DSN 34	TCP Sequential Range	10 sec 60 sec	0.003 cycles 0.5 m
DSN 45	TCP Sequential Range	10 sec 60 sec	0.005 cycles 0.5 m
DSN 54	TCP Sequential Range	10 sec 60 sec	0.003 cycles 0.5 m
DSN 65	TCP Sequential Range	10 sec 60 sec	0.003 cycles 0.005 m
USN/HBK	Azimuth Elevation Doppler	5 sec 5 sec 5sec	0.03 deg 0.02 deg 75 cm/s
NEN/AGO	X Y Range Doppler	5 sec 5 sec 5 sec 5 sec	6 arcsec 6 arcsec 5 m 7.5 cm/s
NEN/WS-1	Azimuth Elevation Range Doppler	5 sec 5 sec 5 sec 5 sec	0.03 deg 0.02 deg 0.1 m 0.15 cm/s

ORT DESIGN OVERVIEW

During operations on a live mission, the true trajectory of the spacecraft is never known. Yet trajectory information is required to schedule science observations, ground contacts, etc. In order to provide an estimate of the trajectory for such purposes during a mission, an orbit determination process is performed using observations of the spacecraft to yield an updated estimate of where the spacecraft was during the times when measurements were taken and provide predictions of the spacecraft position at future times. This relationship between the unknown truth and a determined estimate was emulated during the LADEE ORTs in order to ensure that LADEE's orbit determination process[8] could handle the types of errors and uncertainty that were expected during the mission and create suitable products for other processes, such as the maneuver planning process[9]. Simulated tracking data was constructed based on a series of simulated trajectory segments that were deviated from the nominal mission trajectory through errors in orbit injection from launch, maneuvers, and the dynamical model. The truth trajectory was not known to the Flight Dynamics Team during the test period. The Flight Dynamics Team used the simulated measurements to generate estimates of LADEE's trajectory. The desired dual realizations of the spacecraft trajectory were therefore available for use during the ORTs: the simulated truth trajectory which was used in the generation of all simulated sensor outputs and the trajectory estimate produced by the Flight Dynamics Team which was used for mission planning purposes. The flow of tracking data, ephemeris and derivative information through the various teams and functions involved in the LADEE ORTs and mission operations is depicted in Figure 3 where the focus of this paper, simulated trajectory and tracking data generation, is highlighted.

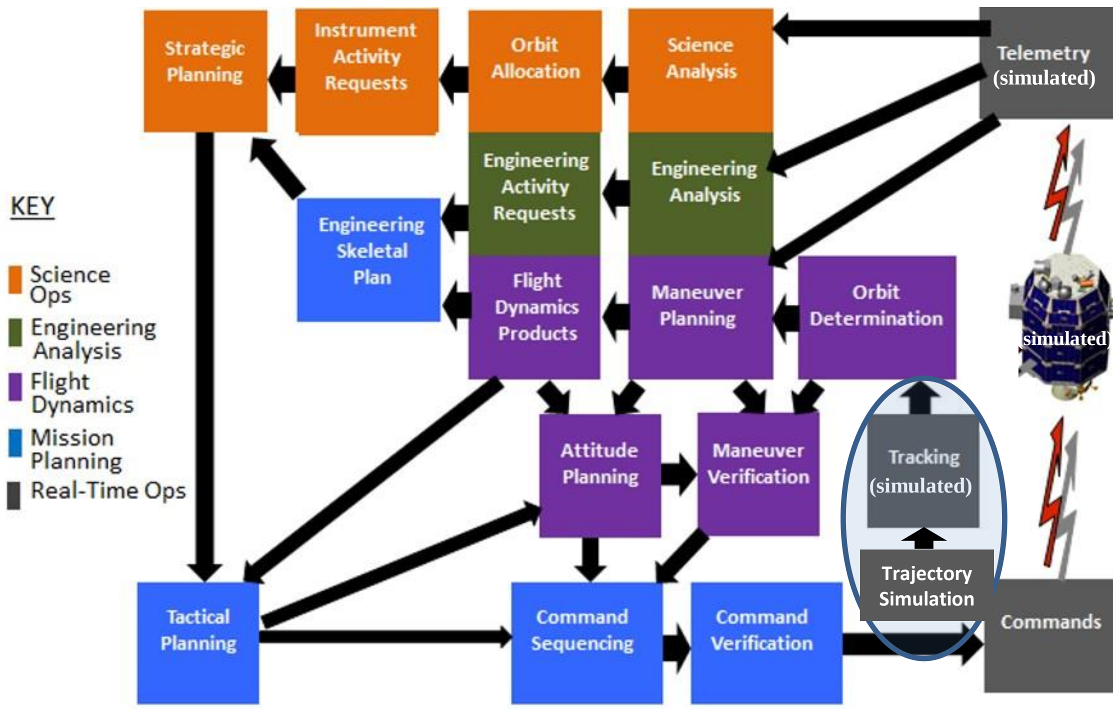

Figure 3. Representative ORT Data Flow Diagram.

The ORTs were designed to exercise the Mission Operations System over critical events in the mission timeline. While it would have been more physically realistic to use a continuous trajectory covering the entire mission as the basis for all of the ORTs, the use of mostly independent trajectory segments for each of the ORT time periods was less complex and provided more flexibility in the design of the tests for individual mission phases. The choice to use test specific trajectory baselines for the ORTs facilitated modifications to the list of challenges inserted into each ORT period at any time up to the start of the ORT without imposing the requirement that data for all ORT periods be regenerated. It also reduced the burden related to the planning of ground contact periods which could be designed based on an a priori set of pre-generated trajectories since orbital perturbations injected into a particular ORT did not accumulate into large enough trajectory differences during the ORT time period to invalidate the planned contact periods. Finally, the additional flexibility of this approach allowed the ORTs to be performed in non-chronological order, thus providing the opportunity to test key activities (e.g., fault management reconfiguration[10] for the lunar orbit insertion, science phase activities, etc.) earlier in the ORT campaign and to adapt to the overall project schedule as necessary. Table 3 presents an overview of the four

ORT test periods including significant trajectory events (such as launch and maneuvers) that occurred during the test period and the type of perturbations added to those events. The times listed in Table 3 represent times in the LADEE mission timeline, not the wall clock times when the tests were performed. The actual order in which the tests were performed is also provided.

Table 3. High Level ORT Descriptions.

ORT	Order	Start/Stop	Trajectory Events	Event Perturbation
1	3	2013-09-06T21:00 2013-09-09T00:00	Launch 2013-09-07T03:31	Off-nominal trajectory consistent within expected launch dispersion
2	4	2013-09-29T15:00 2013-10-03T00:00	Perigee Maneuver 3 2013-10-01T16:30	Start with degraded orbit. Maneuver execution ~3% cold with small pointing error.
3	1	2013-10-06T03:00 2013-10-09T00:00	Lunar Orbit Insertion 1 2013-10-06T12:00	Maneuver execution ~7% hot with small pointing error
5*	2	2013-12-23T14:00 2013-12-28T01:00	Orbit Maint. Maneuver 6 2013-10-28T01:00	Maneuver execution ~2% cold with small pointing error

TRAJECTORY SIMULATION

Truth trajectories were simulated for each ORT. Each truth trajectory was based on the selection of a particular trajectory from a set of feasible trajectories provided by the Trajectory Design Team. Each feasible trajectory was constructed as an independently targeted trajectory starting from an orbit insertion state that was consistent with the expected dispersion about the nominal orbit insertion state. In the case of ORT-1, which covered the launch portion of the LADEE mission timeline, the truth trajectory contained the orbit insertion state and exactly followed the selected feasible trajectory for the duration of the test period. For the remaining ORTs, truth trajectories were generated as variants of the provided feasible trajectories where part of each truth trajectory preceded the test time period. Inside the test period, truth trajectories were allowed to diverge from the feasible reference trajectory via the inclusion of errors in the ORT initial state and incorporated the effects of perturbations to the dynamical model and maneuvers. The truth trajectories were generated using AGI's Orbit Determination Tool Kit (ODTK)[11]. In addition to serving as the basis for the generation of simulated tracking data, these truth trajectories are used in the simulation of ancillary ORT products (attitude, s/c events, etc.).

Initial Condition Errors

Initial condition errors represent deviations from the selected feasible trajectory at the beginning of the ORT test period. Initial condition errors were generated by starting the ODTK tracking data simulation prior to the beginning of the test period, when possible, and allowing the Flight Dynamics Team to process imperfect observations over the time period between the start of tracking data generation and the beginning of the ORT test period. The tracking data generated prior to the start of the ORT followed the planned station contact schedule so as to provide an orbit estimate with accuracy that would be expected during the mission at the start of the ORT test period. For ORT-3 and ORT-5, the simulated truth trajectory exactly followed the selected feasible trajectory during times prior to the test period. For ORT-2, an unexpected RCS thruster

* Originally 5 ORTs were planned, but ORT-4 was eliminated prior to the start of testing

firing was included in the pre-test period trajectory simulation for the purpose of degrading the orbit determination solution at the start of the test period. ORT-1 was a special case where the initial condition errors were incorporated via the selection of a non-nominal, yet feasible trajectory at initial orbit insertion.

Dynamical Model Errors

The dynamical model required for the LADEE mission consisted primarily of Earth and Moon gravity plus solar pressure. Acceleration errors in the baseline dynamical model were injected through the addition of an exponentially correlated stochastic sequence to the solar pressure coefficient for all ORTs. The stochastic accelerations in the solar pressure model were along the sun line with a root variance of approximately 13% of the nominal solar pressure acceleration and a half-life of 2 days.

Maneuver Errors

Nominal acceleration profiles for orbital maneuvers in each ORT test period were provided by the Maneuver Planning Team. The maneuver acceleration profiles consisted of a time series of accelerations and fuel use due only to the thrust force on the spacecraft. Deterministic errors in maneuver magnitude were generated by importing the acceleration profile into EXCEL™ and scaling the accelerations by a predetermined value. For example, to simulate a maneuver that executed 7% hot, all accelerations were multiplied by a factor of 1.07. Maneuver errors also included a small random deviation in the direction of thrust with root variance of a fraction of a degree (varied by maneuver). The simulated maneuver errors were unique and independent for each maneuver.

MEASUREMENT SIMULATION

Simulated measurements were generated based on a station contact schedule provided by the Mission Planning Team. The contact periods were initially determined based on a nominal mission trajectory provided by the Trajectory Design Team. Outside of the period just after launch, the contact periods were mostly unaffected by deviations from the nominal trajectory due to the large distance between the spacecraft and the Earth. Measurement types, accuracy and the time between observations were set to be as expected during the mission based on the capabilities and normal operational procedures of the tracking systems. Reported observations were constructed as the modeled value of the measurements corrupted by white noise and time correlated measurement bias, transponder delay, and troposphere modeling errors. Observation accuracy (as measured by the white noise variance) was determined for each (tracking station – observation type) pairing by processing data from prior missions. Injected tracking data anomalies were not communicated to the Flight Dynamics Team.

Measurement White Noise

The purely random component of observed measurement errors is characterized as Gaussian white noise, which is fully described by only a root variance. During nominal tracking passes, observations were corrupted with white noise with nominal variance that depended upon the tracking station and observation type. In addition, a number of anomalous passes were simulated where the tracking data quality was degraded due to an increase in the variance of the white noise for specific measurement types. Unexpected increases in the measurement white noise model situations where a ground station may not have been placed into the correct configuration prior to a pass.

Measurement Bias Errors and Transponder Delay

Nominal measurement biases were set to zero but were allowed to vary during the simulation according to exponentially correlated stochastic sequences. A separate stochastic sequence was used for each (tracking station – observation type) combination where the amplitude and half-life of each stochastic sequence was chosen to be consistent with results from prior processing of real mission data. During several anomalous passes, step functions were added to selected measurement biases to render the observations useless. This type of anomaly can result from improper ground station configuration, improper spacecraft configuration or hardware modifications at the ground station.

An *a priori* transponder delay was not provided for use in the generation of the simulated tracking data. The transponder delay affects two-way ranging measurements in a manner that makes the observed range larger than would be expected based purely on geometry. To test the ability of the flight dynamics team to detect and solve for an unknown transponder delay, all ranging data for ORT-1 and ORT-2 were generated using a large nearly constant transponder delay. Tracking data for the other ORTs was generated with a zero nominal transponder delay.

USE OF ODTK

Simulated tracking measurements were generated using ODTK, the same software that was used for operational orbit determination during the mission. ODTK provides the capability to generate simulated observations based either on the satisfaction of visibility constraints or following a predetermined schedule as was required during the ORTs to emulate the quantity of tracking data that would be available during the actual mission. There were, however, two requirements for the generation of simulated tracking data that ODTK did not support directly: saving tracking data from each pass to a different file and generating multiple observables from a single tracking station at different rates over a pass.

We were able to leverage two existing ODTK capabilities to generate the tracking data in the desired manner: the option to specify a pre-generated ephemeris as the trajectory reference and the ability to pause and restart simulation runs. To achieve all of the data simulation goals, the ODTK simulator was run multiple times for each ORT. The first run was used to generate the truth trajectory for the ORT including all perturbations to the baseline dynamical model and maneuvers. It covered the entire ORT time frame, including the pre-ORT period during which tracking data was generated to allow for initialization of the orbit estimate. For all subsequent runs by the spacecraft object in ODTK was reconfigured to follow the truth trajectory generated in the first run as the basis for tracking data generation. This procedure ensured that consistent trajectory information was used for the generation of all tracking data. The number of runs required for tracking data generation for each ORT depended upon the existence of simultaneous tracking from multiple ground stations and the need to generate different observables at unique data rates as described below. Any particular run could also be paused and restarted to allow for the injection of tracking data anomalies into the simulation.

The ODTK capabilities to use restart records, pre-generated ephemerides and a customized tracking schedule were key in the generation of simulated tracking data. Contact schedules from the mission planning team were read by the scripts driving the ODTK simulation runs and used to populate the ODTK custom tracking schedule.

Generation of Data at Different Rates

DSN tracking data is typically recorded at two data sample rates where sequential ranging is reported at a lower sample rate than Total Count Phase (TCP). For the LADEE ORTs, TCP measurements were generated every 10 seconds while sequential range measurements were generated every 60 seconds. ODTK does not currently support the generation of data with observation rates dependent upon observation type from a single ground station. To work around this limitation, the ODTK tracking data simulator was run twice for each DSN pass: The first run was performed at the step size required for the generation of TCP and the second run at the step size for sequential ranging. The use of the pre-generated truth trajectories during both runs was critical to ensuring that the observations generated from the two runs were consistent.

Pass Specific Data Files and Generation of Overlapping Tracking Data

Simulated tracking data for each ORT was made available as a set of files where each file contained data from a single pass as collected from a single station. This delivery method was chosen to emulate the delivery of real tracking data and to conform to the design of the Ames Flight Dynamics System.[12] In the absence of simultaneous tracking from multiple stations, the pass specific files were simply generated by pausing the simulation after each tracking pass and renaming the output tracking data file. Continuity of all stochastic parameters in the simulation was maintained by restarting the simulation from a restart record. When simultaneous tracking was present, the simulator was run multiple times in the same manner, once for each ground station, to allow the separation of the tracking data into unique files. An exception to the single pass per file rule was allowed for the LADEE ORTs to permit the delivery of DSN sequential ranging and TCP measurements in a separate file to accommodate the use of different data rates.

Increase in Measurement Noise

Each LADEE tracking station was assigned statistical parameters describing the accuracy of realized observations based on historical performance. In the simulation of measurements in ODTK, measurement white noise is not represented in the state structure of the simulation; it is merely added on to the modeled measurement based on a random draw. Anomalous changes in measurement noise were accommodated during the simulation by increasing the measurement white noise setting while the simulation was paused prior to the affected tracking pass. The nominal setting was then restored during the pause in the simulation prior to the next pass.

Step Functions in Measurement Biases and Transponder Delay

In the ODTK simulations, measurement biases were represented as the sum of a constant bias and an exponentially correlated, zero mean, stochastic sequence. The random component of the bias was an element of the state space. Step changes in the constant component of the bias were inserted during pauses in the simulation prior to and after passes where the anomalous behavior was desired for purposes of the ORTs. The ODTK simulator provides an interface to the list of the current values of the stochastic variables involved in the simulation that allows for their values or the defining parameters for the stochastic sequence to be reset during a pause in the simulation. User provided changes are then incorporated into the simulation when the simulation is restarted. In this manner, step functions can be added to specific parameters while stochastic sequences that have not been altered maintain continuity throughout the simulation.

Similar to the measurement biases, transponder delay was modeled as the sum of a constant and an exponentially correlated, zero mean, stochastic sequence. ORT-5 included a step function in the transponder bias which was generated following the same process as the step functions in measurement biases.

Troposphere Mis-modeling

Errors in the effects of troposphere were introduced in several tracking passes during ORT-5. Unlike measurement biases, troposphere uncertainty was not accounted for in state space. Instead, an effective offset in the local atmospheric conditions was used to alter the computed tropospheric refraction. These offsets were introduced prior to the simulation of data across the affected pass during a pause in the simulation and were removed during the pause in the simulation prior to the next track.

SPECIFIC DESCRIPTIONS OF ORTS

Each ORT covered a significant event in the LADEE mission timeline. The ORTs were numbered—and are listed below—in chronological order with respect to the mission timeline. However, as noted above, the ORTs were not executed in chronological order. Anomalies related to the trajectory and tracking data were incorporated into each ORT to challenge and provide practice for the Flight Dynamics Team and to test the robustness of the Ames Flight Dynamics System. Injected anomalies were designed through interaction between the Test Director and the staff and were based on situations encountered during the processing of tracking data from prior real missions. Anomalies were not designed purely to trick the Flight Dynamics Team.

ORT-1 and ORT-2 were subject to the additional constraint that they use the same reference trajectory so that ORT-1 tracking data could be used in ORT-2. Trajectory selection was important since the focal point of ORT-2 was the PM-3 maneuver. In the absence of a large enough deviation from the nominal trajectory, the PM-3 maneuver could be waived (as it was during the actual execution of the mission) which would circumvent the purpose of ORT-2. For this reason, the highest C3 energy trajectory from a set of trajectories[13] provided by the Trajectory Design Team was selected.

ORT-1: Launch, Activation, and Checkout

The ORT-1 test time period covered launch and early operations. The maximum C3 energy trajectory selected for ORT-1 was used as provided (though unknown to the Flight Dynamics Team), no additional perturbations were modeled, to ensure continuity of the trajectory at the start of ORT-2. Trajectory generation and orbit determination for ORT-1 was performed using the Earth as the primary central body. A description of the tracking data anomalies for ORT-1 is provided in Table 2. Also included in Table 4 is short summary of how the anomalies were handled during the execution of ORT-1. Additional information is provided for the anomalies in ORT-1 in the sequel.

ORT-2: Phasing Loop Maneuver

The ORT-2 test time period occurred during the phasing loop period of the mission and covered the third perigee maneuver, PM-3. The baseline trajectory for ORT-2 was selected as the highest C3 energy trajectory to maintain continuity with ORT-1. Integration of the ORT-2 truth trajectory in ODTK began 5 hours prior to the start of the test period. The trajectory was allowed to deviate at integration start point from the selected baseline trajectory due to differences in solar pressure modeling, the inclusion of an unexpected Reaction Control System (RCS) thruster firing—partly inspired by a mass ejection anomaly on a prior mission[14]—and off-nominal performance of the PM-3 burn. Trajectory generation and orbit determination for ORT-2 was performed using the Earth as the primary central body. Details of the acceleration anomalies included in the ORT-2 truth trajectory are described in further detail in Tables 5 and 6.

Table 2. Tracking Data Anomalies for ORT-1.

Station	Start/Stop	Description	Response
All	N/A N/A	The nominal transponder delay on the spacecraft was set to 1873 ns and allowed to slowly vary in a small range about the nominal value using a short term delay root variance of 5 ns and correlation half-life of 20 days.	Transponder delay was detected and the constant mostly removed.
HBK	2013-09-07T03:56:16 2013-09-07T18:11:37	Azimuth and Elevation angles are degraded: Short term bias root variance raised from 1 to 2 deg, correlation half-life reduced from 2 to ½ days, measurement white noise root variance increased by 0.05 deg.	Degraded angles were noticed and reported. No immediate action was taken based on decision to wait for more tracking data to see if the issue persisted.
DSS34	2013-09-07T04:30:00 2013-09-07T09:23:31	Sequential ranging degraded: Measurement white noise root variance increased from 0.5 to 30 meters.	Degraded range observations were noticed and reported. No immediate action was taken based on decision to wait for more tracking data to see if the issue persisted.
DSS27	2013-09-07T18:13:17 2013-09-08T00:45:00	Sequential ranging degraded: Constant range bias increased by 1.8 Km.	All range measurements were rejected. No immediate action was taken based on decision to wait for more tracking data to see if the issue persisted.
DSS34	2013-09-08T00:35:00 2013-09-08T10:10:00	Total Count Phase (Doppler) degraded: Measurement white noise increased from 0.003 to 0.30 cycles.	Degraded angles were noticed and reported. No immediate action was taken based on decision to wait for more tracking data to see if the issue persisted.

Table 5. Trajectory Anomalies for ORT-2.

Source	Start/Stop	Description
RCS	2013-09-29T10:13:11 2013-09-29T10:13:13	Errant Reaction Control System (RCS) thruster firing: 2 second pulse of a 22N thruster canted 45 degrees off the Z axis of the spacecraft. Prior to ORT test period.
Cp	N/A N/A	Solar pressure variation: The solar pressure coefficient was allowed to vary during the simulation based on the generation of a random stochastic sequence. The nominal one sigma value for the time dependent variation was set to 13% of the nominal value and the time correlation half-life was 2 days.
PM-3	2013-10-01T20:54:19 2013-10-01T20:54:51	PM-3 Perturbation: The nominal PM-3 burn as provided by the trajectory team was biased to be 3.1415% cold with a small random component of magnitude (1 sigma = 0.5%) and a small random directional error (1 sigma = 0.5 degrees).

Table 6. Errant RCS Thruster Firing (ICRF Coordinates).

Epoch	29-Sep-2013 10:13:11
Delta Vx	-0.0767348 m/s
Delta Vy	-0.0622362 m/s
Delta Vz	-0.0650268 m/s

The tracking data anomalies added for ORT-2 are listed in Table 7. This ORT was executed last and provided the opportunity to leverage the experience gained by the Flight Dynamics Team during the earlier exercises to overcome a more dense set of challenges. Some of the anomalies included for ORT-2, such as large jumps in measurement biases, were meant to render tracking data from a particular pass useless.

ORT-3: Lunar Orbit Acquisition

The ORT-3 test time period covered the first of three Lunar Orbit Insertion (LOI) maneuvers, LOI-1. The baseline trajectory for ORT-3 was selected as the nominal launch trajectory in order to allow for the use of the nominal station contact schedule and nominal LOI-1 plan. The LOI-1 uplink time is located prior to the start of the ORT-3 test period. Integration of the ORT-3 truth trajectory in ODTK began 5 days prior to the start of the test period as LADEE was approaching the Moon. The ORT-3 truth trajectory was allowed to deviate at this point from the selected baseline trajectory due to differences in solar pressure modeling and off-nominal performance of the LOI-1 burn. Trajectory generation and orbit determination for ORT-3 was performed using the Moon as the primary central body. Details of the acceleration anomalies included in the ORT-3 truth trajectory are described in further detail in Table 8. Tracking data anomalies for ORT-3 are shown in Table 9.

The Lunar Apogee Maneuver 1 (LAM-1) was part of the mission timeline after LOI to be used to correct for off-nominal performance of the LOI-1 maneuver and place LADEE in the correct orbit to perform the LOI-2 maneuver. Following a near-nominal LOI-1 maneuver, the LAM-1 maneuver could be waived (which was the case during the actual mission). During ORT-3, the simulated LOI-1 maneuver was biased to be 7% hot. The overburn lowered the aposelene and reduced the amount of expected periselene decay (due to Earth gravity perturbations) which was needed to lower LADEE’s periselene to the altitude required for the Commissioning Phase. This 7% maneuver over-performance was detected by the Flight Dynamics Team through examination of the orbit determination results. The post LOI-1 trajectory was then examined by the trajectory design team and the need for the LAM-1 maneuver was determined. LAM-1 was subsequently planned, executed, and reconstructed during the ORT. Planning of the LOI-2 maneuver followed the execution of the LAM-1 maneuver. The orbit determination team determined LAM-1 to be about 1% cold with a small directional error.

Table 7. Tracking Data Anomalies for ORT-2

Station	Start/Stop	Description
All	N/A N/A	The nominal transponder delay on the spacecraft was set to 1873 ns and allowed to slowly vary in a small range about the nominal value using a short term delay root variance of 5 ns and correlation half-life of 20 days.
WS-1	2013-09-15T11:54:31 2013-09-15T16:34:06	Ranging degraded: Constant range bias increased from 0.0 to 34.567 Km.
DSS 27	2013-09-16T17:24:51 2013-09-17T01:14:58	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.222 cycles.
DSS 34	2013-09-17T23:35:00 2013-09-18T03:45:00	Sequential Range degraded: Constant range bias increased from 0.0 to 40 m.
DSS 34	2013-09-26T07:45:00 2013-09-26T08:45:00	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.01111 cycles, bias of 0.012 cycles added. Sequential Range degraded: Bias sigma increased from 1.5 m to 22 m.
DSS 34	2013-09-27T07:45:00 2013-09-27T08:45:00	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.077 cycles.
DSS 54	2013-09-29T12:40:00 2013-09-29T18:40:00	Sequential Range degraded: Measurement white noise root variance increased from 1.5 m to 13.7 m.
DSS 65	2013-09-30T10:05:00 2013-09-30T19:20:00	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.0888 cycles.
DSS 45	2013-10-01T01:30:00 2013-10-01T09:40:00	Sequential Range degraded: Measurement white noise root variance increased from 0.5 m to 9.4 m.
DSS 34	2013-10-01T21:15:00 2013-10-02T07:45:00	Sequential Range degraded: Constant range bias increased from 0.0 to 717 m.

ORT-5: Science Phase Activities

The ORT-5 test time period covered the sixth in a series of 22 Orbit Maintenance Maneuvers (OMM) that were performed after LADEE entered its lunar science orbit. The baseline trajectory for ORT-5 was selected as the nominal launch trajectory in order to allow for the use of the nominal station contact schedule and nominal OMM-6 plan. The OMM-6 uplink time was placed prior to the start of the ORT-5 test period. Tracking data generation began 11 days prior to the start of the ORT test period. The ORT-5 truth trajectory followed the nominal trajectory up to the ORT start time at which point numerical integration of the remainder of the ORT-5 truth trajectory began and the truth trajectory was allowed to deviate nominal launch trajectory due to differences in solar pressure modeling and off-nominal performance of the OMM-6 burn. Trajectory generation and orbit determination for ORT-5 was performed using the Moon as the primary central body. Details of the acceleration anomalies included in the ORT-5 truth trajectory are described in further detail in Table 10. Tracking data anomalies for ORT-5 are shown in Table 11.

Table 8. Trajectory Anomalies for ORT-3.

Source	Start/Stop	Description
Cp	N/A N/A	Solar pressure variation: The solar pressure coefficient was allowed to vary during the simulation based on the generation of a random stochastic sequence. The nominal one sigma value for the time dependent variation was set to 13% of the nominal value and the time correlation half-life was 2 days.
LOI-1	2013-10-06T11:48:21 2013-10-06T11:52:45	LOI-1 Perturbation: The nominal LOI-1 burn was biased to be 7% hot with a small random directional error (1 sigma = 0.25 degrees).
LAM-1	2013-10-08T11:50:20 2013-10-08T11:50:55	LAM-1 Perturbation: A LAM maneuver opportunity was utilized based on orbit determination results following the LOI-1 maneuver. The planned LAM-1 burn was biased to be 1.5% cold with very small directional error of 0.055 degrees.

Table 9. Tracking Data Anomalies for ORT-3.

Station	Start/Stop	Description
DSS 54	2013-10-06T09:04:49 2013-10-06T11:16:05	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.07 cycles. Sequential ranging degraded: Measurement white noise root variance increased from 1.5 to 18 meters.
DSS 54	2013-10-07T10:07:59 2013-10-07T11:11:48	Sequential ranging degraded: Constant range bias increased from 0.0 to 1.8 Km.
DSS65	2013-10-08T11:38:16 2013-10-08T19:05:00	Sequential ranging degraded: Measurement white noise root variance increased from 0.005 to 30 meters.

Table 10. Trajectory Anomalies for ORT-5.

Source	Start/Stop	Description
Cp	N/A N/A	Solar pressure variation: The solar pressure coefficient was allowed to vary during the simulation based on the generation of a random stochastic sequence. The nominal one sigma value for the time dependent variation was set to 13% of the nominal value and the time correlation half-life was 2 days.
OMM-6	2013-12-27T04:06:59 2013-12-27T04:07:32	OMM-6 Perturbation: The nominal OMM-6 burn was biased to be 2% cold with a small random directional error (1 sigma = 0.25 degrees).

Table 11. Tracking Data Anomalies for ORT-5.

Station	Start/Stop	Description
DSS 65	2013-12-24T04:10:38 2013-12-24T05:10:38	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.015 cycles.
DSS 65	2013-12-24T06:08:58 2013-12-24T07:08:58	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.015 cycles.
DSS45	2013-12-24T17:52:30 2013-12-24T18:22:30	Total Count Phase (Doppler) degraded: Surface refractivity in the troposphere model decreased by 13%.
DSS45	2013-12-24T23:37:30 2013-12-25T00:07:30	Total Count Phase (Doppler) degraded: Surface refractivity in the troposphere model decreased by 13%.
DSS 65	2013-12-25T03:19:58 2013-12-25T04:19:58	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.02 cycles.
DSS 65	2013-12-25T05:15:00 2013-12-25T06:15:00	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.02 cycles.
DSS45	2013-12-26T19:45:30 2013-12-26T20:15:30	Total Count Phase (Doppler) degraded: Surface refractivity in the troposphere model decreased by 10%.
DSS45	2013-12-26T23:36:30 2013-12-27T00:06:30	Total Count Phase (Doppler) degraded: Surface refractivity in the troposphere model decreased by 10%.
DSS54	2013-12-27T05:22:43 2013-12-27T06:22:43	Sequential Range degraded: Constant transponder bias increased from zero to 187 ns.
DSS65	2013-12-28T04:45:21 2013-12-28T05:45:21	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.007 cycles.
DSS65	2013-12-28T06:42:16 2013-12-28T07:42:16	Total Count Phase (Doppler) degraded: Measurement white noise root variance increased from 0.003 to 0.007 cycles.

ORT RESULTS

The entire Flight Dynamics Team, specifically the Orbit Determination team members who processed the simulated tracking data, gained useful and relevant experience through the ORTs. The tracking simulations with anomalies allowed the team to exercise the flight dynamics processes and tools in a true operational sense. The team needed to use the Ames Flight Dynamics System to process the tracking data, assess whether the data received was as expected, perform tracking system calibration, perform maneuver reconstruction, and then report their finding to the Mission Operations Management Team in operational-like meetings and anomaly reports when necessary.

As a result of the ORTs, the Flight Dynamics Team made several improvements to the Flight Dynamics System and operational documentation for improved Flight Operations. Updates were made to the Flight Dynamics System procedures, which consist of software workflows and scripts. The team uncovered areas in the workflow scripts that needed to be streamlined, such as creating more useful and quick-turnaround graphical outputs for decision-making. Errors in scripts, detected during the examination of realistic data outputs, were corrected and tested for use in Flight Operations. Additionally, because of the ORTs' flight-like processing environment, the Flight Dynamics Team made updates to their team logging interface, the "Virtual Whiteboard". These improvements provided clarification in communications indicating which data products were completed and validated for use, both between team members on the same shift, and for shift handovers. Furthermore, the Flight Dynamics Team was able to update their Handbook after the ORTs, adding information where needed and clarifying previously confusing content based on their experience using the Handbook in the flight-like environment.

As described above, each ORT was designed to present specific orbit determination challenges. Several of the reported anomalies from ORT-1 are described below. The anomaly reports are presented here as documented in the LADEE issue tracking system during the execution of the ORTs with only minor editing for format and typographical corrections.

[LADOPS-531] Constant Transponder Range Bias is Now Trending in OD Plots

The OD Filter tuning process has uncovered a Transponder Range Bias. The constant bias is 550 meters, +/- 120 meters, 3-sigma. This constant bias is now consistently working as part of our solution throughout the beginning of the mission. We will continue to monitor this, and will adjust (lower) the sigma on this if possible, or adjust the Constant Bias if we see that it is trending away from 550 meters.

Attached is the Transponder range bias graph, Figure 4, in terms of nanoseconds. The "zero" line on the Y axis is the Constant Bias. The Constant Bias (zero line on Y axis) is 1834.6 nanoseconds, or 550 meters. The blue line is the estimated bias off of that constant bias throughout the timeline. An estimate of the transponder bias is updated whenever the filter has accepted range tracking data.

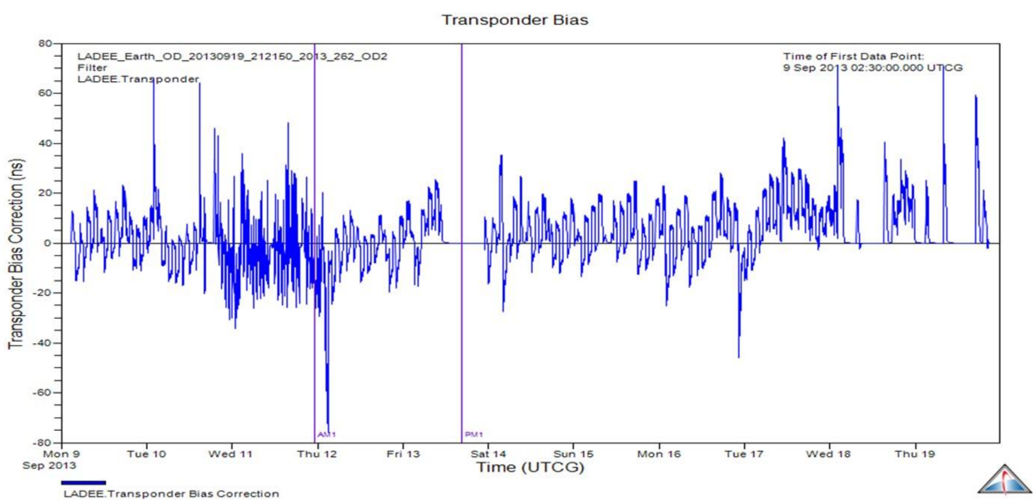

Figure 4. Initial Resolution of LADEE Transponder Delay (ORT-1).

[LADOPS-530] HBK elevation measurements seemed outside of normal bounds for short period of time

On Sept 7 08:06 through 08:14 the elevation measurements from the HBK antenna are being rejected from the OD Filter. We have not correlated this time to any other events that would indicate a required change in our modeling. Just wanted to note this. The priority of going back and looking into this is low, since it is less than 10 minutes of data. But we wanted to note it. A graph, Figure 5, of the few minutes of the HBK data is attached, for reference, to accompany the description of this anomaly report.

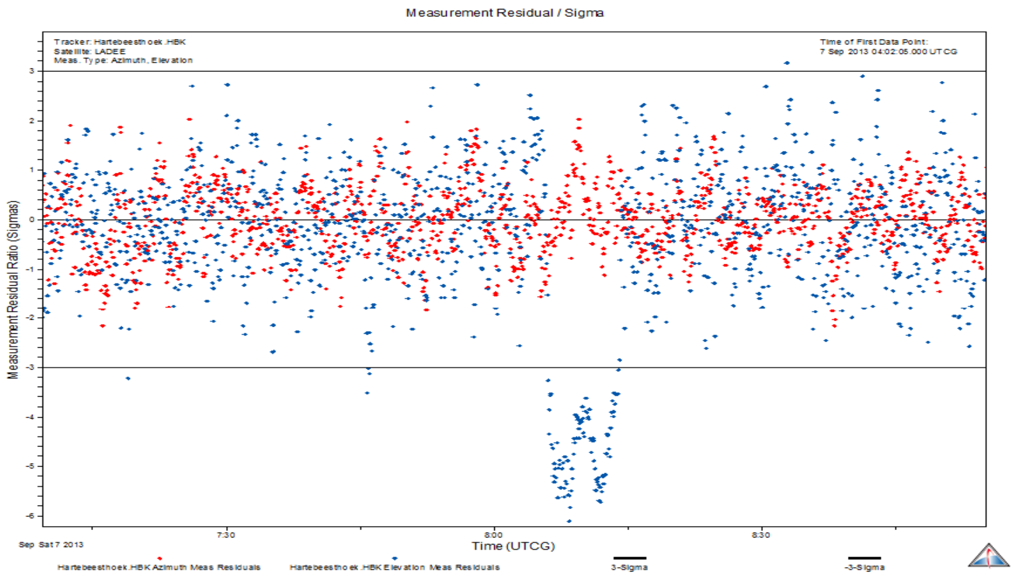

Figure 5. Detection of Degraded Angle Measurements (ORT-1).

[LADOPS-529] DSS27 Sequential Range Bias

All of the sequential range data from the DSS27 Sep 7 @18:13:16 to Sep 8 @ 00:44:56 contact is being rejected from the OD solution. It is showing a constant bias of about 1.7 km, and which ranges from about 20 to 30-sigma during that portion of the solution. We are choosing not to set a constant bias on this antenna at this time (which would force the Filter to include this data). We are allowing the rejection to occur, and instead report this as an anomaly.

Attached is a residual ratios graph, Figure 6. This version of the graph is plotting all of the residuals from all stations, for all measurement types, using the current (as of Sep 8, 08:28 UTC) statistics settings including the transponder bias settings. The wavy brown line that is way above where all of the other colors are mashed up is the DSS27 range residuals that the filter is rejecting. The second contact we had on DSS-27 did not have the range bias. The range data was accepted without any problems during the second contact with DSS-27.

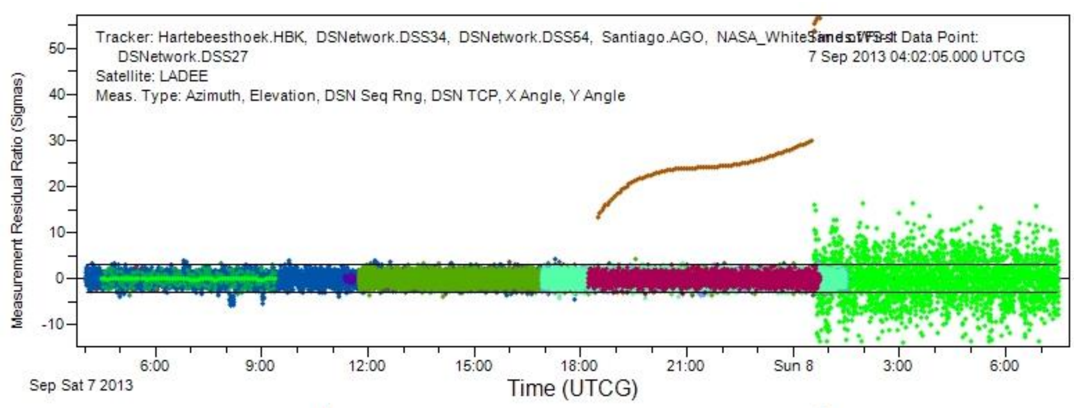

Figure 6. Detection of Anomalous Range Bias (ORT-1).

[LADOPS-533] Noisy Doppler on DSS34 Sep 8 00:35-10:10

Reported noisy TCP (Doppler) data from the DSS34 antenna from the second contact we had with that antenna. This behavior was not observed in the measurements during the first DSS34 contact on Sep 7th. Attached is a plot of all of the Doppler (TCP) measurements, Figure 7, received from all of the DSN antennas thus far. The last contact was on DSS34 and there is much noisier Doppler during this contact. One question to ask the DSN is to find out if the station performed their antenna calibration prior to this pass, like they were scheduled to do. If not, it is possible that something could be off that would make this occur.

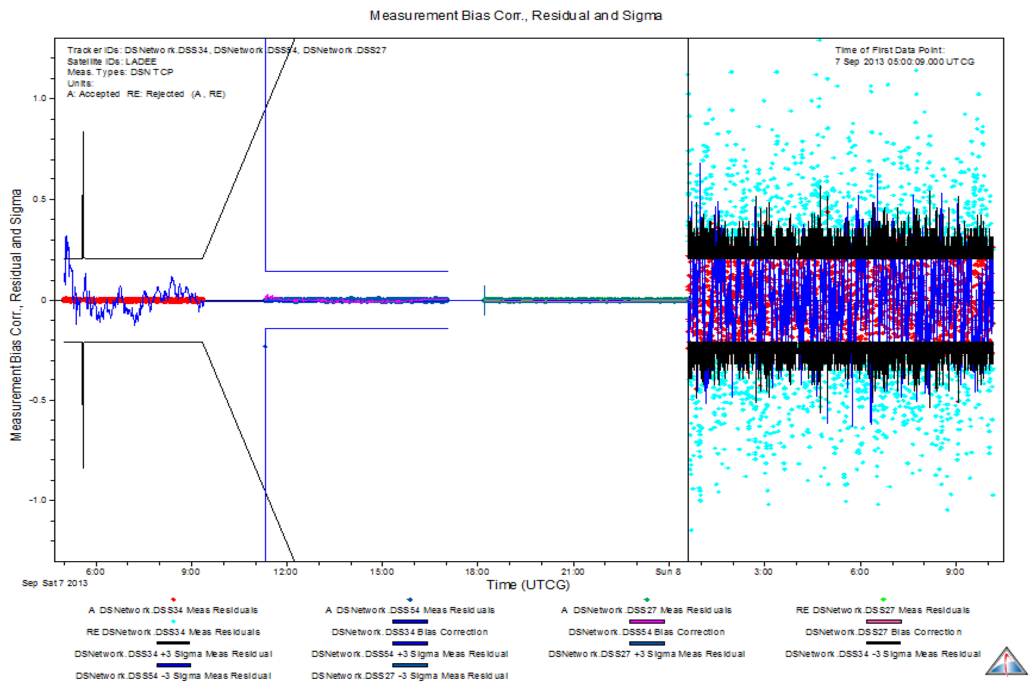

Figure 7. Detection of Degraded TCP Performance (ORT-1).

Maneuver reconstruction

The Flight Dynamics Team was also able to successfully reconstruct the maneuver performances from the orbit determination estimates during the ORTs. Below are two examples from Maneuver Assessment Meeting presentations during the ORTs. Table 12 shows the results from ORT-2's PM3 maneuver assessment. Table 13 describes the results from ORT-3's LOI-1 maneuver. The orbit determination and maneuver planning team members were able to exercise a flight-like maneuver reconstruction process, with results presented in the flight-like status meeting. This whole experience enabled the team members to practice working through the challenges and results on a flight-like timeline, and practice communicating those results within the mission operations team.

Table 12. ORT-2 Maneuver Assessment from OD Results at PM-3 Plus 7 Hours.

Key Parameters	Expected Value	Recovery From Tracking Data
Main Burn Start Time	01 Oct 2013 20:54:39.000	N/A
Main Burn DV (m/s)	17.0 m/s	16.5 m/s
Performance Error	Nominal Burn (0%)	**3.1% Cold**
Pointing Error	0 deg.	0.4 deg.

Table 13. ORT-3 Maneuver Assessment from OD Results at LOI-1 Plus 12 Hours.

Key Parameters	Expected Value	Simulated Truth	Recovery from Tracking Data
Main Burn Start Time	06 Oct 2013 11:48:42.000	N/A	N/A
Main Burn DV (m/s)	332.75 m/s	356 m/s	356 m/s
Propulsion Performance	Nominal Burn (0%)	**7% Hot**	**7% Hot**
Pointing Error	0 deg.	Random	1.5 deg.

CONCLUSION

The generation and use of simulated spacecraft trajectories and corresponding tracking data allowed for the use of consistent true and estimated spacecraft positional information across all groups involved in the LADEE Operational Readiness Tests. Anomalies introduced into maneuver execution, environmental effects, and tracking system phenomenology provided stressing challenges for the Flight Dynamics Team to overcome in a simulated real-time environment using the soon to be operational Flight Dynamics System. The ability of the flight dynamics, mission planning, spacecraft engineering, real-time operations, and mission operations management teams to overcome these challenges and deliver accurate flight dynamics products provided reasonable assurance that the team and Flight Dynamics System were ready to fly the LADEE mission.

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