

AN ORBIT DETERMINATION COMPARISON STUDY AND DEMONSTRATION FOR RENDEZVOUS AND DOCKING IN A NEAR RECTILINEAR HALO ORBIT FROM THE LUNAR SURFACE

David C. Woffinden^{*}, Duane C. Roth[†], Juan I. Orphee[‡], Brian T. Young[§]

For the upcoming NASA Artemis III mission and those that follow, both the Human Landing System (HLS) and Orion programs are invested in understanding the impacts of ground tracking performance in supporting rendezvous and docking in a Near Rectilinear Halo Orbit (NRHO). Several critical questions must be answered to ensure mission success and crew safety and an assortment of analysis tools are being incorporated to address them. Two of these tools, LINCOV and MONTE, are currently providing program decision making results through HLS Insight, HLS NASA-collaborations, and Orion/Gateway cross-program analysis. To ensure consistency in the orbit determination performance, a comparison trade-study is performed using a low-lunar orbit to NRHO rendezvous scenario anticipated for the upcoming Artemis missions. An overview of the two analysis tools is provided along with a detailed step-by-step evaluation of the core capabilities and models related to the orbit determination process. This incremental comparison effort reveals both tools produce consistent solutions for the criteria investigated to within 0.3% difference in the absolute position state estimate at key decision making epochs with all errors sources activated.

INTRODUCTION

To support rendezvous and docking missions, it is not unreasonable to focus on the relative navigation sensors such as LiDARs, optical navigation cameras providing relative angle measurements, and communication systems that produce relative range and range-rate information vital in determining the relative motion between two spacecraft. Even though those types of relative measurements play a critical role, another subtle yet key element to support rendezvous and docking in a Near Rectilinear Halo Orbit (NRHO) is the orbit determination of the absolute state of both the active chaser vehicle and the passive target vehicle. By taking the state vector difference of the ground tracking solution of both spacecraft, the relative state can be determined. Then, it becomes possible to target the necessary relative constraints to support an assortment of rendezvous and proximity operations.

For the upcoming NASA Artemis III mission and those that follow, both the Human Landing System (HLS) and Orion programs are invested in understanding the impacts of ground tracking performance in supporting rendezvous and docking in a Near Rectilinear Halo Orbit (NRHO). Several critical questions must be answered to ensure mission success and crew safety and an assortment of analysis tools are being incorporated to address them. Two of these tools, LINCOV and MONTE, are currently providing program decision making results through HLS Insight, HLS NASA-collaborations, and Orion/Gateway cross-program analysis. To ensure consistency in the orbit determination performance, this paper performs a comparison trade-study using a low-lunar orbit to NRHO rendezvous scenario anticipated for the upcoming Artemis missions.

^{*}GN&C Autonomous Flight Systems Engineer, NASA Johnson Space Center, david.c.woffinden@nasa.gov

[†]Navigation Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, duane.roth@jpl.nasa.gov

[‡]Human Landing System GN&C Lead, NASA Marshall Space Flight Center, juan.i.orphee@nasa.gov

[§]Navigation Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, brian.t.young@jpl.nasa.gov

The first section provides an overview of the orbit determination performance metrics and a description of the two analysis tools. Then the NRHO rendezvous trajectory and concept of operations is introduced followed by a detailed step-by-step evaluation of the core capabilities and models related to the orbit determination process. For the comparison study, generic parameters are utilized that do not reflect mission design values anticipated by the HLS program, rather they capture relevant assumptions to adequately support the orbit determination comparison study. A summary of the developments and core results is then captured in the concluding section.

ORBIT DETERMINATION ANALYSIS APPROACH AND TOOLS

To introduce the different techniques and analysis tools to perform the ground tracking orbit determination results, there are several performance metrics that must be defined which include the true trajectory dispersions $\delta \mathbf{x}$, the navigation dispersions $\delta \hat{\mathbf{x}}$, the true navigation error $\delta \mathbf{e}$, and the onboard navigation error $\delta \hat{\mathbf{e}}$ as depicted in Figure 1. The true dispersions $\delta \mathbf{x}$ are defined as the difference between the true state $\mathbf{x}$ and the

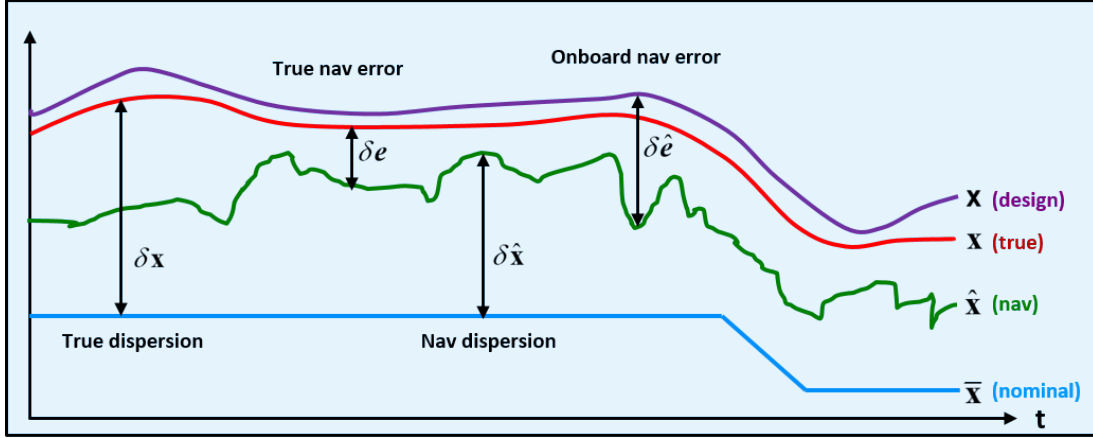


Figure 1. GN&C performance metric variables

nominal state $\bar{\mathbf{x}}$. The true state $\mathbf{x}$ is an n -dimensional vector that represents the *real world* environment or actual state.

$$\delta \mathbf{x} \triangleq \mathbf{x} - \bar{\mathbf{x}} \quad \mathbf{D} = E [\delta \mathbf{x} \delta \mathbf{x}^T] \quad (1)$$

The nominal state $\bar{\mathbf{x}}$ is also an n -dimensional vector that represents the desired or reference state. The covariance of the environment dispersions, $\mathbf{D}$, indicates how precisely the system can follow a desired trajectory.

The navigation dispersions $\delta \hat{\mathbf{x}}$ are defined as the difference between the navigation state $\hat{\mathbf{x}}$ and the nominal state $\bar{\mathbf{x}}$. The navigation state is an $\hat{n}$ -dimensional vector ($\hat{n} < n$) that represents the filter's estimated state.

$$\delta \hat{\mathbf{x}} \triangleq \hat{\mathbf{x}} - \mathbf{M}_x \bar{\mathbf{x}} \quad \hat{\mathbf{D}} = E [\delta \hat{\mathbf{x}} \delta \hat{\mathbf{x}}^T] \quad (2)$$

The matrix $\mathbf{M}_x$ is an $(\hat{n} \times n)$ matrix that maps the estimated state in terms of the true and nominal state. The covariance of the navigation dispersions, $\hat{\mathbf{D}}$, reflect how precisely the onboard system thinks it can follow a prescribed reference trajectory.

The true navigation error $\delta \mathbf{e}$ is the difference between the environment and navigation states. It is also the difference between the environment and the navigation dispersions.

$$\delta \mathbf{e} \triangleq \mathbf{M}_x \mathbf{x} - \hat{\mathbf{x}} = \mathbf{M}_x \delta \mathbf{x} - \delta \hat{\mathbf{x}} \quad \mathbf{P} = E [\delta \mathbf{e} \delta \mathbf{e}^T] \quad (3)$$

The covariance of the true navigation error, $\mathbf{P}$, quantifies how precisely the onboard navigation system can estimate the actual state.

The onboard navigation error $\delta\hat{\mathbf{e}}$ itself is never computed, but it is used to develop the onboard navigation filter equations. It is defined as the difference between the design state, $\mathbf{x}$, and the navigation state $\hat{\mathbf{x}}$.

$$\delta\hat{\mathbf{e}} \triangleq \mathbf{x} - \hat{\mathbf{x}} \quad \hat{\mathbf{P}} = E [\delta\hat{\mathbf{e}}\delta\hat{\mathbf{e}}^T] \quad (4)$$

The covariance of the onboard navigation error, $\hat{\mathbf{P}}$, quantifies how precisely the onboard navigation system expects it can determine the actual state. The performance of the onboard navigation system is determined by comparing $\hat{\mathbf{P}}$ to the actual navigation performance $\mathbf{P}$. If the *true* states and the *design* states are assumed to be the same, then the true navigation covariance will equal the onboard navigation covariance.

The covariances of the true dispersions, navigation dispersions, true navigation error, and the onboard navigation error are ultimately used to analyze and assess the performance of a proposed GN&C system. A common approach to obtain these performance metrics is to use a Monte Carlo simulation outlined in Figure 2, where the sample statistics of hundreds or thousands of runs, N , are used to numerically compute the desired covariance matrices.

$$\mathbf{D} = \frac{1}{N-1} \sum \delta\mathbf{x}\delta\mathbf{x}^T \quad \hat{\mathbf{D}} = \frac{1}{N-1} \sum \delta\hat{\mathbf{x}}\delta\hat{\mathbf{x}}^T \quad \mathbf{P} = \frac{1}{N-1} \sum \delta\mathbf{e}\delta\mathbf{e}^T \quad (5)$$

The onboard navigation error covariance $\hat{\mathbf{P}}$ is the navigation filter covariance for each run. This same statistical information can be obtained using linear covariance analysis techniques.

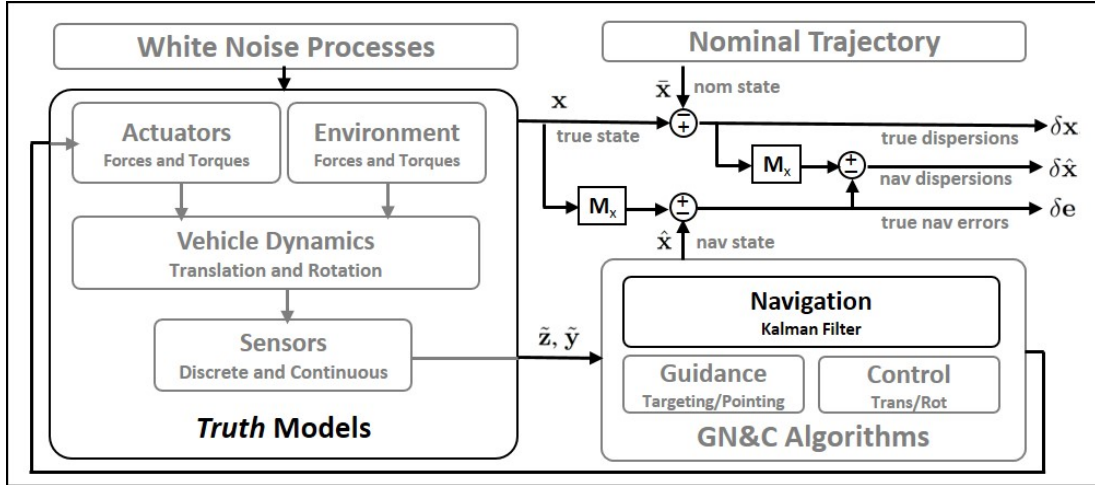


Figure 2. Extracting GN&C performance metrics using Monte Carlo techniques

LINCOV: Linear Covariance Analysis

LINCOV or the linear covariance analysis tool (LinCov) utilizes augmented and onboard state covariance matrices to produce the statistical performance metrics of a closed-loop GN&C system in a single-run, compared to hundreds or thousands of runs typically required for Monte Carlo analysis. Linear covariance analysis incorporates the non-linear system dynamics models and GN&C algorithms to generate a nominal reference trajectory $\bar{\mathbf{x}}$ which is then used to propagate, update, and correct an onboard navigation covariance matrix $\hat{\mathbf{P}}$ and an augmented state covariance matrix $\mathbf{C}$,

$$\mathbf{C} = E [\delta\mathbf{X}\delta\mathbf{X}^T] \quad (6)$$

where the augmented state $\delta\mathbf{X}^T = [\delta\mathbf{x}^T \ \delta\hat{\mathbf{x}}^T]$ consists of the true dispersions and the navigation dispersions. Pre- and post-multiplying the augmented state covariance matrix by the following mapping matrices, the

covariances for the trajectory dispersions, navigation dispersions, and the navigation error can be obtained.

$$\begin{aligned} \mathbf{D} &= [\mathbf{I}_{n \times n}, \mathbf{0}_{n \times \hat{n}}] \mathbf{C} [\mathbf{I}_{n \times n}, \mathbf{0}_{n \times \hat{n}}]^T \\ \hat{\mathbf{D}} &= [\mathbf{0}_{\hat{n} \times n}, \mathbf{I}_{\hat{n} \times \hat{n}}] \mathbf{C} [\mathbf{0}_{\hat{n} \times n}, \mathbf{I}_{\hat{n} \times \hat{n}}]^T \\ \mathbf{P} &= [\mathbf{I}_{\hat{n} \times n}, -\mathbf{I}_{\hat{n} \times \hat{n}}] \mathbf{C} [\mathbf{I}_{\hat{n} \times n}, -\mathbf{I}_{\hat{n} \times \hat{n}}]^T \end{aligned} \quad (7)$$

For details regarding the development and implementation of the linear covariance simulation, see the following references [1–3].

The LinCov tool used for the HLS and Orion programs is developed and maintained by the Johnson Space Center community and has been utilized for multiple space programs for almost two decades for all critical flight phases. The LinCov ground tracking models [4] depicted in Figure 3 have been utilized to support several programs, including the Orion program for Artemis I flight analysis, Artemis II trajectory performance analysis [5] and venting analysis [6], Artemis III NRHO orbit maintenance analysis [7], the Safe and Precise Landing Integrated Capabilities Evolution (SPLICE) Project for descent and landing [8], the Human Landing System (HLS) program [9], and other lunar program studies [10].

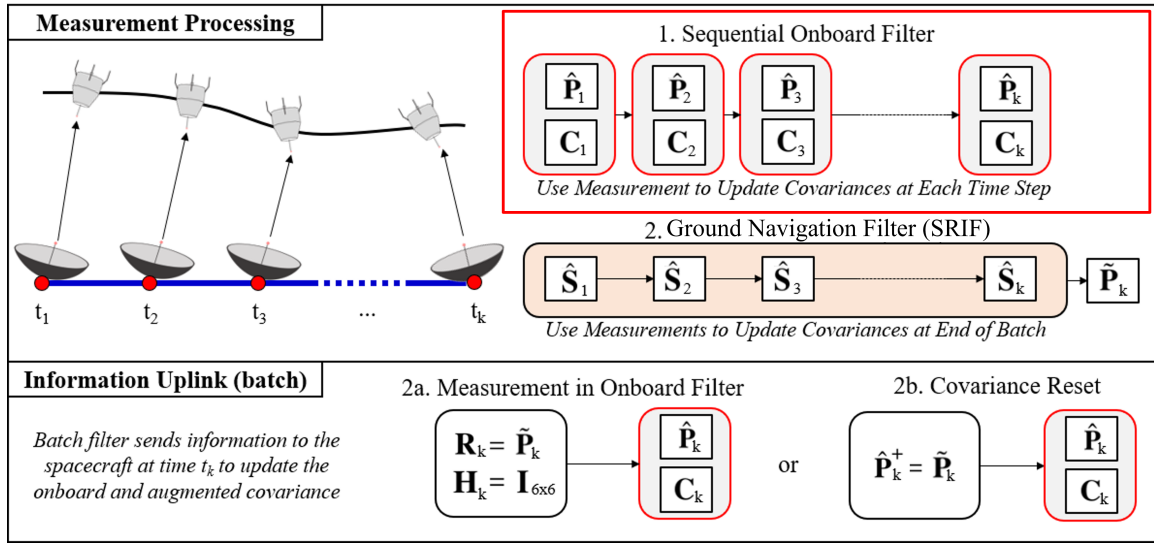


Figure 3. Notional ground tracking modeling options for the orbit determination problem

MONTÉ: The Mission Analysis Operations and Navigation Toolkit Environment

MONTÉ is a *state-of-the-art astrodynamics Python library* produced by the Jet Propulsion Laboratory (JPL) [11, 12]. It supports all phases of space mission development from early space design and analysis through flight navigation services and has over a decade of operational use on NASA's deep space robotic missions. It supplies an infrastructure for trajectory models, coordinate frames, timing, events, sensitivity analysis, numerical integrators, and optimization. The Johnson Space Center has determined MONTÉ will be used to support future Artemis II+ missions for orbit determination. The MONTÉ-based tool at the Johnson Space Center (JSC) utilized by the Flight Operations Directorate (FOD) is known as MANDO.

NRHO RENDEZVOUS FROM LOW LUNAR ORBIT

The NASA Human Landing System (HLS) Flight Dynamics team has produced multiple lunar ascent site-specific epoch scans spanning several years from thirteen different potential crewed landing regions. The trajectory data sets evaluate a variety of different low-lunar orbit (LLO) revolutions and transfer durations

from the lunar surface to the NRHO. The selected trajectory profile for the comparison trade study launches from Malapert crater near the south pole of the moon as depicted in Figure 4, orbits in low-lunar orbit for several revs following the lunar orbit insertion burn, then executes the low-lunar orbit departure (LLOD) burn to transfer to the designated NRHO insertion (NRI) point in preparation to rendezvous and dock with the Orion spacecraft. During the outbound phase to the NRHO, two trajectory correction maneuvers (TCM) with nominal delta-v magnitudes of zero are allocated for trajectory dispersion control. The insertion point in the NRHO has a specific relative position offset to the Orion spacecraft in preparation for the final rendezvous, proximity operations, and docking phase. The epoch of the lunar ascent scenario for the comparison study is 6-Oct-2027 16:45:25.

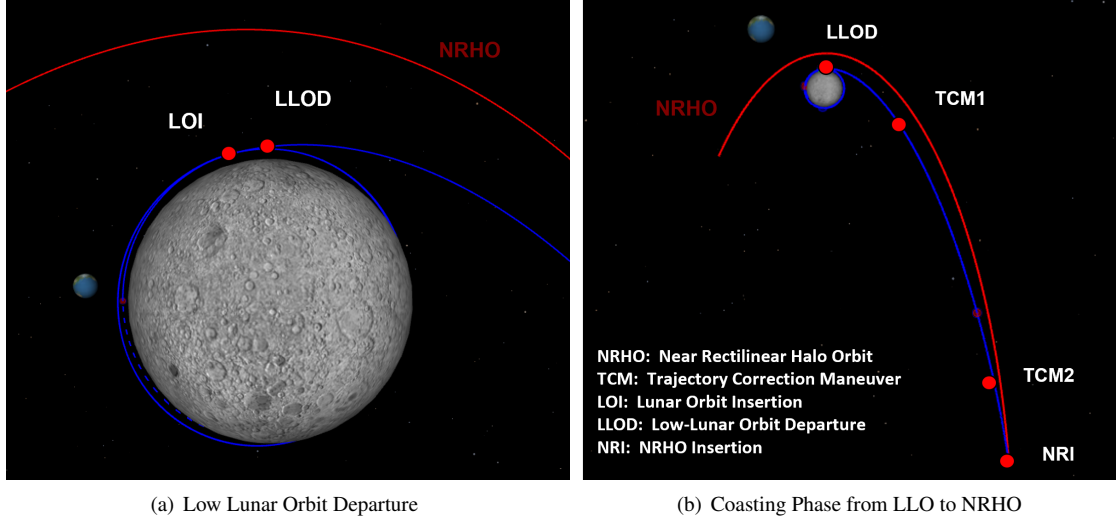


Figure 4. Notional HLS lunar surface to NRHO return rendezvous scenario for Artemis III

Ground Tracking Navigation Parameters

For the HLS ground tracking comparison study, six arbitrary ground stations are incorporated with differing performance specifications such as the range noise and bias, doppler noise and bias, and ground station location accuracy for each complex. The tracking ground station is selected based on the maximum elevation angle of the vehicle to each facility and only one ground station is active any given period such that three-way doppler is not considered. Each ground asset is assumed to be able to generate both ranging and doppler measurements such that both continuous doppler and ranging are available. No communication outages are assumed due to switching between complexes or planetary occlusion. The elevation mask is assumed to be zero degrees with measurements processed once every minute.

Vehicle Performance Assumptions

The assumptions related to the vehicle performance includes the initial navigation errors, disturbance accelerations, and maneuver execution errors. The initial navigation errors are assumed to be 5.0 km 3-sigma per axis for the absolute position state and 500.0 mm/s 3-sigma per axis for the absolute velocity state. The disturbance acceleration is modeled as white noise or process noise for this comparison study, though other models are available. In MONTE, the disturbance acceleration process noise is modeled as acceleration batches. For example, a process noise with a power spectral density, Q , is converted to an acceleration, $\mathbf{a}$, over a batch interval, t , of one minute such that

$$\mathbf{a} = \sqrt{\frac{Q}{t}} \quad (8)$$

Since the tracking data is simulated at 60 second intervals, there is no benefit evaluating at shorter batch intervals. The Gate's maneuver execution error model [13] is utilized to capture the impacts of the translational burns to the orbit determination process. The planetary ephemeris models adopted for the nominal trajectory generation is provided in Table 1. They are extracted from the JPL Navigation and Ancillary Information Facility (NAIF) site*.

Table 1. Planetary Ephemeris Models

Parameter	Source
Planetary Ephemeris	DE440 (JPL/NAIF/SPICE)
Lunar Gravity Harmonics	8x8, GL0900D (GRAIL)
Point Mass Gravity Bodies	Sun, Earth, and Moon
NRHO Reference Orbit	receding_horiz_3189_1burnApo_DiffCorr_15yr.bsp
Solar Radiation Pressure	None

MONTE / LINCOV COMPARISON TRADE STUDY RESULTS

There are several facets regarding the MONTE/LINCOV comparison trade study that are investigated. First, the trajectories generated within each tool set are compared to ensure the state initial conditions, propagation routines, maneuver execution, and ground station placement modeling are consistent. Second, the orbit determination solution generated from each simulation tool is compared in terms of the HLS vehicle absolute position and velocity accuracy along with ground station selection consistency, and resulting elevation angle profiles observed from each complex. Lastly, a sensitivity comparison study of the orbit determination solution is performed by incrementally activating core elements of the ground tracking models to highlight the impacts they have on the overall solution and to verify proper implementation and performance. These basic capabilities include the propagation and discrete updates of the resulting state uncertainty due to: disturbance accelerations, maneuver execution errors, initial navigation uncertainty, processing doppler measurements with noise and bias, ranging measurements with noise and bias, and ground station location biases.

HLS NRHO Outbound Trajectory Comparison

As shown in Figure 5, the time history of the propagated HLS vehicle components of the nominal absolute position and velocity states by both the LINCOV and MONTE tools are co-plotted and shown in the top left plots respectively. The solid lines represent the values produced by LINCOV and the dashed lines represent the trajectory elements generated by MONTE. The difference of the nominal HLS position and velocity predicted by both simulations is provided in the bottom left plot. In general, the trajectory profiles do not differ more than 50-60 meters at any time interval. The tabulated data in the top right portion of the figure shows the numerical values of the states in the planet (moon) centered inertial frame at key epochs of the scenario with the LINCOV predictions on the left and the MONTE results on the right (in parenthesis). The bottom right image shows the HLS outbound trajectory (blue line) from the lunar vicinity to the NRHO insertion (NRI) point in the Earth/Moon rotating frame in context of the target vehicle (red line) coasting in the predetermined NRHO.

HLS Orbit Determination Comparison

The metrics selected to compare the orbit determination solution for the HLS vehicle are illustrated in Figure 6 containing the time history of the absolute position and velocity 1-sigma navigation errors in the Earth-centered, UVW-coordinates as predicted by both the LINCOV and MONTE ground based models shown in the top-left plots, the resulting elevation angles of the HLS vehicle relative to each ground complex

*<https://naif.jpl.nasa.gov/naif/>

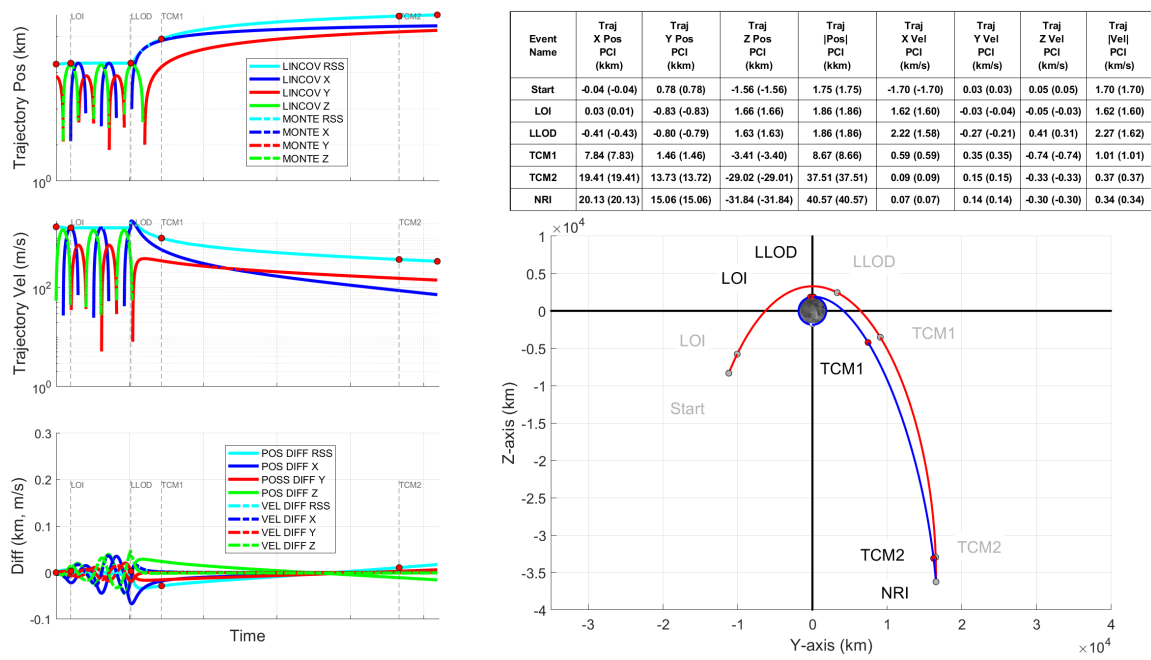


Figure 5. LINCOV and MONTE Comparison of Simulated HLS NRHO Outbound Trajectory

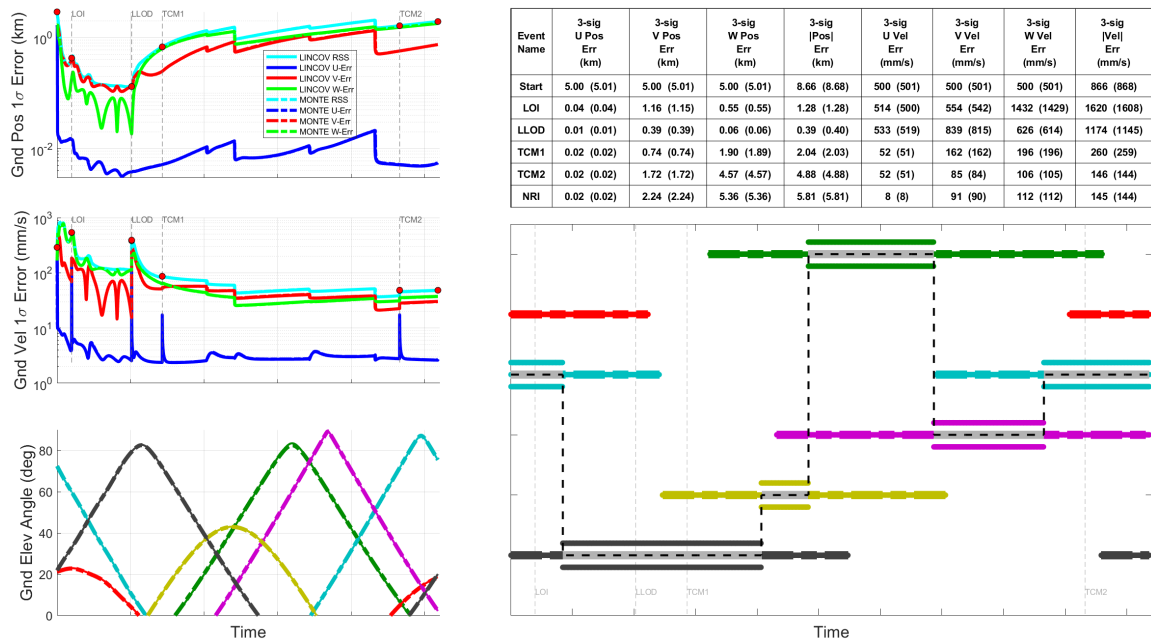


Figure 6. LINCOV and MONTE Orbit Determination Comparison of Performance Parameters

provided in the bottom-left plot, and the ground station visibility (middle line), complex selection (black dashed line for LINCOV and solid thick gray line for MONTE), and measurement types (processed doppler measurements indicated with top line and ranging measurements are represented with the solid bottom line)

depicted in the bottom-right plot. The numerical navigation values from LINCOV and MONTE at key epochs are displayed with the LINCOV values on the left and the MONTE predicted solutions on the right (in parenthesis). In general, the predictions from the LINCOV tool are shown with solid lines and those values from MONTE are presented with dashed lines.

The plots in this figure highlight a fundamental trait beyond the consistent numerical values produced at specific epochs. They show the time-correlated characterization of the navigation error to be very consistent for the error magnitudes in position and velocity throughout the entire profile, along with accurately describing the time history of the specific components in each axis. The next section will formally quantify this consistency in terms of the percent difference of the orbit determination results generated by the two analysis tool sets.

HLS Orbit Determination Sensitivity Comparison

The development of the comparison study took incremental steps evaluating each core component with particular emphasis on the implementation of the disturbance accelerations. Since there are multiple models to capture these perturbations on the vehicle's dynamics and the resulting uncertainty in the orbit determination process, a step-by-step approach of activating each error source was adopted to see the sensitivity of each element, particularly to any discrepancies generated in the percent difference of the two predictions. For example, Table 2 summarizes the percent difference in the position and velocity magnitude estimates at the times where key targeted burns are performed that rely upon the orbit determination solution given a variety of different active ground tracking modeling assumptions.

This summary highlights the impact of the disturbance accelerations, maneuver or burn execution errors, initial navigation errors, processing doppler measurements with noise and bias terms active, impacts of utilizing ranging measurements with noise and biases included, and various combinations until all the error sources are active (see the bottom row in the table). The percent difference in the position magnitude estimates varies between 0.1% to 0.3% with the velocity percent difference being 0.2% to 2.5% when all the ground models errors identified are active. For some of the particular scenarios with larger max discrepancies, they represent a small fraction of the overall time period and are not considered to be significant though noticed.

Table 2. LINCOV and MONTE Orbit Determination Comparison Performance Summary

Active Ground Tracking Model Components	Percent Difference	
	Position Mag	Velocity Mag
Disturbance Accelerations Only	0.1% to 3.4%	0.1% to 3.4%
Maneuver (or Burn) Execution Error Only	0.0% to 1.0%	0.0% to 2.7%
Initial Conditions (IC) Only	0.2% to 7.5%	0.2% to 9.8%
IC with Burns	0.2% to 7.2%	0.2% to 8.7%
IC with Doppler Noise	0.2% to 10.9%	0.2% to 11.3%
IC with Ranging Noise	0.2% to 5.5%	0.2% to 5.8%
IC with Doppler Noise/Bias	0.2% to 12.7%	0.2% to 13.1%
IC with Ranging Noise/Bias	0.2% to 4.3%	0.2% to 5.5%
IC with Doppler/Ranging Noise/Bias	0.2% to 12.1%	0.2% to 12.6%
IC with Doppler/Ranging Noise/Bias and Burns	0.2% to 9.0%	0.2% to 2.7%
IC with Doppler/Ranging Noise/Bias and Dist Accels	0.1% to 0.3%	0.1% to 0.3%
IC with Doppler/Ranging Noise/Bias, Dist Accels, and Burns	0.2% to 0.7%	0.2% to 2.5%
IC with Doppler/Ranging Noise/Bias, Dist Accels, Burns, Gnd Stations	0.0% to 0.3%	0.2% to 2.5%

The time history orbit determination performance results related to the comparison study for each specific component are provided in Figures 7 through Figure 12. For example, Figure 7 contains the 1-sigma

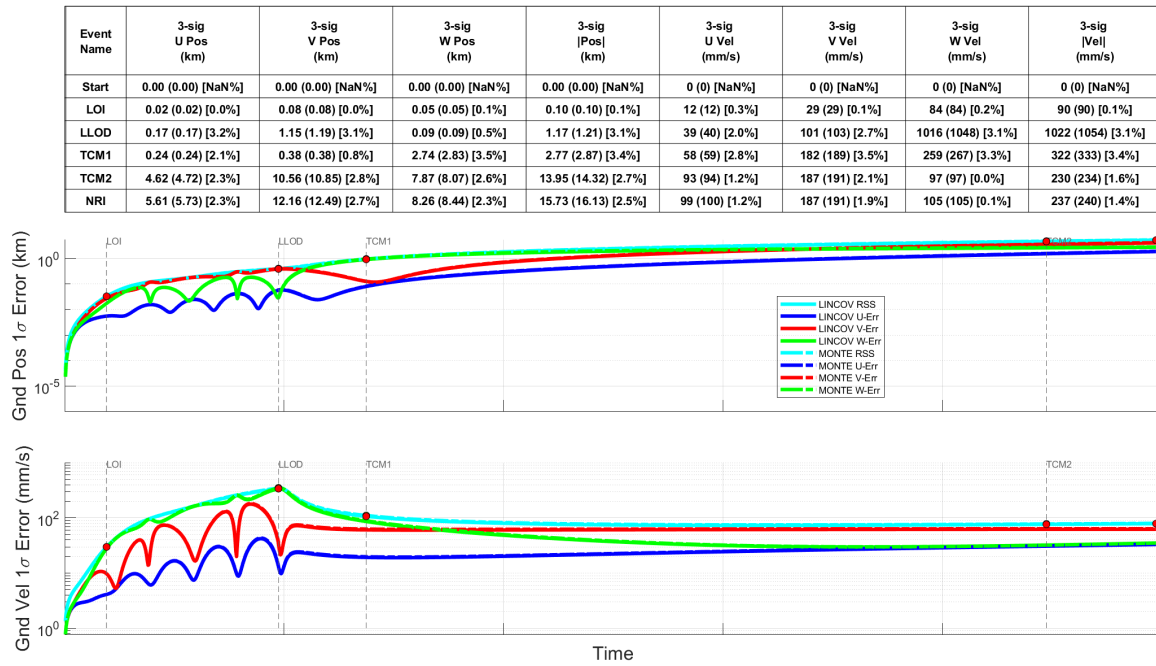


Figure 7. LINCov and MONTE Orbit Determination Comparison with Only the Disturbance Acceleration Error Source Active

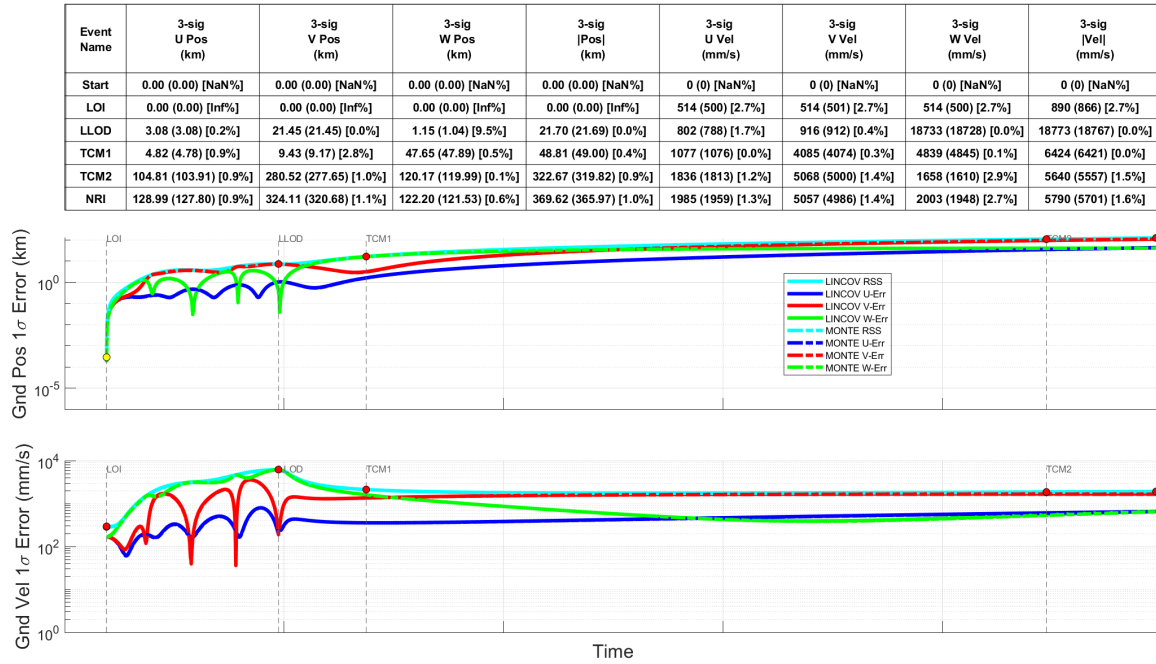


Figure 8. LINCov and MONTE Orbit Determination Comparison with Only the Maneuver Execution (or Burn) Errors Active

Event Name	3-sig U Pos (km)	3-sig V Pos (km)	3-sig W Pos (km)	3-sig Pos (km)	3-sig U Vel (mm/s)	3-sig V Vel (mm/s)	3-sig W Vel (mm/s)	3-sig Vel (mm/s)
Start	5.00 (5.01) [0.2%]	5.00 (5.01) [0.2%]	5.00 (5.01) [0.2%]	8.66 (8.68) [0.2%]	500 (501) [0.2%]	500 (501) [0.2%]	500 (501) [0.2%]	866 (868) [0.2%]
LOI	7.63 (7.64) [0.2%]	50.37 (50.50) [0.3%]	18.02 (18.10) [0.5%]	54.04 (54.18) [0.3%]	799 (798) [0.2%]	8084 (8090) [0.1%]	44479 (44650) [0.4%]	45215 (45384) [0.4%]
LLOD	34.18 (36.37) [6.4%]	234.14 (248.97) [6.3%]	2.70 (3.84) [42.0%]	236.63 (251.64) [6.3%]	5866 (6296) [7.3%]	18055 (19391) [7.4%]	207405 (220138) [6.1%]	208272 (221080) [6.1%]
TCM1	32.76 (34.99) [6.8%]	74.17 (76.82) [3.6%]	532.59 (568.16) [6.7%]	538.72 (574.40) [6.6%]	9271 (9935) [7.2%]	29431 (31840) [8.2%]	48886 (52101) [6.6%]	57810 (61862) [7.0%]
TCM2	510.88 (559.99) [9.6%]	1195.97 (1320.32) [10.4%]	575.75 (1660.09) [5.4%]	2043.12 (2193.79) [7.4%]	6074 (6807) [12.1%]	14512 (16433) [13.2%]	10697 (10813) [1.1%]	19024 (20816) [9.4%]
NRI	594.45 (653.50) [9.9%]	1338.44 (1480.12) [10.6%]	642.07 (1724.14) [5.0%]	2200.27 (2364.42) [7.5%]	5977 (6743) [12.8%]	13354 (15216) [13.9%]	9402 (9346) [0.6%]	17391 (19088) [9.8%]

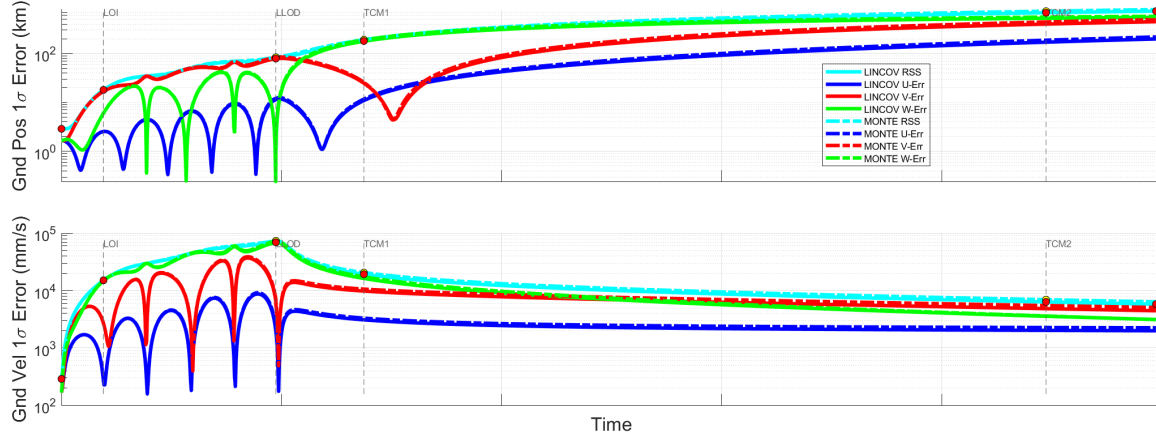


Figure 9. LINCov and MONTE Orbit Determination Comparison with Only the Initial Navigation Errors Active

Event Name	3-sig U Pos (km)	3-sig V Pos (km)	3-sig W Pos (km)	3-sig Pos (km)	3-sig U Vel (mm/s)	3-sig V Vel (mm/s)	3-sig W Vel (mm/s)	3-sig Vel (mm/s)
Start	5.00 (5.01) [0.2%]	5.00 (5.01) [0.2%]	5.00 (5.01) [0.2%]	8.66 (8.68) [0.2%]	500 (501) [0.2%]	500 (501) [0.2%]	500 (501) [0.2%]	866 (868) [0.2%]
LOI	0.08 (0.08) [0.7%]	1.86 (1.81) [2.4%]	0.86 (0.85) [0.7%]	2.04 (2.00) [2.1%]	23 (21) [7.1%]	311 (310) [0.2%]	2131 (2095) [1.7%]	2154 (2117) [1.7%]
LLOD	0.01 (0.01) [2.6%]	0.19 (0.22) [12.9%]	0.02 (0.02) [2.1%]	0.19 (0.22) [12.7%]	3 (3) [2.2%]	16 (17) [7.3%]	163 (185) [13.2%]	164 (186) [13.1%]
TCM1	0.02 (0.02) [2.8%]	0.06 (0.06) [1.1%]	0.18 (0.19) [7.1%]	0.19 (0.20) [6.5%]	3 (3) [1.2%]	14 (15) [4.2%]	19 (20) [5.8%]	24 (25) [5.2%]
TCM2	0.11 (0.11) [0.6%]	0.51 (0.52) [2.3%]	0.56 (0.60) [5.9%]	0.77 (0.80) [4.2%]	2 (2) [0.7%]	8 (8) [0.7%]	5 (6) [4.9%]	10 (10) [2.0%]
NRI	0.12 (0.12) [0.5%]	0.53 (0.54) [2.3%]	0.60 (0.63) [5.9%]	0.81 (0.84) [4.2%]	2 (2) [0.8%]	6 (6) [0.3%]	5 (5) [5.0%]	8 (9) [2.1%]

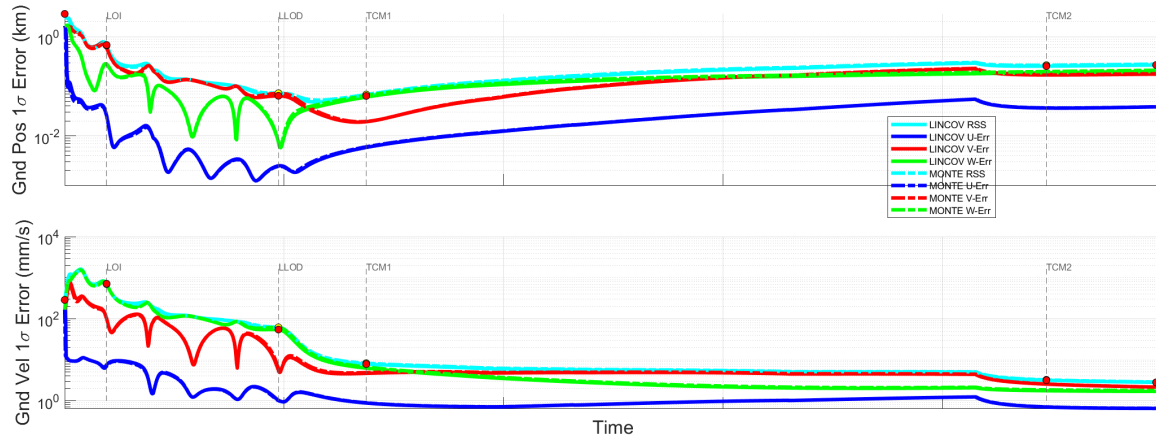


Figure 10. LINCov and MONTE Orbit Determination Comparison with Only the Doppler Noise and Bias Error Sources Active

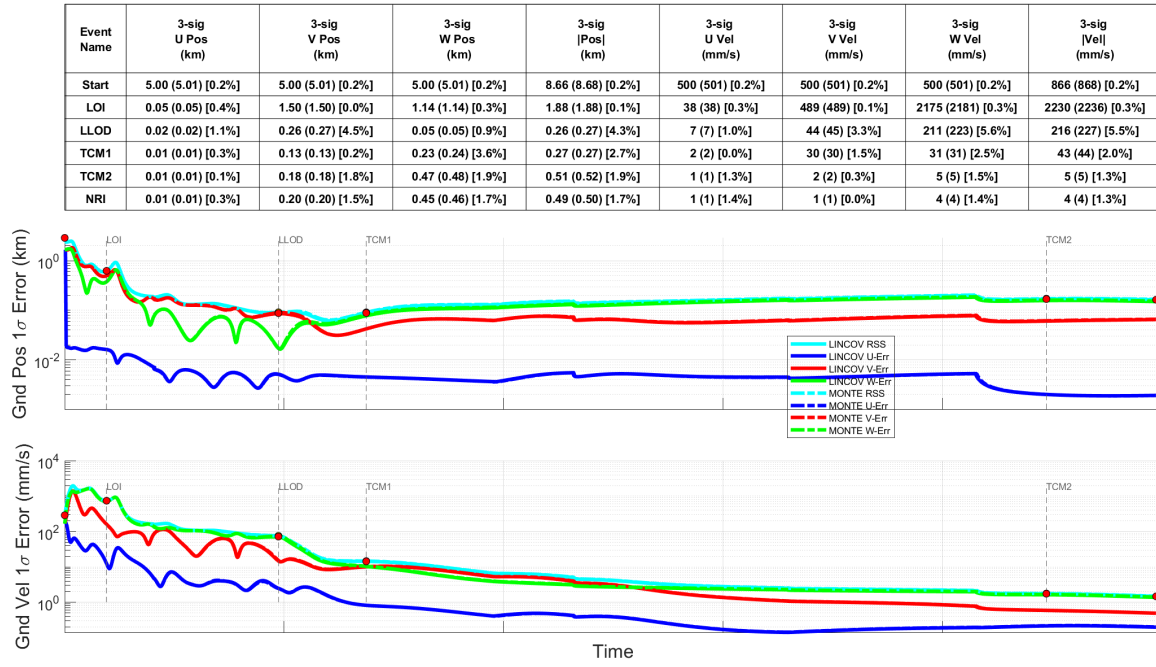


Figure 11. LINCOV and MONTE Orbit Determination Comparison with Only the Ranging Noise and Bias Error Sources Active

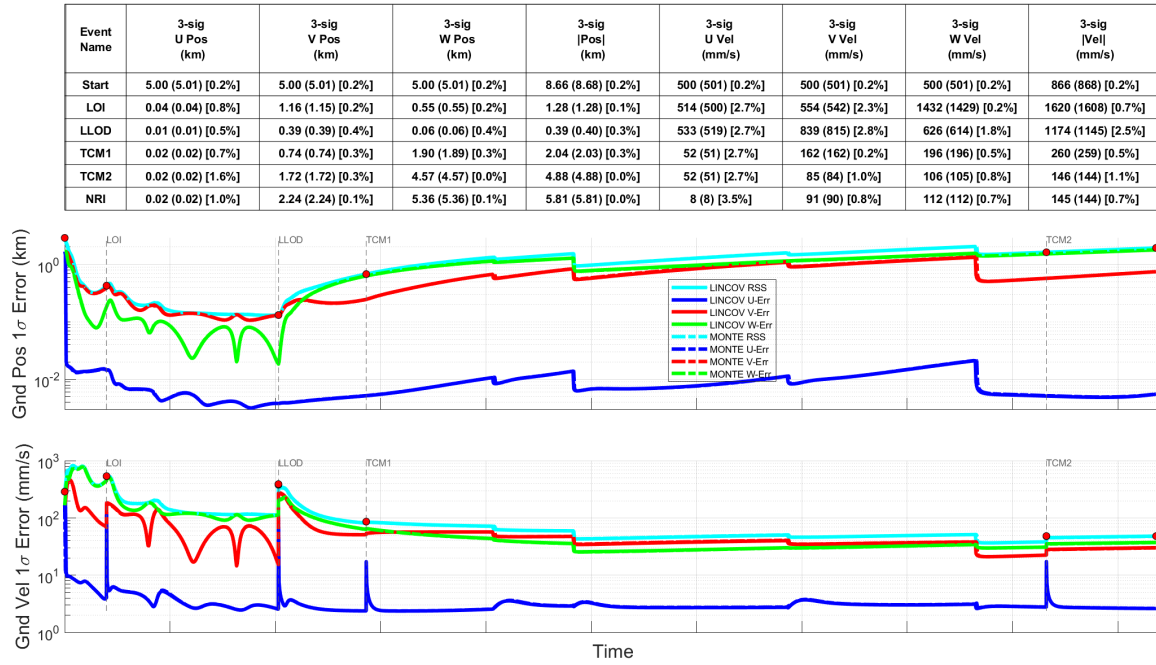


Figure 12. LINCOV and MONTE Orbit Determination Comparison with All Error Sources Including Disturbance Accelerations, Maneuver Execution Error, Initial Navigation Errors with Doppler and Ranging Measurements

position and velocity navigation errors generated by both LINCOV and MONTE when only the disturbance accelerations are active. The tabulated data provides the navigation uncertainty in the Earth-centered, UVW-coordinates at each of the translational burns planned for the lunar ascent to NRHO rendezvous scenario. For each axes in position and velocity, three sets of numerical values are provided. The first value is the LINCOV solution, the second (in parenthesis) is the MONTE prediction, and the third [in square brackets] captures the percent difference between the two estimates. The corresponding data points captured are indicated in the time history plots for both position and velocity. The LINCOV values are indicated with a solid red dot and the MONTE estimate is captured with a solid yellow dot. These plots not only capture the snap shot at key epochs, they also highlight the consistency in the trends for both the total RSS error as well as each component.

Figure 7 which contains the results for modeling the impacts of the orbit determination uncertainty when only the disturbance accelerations are active, shows that both tools have very similar predictions when the modeling is consistent, even when it is represented as a process noise term. Of course other disturbance models and levels of fidelity are available, and as the design matures and more details regarding the vehicle disturbances are known, these will be utilized and compared. For now, the current implementation for the comparison study is similar for classic Kalman filter assumptions and analysis. Under these conditions, the estimated position and velocity magnitude percent difference is less than 3.4% with the peak discrepancy at the first trajectory correction maneuver (TCM1).

Figure 8 provides valuable insight into the consistency of the expected impact of the burn execution error model to the orbit determination process. As mentioned previously, the Gate's model [13] is adopted and these resulting time history plots shows both tools are capturing the proportional pointing and magnitude errors along with the fixed pointing and magnitude terms to within 1.0% in position magnitude and 2.7% in the velocity uncertainty. The percent difference in the velocity estimate occurs with the lunar orbit insertion (LOI) burn while the peak position difference is at the NRHO insertion (NRI) epoch.

Figure 9 shows how both tools initialize and propagate the initial navigation errors. Some of the larger result differences between the two tools seems to be reflected with the initial position and velocity navigation errors. Although at the initial epoch the values are within 0.2%, they reach a maximum at 7.5% at NRI in position and 9.8% in velocity. Typically MONTE is showing a slightly more conservative prediction than LINCOV.

Figure 10 is the first set of results that actually incorporates measurements from the ground complexes. Given the initial navigation errors, doppler measurements with both the noise and bias terms are activated and it becomes evident the reduction in the orbit determination prediction by processing these ship-to-ground range-rate measurements. Rather than the propagated only solution having position errors on the order of thousands of kilometers, the doppler measurements keep them within less than a kilometer (1-sigma, RSS) for the majority of the transfer from the lunar surface to the NRHO.

Figure 11 highlights the benefit of processing ranging measurements to each selected ground station with the corresponding noise and bias terms reflected in the orbit determination solution. Even though only the initial navigation errors and measurement errors are accounted for, with the ship-to-ground ranging data available, the position navigation error is typically less than half a kilometer (1-sigma, RSS) compared to several thousand kilometers when no ranging measurements were processed. When comparing the results between LINCOV and MONTE, the percent difference in position error is less than 4.3%.

Figure 12 brings everything together and shows the integrated performance results when both doppler and ranging measurements are being processed while both disturbance accelerations, maneuver execution errors, and the initial navigation errors are included. With the transfer completion at NRI, the position error is 5.81 km (1-sigma, RSS) with a percent difference between the tools of 0.0%. For the entire profile, the position magnitude estimate of both tools never diverged by more than 0.3% and the predicted navigation error in each component never differed by more than 0.4% in position. In general, both tools provide very similar results though they each have a different heritage, language, framework, and core algorithms.

CONCLUSION

Rendezvous and docking will play a vital role in accomplishing NASA's upcoming Artemis III mission and those that follow. Both the Human Landing System (HLS) and Orion programs are invested in understanding the impacts of ground tracking performance in supporting rendezvous and docking in a Near Rectilinear Halo Orbit (NRHO). It could be argued that the most critical relative navigation *sensors* for the upcoming Artemis III mission are the ground complexes tracking both the HLS and Orion spacecraft. The difference of the orbit determination solution from both vehicles will ultimately provide the relative state estimate that will be targeted to initiate the far-range RPOD phase following insertion into the NRHO. If the desired relative offset point is unable to be achieved successfully, the subsequent rendezvous sequence capitalizing on additional relative sensors producing relative range, range-rate, and angles may be jeopardized.

Extensive resources and analysis are being applied to identify the required accuracy and performance specifications that will ensure a successful rendezvous and docking while maintaining crew safety. An assortment of analysis tools, such as LINCOV and MONTE, are currently providing program decision making results through HLS Insight, HLS NASA-collaborations, and Orion/Gateway cross-program analysis. A detailed comparison study between the two tool sets has been performed using a low-lunar orbit to NRHO rendezvous scenario anticipated for the upcoming Artemis missions to ensure consistency in the orbit determination performance. An incremental comparison effort culminated in demonstrating both tools produced consistent absolute position and velocity estimates to within a 0.0% to 2.5% difference at critical epochs when the core model parameters were activated. A sensitivity analysis decomposing the impacts of each error source such as disturbance accelerations, maneuver or burn execution error, initial condition uncertainty, and doppler and ranging measurement processing is provided. Though both tools have different heritages, languages, framework, and core algorithms; when common analysis assumptions are adopted and implemented, this comparison study has shown both LINCOV and MONTE produce similar and complementary orbit determination results.

REFERENCES

- [1] P. S. Maybeck, *Stochastic models, estimation, and control*, vol. 1. New York: Academic Press, 1979.
- [2] D. K. Geller, "Linear covariance techniques for orbital rendezvous analysis and autonomous onboard mission planning," *Journal of Guidance, Control, and Dynamics*, vol. 29, pp. 1404–1414, November–December 2006.
- [3] D. Woffinden, S. Robinson, J. Williams, and Z. Putnam, "Linear covariance analysis techniques to generate navigation and sensor requirements for the safe and precise landing - integrated capabilities evolution (splice) project," in *AIAA Scitech 2019 Forum*, (San Diego, CA), AIAA 2019-0662, 7–11 January 2019.
- [4] B. C. Collicott and D. C. Woffinden, "Lunar navigation performance using the deep space network and alternate solutions to support precision landing," (Virtual), *AIAA SciTech Forum*, AIAA 2021-0375, 4 January 2021.
- [5] D. Woffinden, R. Eckman, and S. Robinson, "Optimized trajectory correction burn placement for the nasa artemis ii mission," (Breckenridge, CO), AAS 23-062, 1 Feb - 6 Feb 2023.
- [6] J. Joshi and C. D'Souza, "Modeling venting disturbance within linear covariance toolset for crewed artemis missions," (Big Sky, MT), AAS 23-317, 13–17 August 2023.
- [7] D. Woffinden and B. Barton, "Optimized trajectory correction burn placement for nrho orbit maintenance," in *33rd AAS/AIAA Space Flight Mechanics Meeting*, (Austin, TX), AAS 23-364, 15 - 19 January 2023.
- [8] D. C. Woffinden, S. B. Robinson, J. W. Williams, and Z. R. Putnam, "Linear covariance analysis techniques to generate navigation and sensor requirements for the safe and precise landing integrated capabilities evolution (splice) project," *AIAA SciTech 2019*, San Diego, CA, January 2019.
- [9] D. Woffinden, "Linear covariance techniques to analyze a multi-vehicle, multi-gn&c system with applications to rendezvous in a near rectilinear halo orbit," (Breckenridge, CO), AAS 23-067, 1 Feb - 6 Feb 2023.
- [10] D. Woffinden, "Evaluating lunar descent and landing performance from a near rectilinear halo orbit using linear covariance resetting techniques," (Breckenridge, CO), AAS 22-107, 1 Feb - 6 Feb 2022.
- [11] S. Evans, W. Taber, T. Drain, J. Smith, H.-C. Wu, M. Guevara, R. Sunseri, and J. Evans, "Monte: the next generation of mission design and navigation software," *CEAS Space Journal*, vol. 10, pp. 79–86, January 2018.

- [12] "MONTE: Mission Analysis Operations and Navigation Toolkit Environment,"
<https://montepy.jpl.nasa.gov/static/document/brochure.pdf>.
- [13] C. R. Gates, "A simplified model of midcourse maneuver execution errors," Tech. Rep. Technical Report No. 32-504, NASA Jet Propulsion Laboratory, California Institute of Technology, 15 October 1963.