ARCHITECTURE OPTIONS FOR NAVIGATION IN CISLUNAR SPACE FOR HUMAN LANDING SYSTEM VEHICLES

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As part of architecture studies and insight analysis focused on requirements development into Human Landing System lunar architecture designs, multiple studies are underway to understand the sensitivities and options for achieving high precision landing on the lunar surface. The baseline approach utilizes a combination of multiple sensors to capture autonomous state observations of the lander with respect to the lunar surface. These systems are typically constrained in terms of operational altitudes by parameters such as onboard map size, camera focus, or sensor transmitted power (for altimeter observations). While these sensor suites do enable high precision landing, they are typically very complex and expensive. For a human-rated vehicle, fault detection algorithms are needed in addition to redundant sensors, which drive additional design complexity. Conversely, for these early missions, mass performance is key, so extended analysis is required to identify numbers of sensors, their ideal placement, and integration algorithms. A key part of this analysis is to help identify key sensor suites and options to help alleviate this design tension.

An alternate approach is to take advantage and build out in-situ assets to allow for GPS-like navigation within the lunar regime through the use of navigation references or beacons. This can be achieved through the integration of navigation services into potential relays and pre-placed lunar surface assets. This research focuses on the capability of this infrastructure to support navigation in all areas of cislunar space such as: approach to the moon, in orbit around the moon, and ascent/descent operations to the surface. Augmented state linear covariance analysis (LinCov) and navigation state covariance analysis (NavCov) tools were used to assess a variety of navigation reference locations and how they can support vehicle operations through both understanding of state uncertainties and trajectory dispersions. This research helps to supplement existing studies focused on communication link analysis by providing additional insight into specific vehicle operational scenarios that are tied closely to potential Human Landing System scenarios. Key aspect of this analysis focus on the sensitivity to state knowledge of the references, the accuracy of inter-asset measurements, and placement in support of the various scenarios.

INTRODUCTION

The design of missions for lunar landing as part of the Human Landing System have been provided as part of a Reference Government Design that lays out some initial constraints and approaches. Some initial results and characteristics have been released as in [1] and [2]. These mission profiles typically include a transfer from Earth to a Near-Rectilinear Halo Orbit (NRHO) where a human crew docks with the landing element. The notional timeline from this point to lunar landing is provided in Figure 1 with details describing each phase. As seen in this approach (which is similar to other lunar surface missions), the first step is to transition to a lower altitude lunar orbit in preparation for lunar orbit. During this transfer, key systems can be checked out and preparations made for lunar. Once in Low Lunar Orbit (per the reference design), final checkouts can be performed to ensure systems are ready for descent and the crew prepares for final descent. After a number

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of orbits, powered descent initialization occurs, at which point the vehicle performs a burn to exit lunar orbit and descend to the surface.

The length of time in each of these is vastly different. A notional transfer from NRHO to LLO may take on the order of 6-8 hours, while only 2-3 orbits will be in Low Lunar Orbit. Finally, powered descent may take less than 1 hour. This timing is important in order to understand the impact of state and knowledge dispersions. Standard practice is to perform ground-based orbit determination before and after any powered flight segments to optimize the maneuver (before) and to capture the efficiency of the burn (after) in order to understand how well the reference design trajectory is being followed. As the transitions between these phases is reduced, so does the time for generating and providing a ground-based knowledge update. Conversely, the longer the time is between ground updates, the more uncertainty will be prevalent in both navigation knowledge and trajectory dispersions. Each of these transition points also represents a powered burn, at which point state knowledge uncertainty can couple into trajectory dispersions. This is due to the interaction between onboard guidance laws and navigation uncertainty.

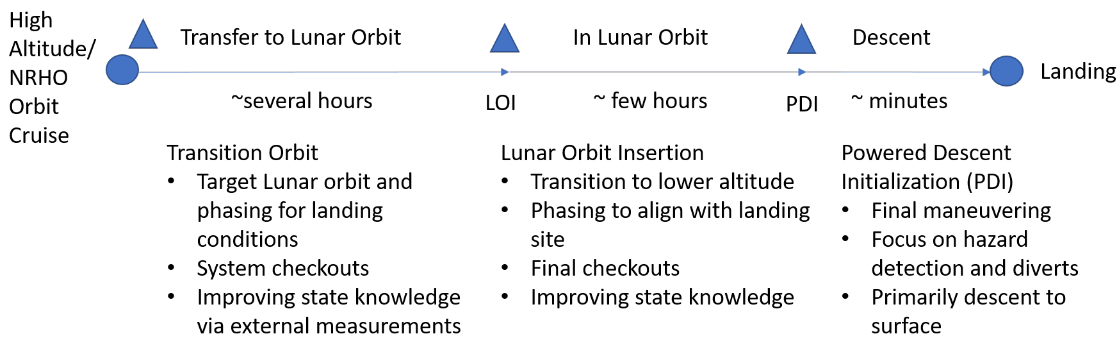


Figure 1. Mission Phases on Approach to Lunar Descent

For missions being designed for lunar landings, a driving requirement is the need for high accuracy, precise landings with the ability for autonomous diversions to avoid obstacles. These capabilities are necessary for long-term sustainability and landing in the harsh polar regions of the moon. This article focuses on several key sensitivities that lead into the final powered flight segment. As opposed to trading specific sensor requirements or mission designs, the work herein focuses more on system-level architectures and how external systems impact the descent-focused requirements. The prime example of this is the initial uncertainties of the vehicle in lunar orbit prior to any descent operations. This uncertainty results in knowledge and trajectory dispersion that must be corrected for during powered descent, flowing requirements both to the vehicle level (in terms of delta-velocity capability) and to individual sensors.

DESCENT-FOCUSED SENSITIVITY AND IMPACTS ON APPROACH

The first section of this article provides an overview of the impact of initial errors and how Earth-based systems support operations. This is particularly important in order to understand how this uncertainty can impact other vehicle sub-systems as well as mission design constraints. A key metric driving this performance is the amount of time spent in LLO before powered descent. But, the time spent in orbit performing critical operations is limited by the amount of time a crew can spend active at once. For example, including multiple orbits in a checkout phase combined with descent operations may overstretch the crew. As such, it is important to understand this impacts. This section will provide details to the sensitivity in terms of the need, provide detailed analysis on vehicle-level impacts, and show the potential improvements that can be made by providing other navigation aids.

Sensitivity to Knowledge Uncertainty Prior to Powered Descent

For any powered descent, the efficiency and accuracy of the maneuver has a limit derived from the onboard knowledge dispersions. Effectively, a vehicle can only guide itself as well as it knows its current state. To understand the impact of this, which is discussed throughout this article, this sensitivity should be understood. Starting with just assessing the impact of a knowledge, a Monte Carlo analysis was performed over a notional descent profile with the baseline sensor suite, including terrain relative navigation, star tracker, velocimeter, altimeter, and a navigation-grade IMU. Over the course of descent, the first navigation solution that is applied to give an absolute position measurement is TRN. This system compares collected imagery to an onboard map [3] to calculate the relative location of the vehicle in reference to the map. As this is the earliest sensor to provide an absolute measurement, it is critical to meeting landing accuracy.

Figure 2 shows the results of a scenario where TRN is disabled, to show the sensor's impact to overall performance. This plot provides a comparison between knowledge at landing (on the left y-axis with solid lines) simultaneously with the knowledge uncertainty at an altitude of 15 km (on the right y-axis with dotted lines), when TRN would nominally come online. This altitude was taken from the initial Government Reference Design to capture a notional expected capability and is represented by the vertical dashed line on the plot. These are plotted as a function of initial knowledge errors at the start of the trajectory. Each axis is plotted individually as X, Y, Z. These are defined as landing station relative inertial coordinates with Z being the vertical distance and X,Y derived relative to the landing sites local directions completing the frame. As seen in the plots, without TRN, if the initial knowledge is below 100 meters, the accuracy at landing is fairly consistent with final knowledge errors on the order of 1 and 10 km in the lateral directions. The vertical direction is tightly controlled due to the altimeter coming online late in the descent profile.

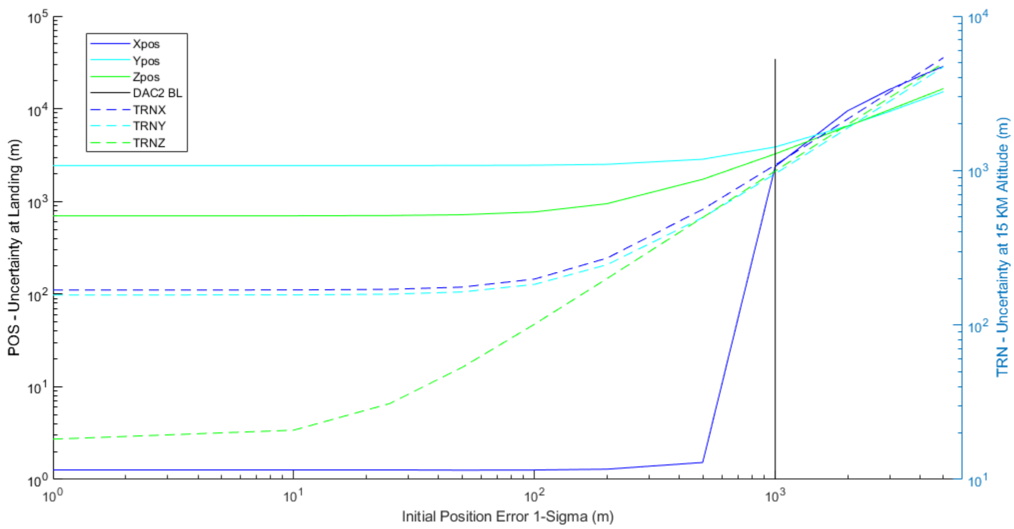


Figure 2. Landing Accuracy and Dispersions without TRN

Conversely, Figure 3 provides insight to the performance with a TRN system engaged. While this system only provides its first solution at 15 km altitude, it is able to greatly reduce and correct for a large dispersion of initial knowledge errors from the start of descent. As seen, with this TRN system, the landing accuracy is essentially independent of initial knowledge errors. There is one significant caveat here, and that is the uncertainty of the onboard solution at the start of TRN. To improve computational efficiency for real-time estimation, the algorithms typically require an a-priori estimate of the vehicle location. This is needed to focus the search only a specific section of the onboard map. As this uncertainty grows, the search for an initial solution becomes increasingly difficult and may not meet onboard processing capability (i.e. if trying to calculate measurement updates at a specific rate). Thus, the impact of the initial dispersions on the knowledge uncertainty at 15 km (when this system would come online) is of high value. In Figure 3, this is seen as the dashed lines against the right y-axis. As seen in the plots, this behavior is correlated with the initial errors. Or particular import is the uncertainty growth in the right-hand side of the graph, where the uncertainty logarithmically grows with respect to initial uncertainty. As such, the accuracy at the start of the descent phase may have constraints from the ability of the TRN algorithms to compute a first fix. This is also dependent on the flight profile and whether the vehicle is in powered flight or not. The next sections provide expanded analysis on this area to provide insight to the impact of these initial errors, as well as their sources, and ways to mitigate their impact.

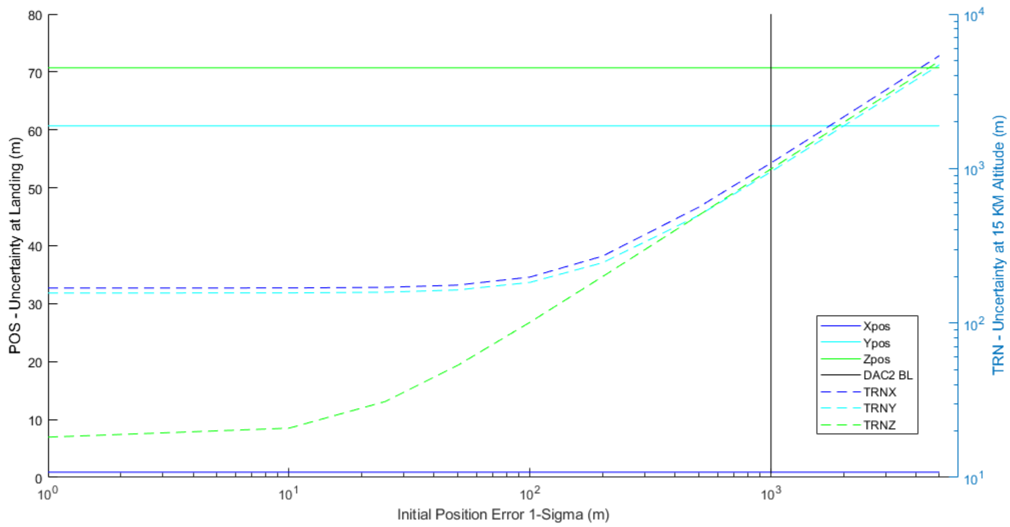


Figure 3. Landing Accuracy and Dispersions with TRN

Sensitivity to Number of Orbits Prior to Descent

The benefit and critical functionality of a TRN system to support precision landing has been introduced for the powered descent and landing flight phase. This section now focuses on identifying the necessary navigation performance at the deorbit insertion (DOI) burn and determining the impacts the duration of DSN tracking passes prior DOI has on initiating powered descent and ultimately lunar touchdown. In short, the following question is addressed, what are the impacts of the DSN navigation solution and subsequent system performance if the number of revolutions in lunar orbit are reduced or increased prior to DOI?

The metrics used to quantify the integrated GN&C system performance includes relative dispersions, relative navigation errors, and delta-v dispersions at key epochs such as PDI and touchdown. These performance metrics are generated using linear covariance analysis techniques which allows for inclusion of trajectory dispersion effects through modeling of guidance and control laws [4–8]. Along with DSN ground updates, the lander processes high quality accelerometer, gyro, star tracker, TRN, altimeter, and velocimeter measurements [9]. This suite is based on what was used for Human Landing System program government-reference design that was analyzed early in the program [1] and in design of high precision landers [10]. To show the sensitivity to the DSN tracking duration for 1-orbit, 2-orbit, and 3-orbit tracking passes, the navigation performance accuracy of the DSN update as a function of the number of lunar orbit ground tracking passes is extracted from a study produced by Emil Schiesser for the Autonomous Landing and Hazard Avoidance Technology (ALHAT) program [11] summarized in Table 1. The report provided a straw-man position and velocity navigation uncertainties in UVW (a reference frame defined by U along the position vector, W along angular momentum, V = - U x W) coordinates for a 100 x 100 km lunar orbit. A higher fidelity DSN model in the LinCov framework has been derived and validated for more accurate performance analysis results [12].

Case	DSN Pos, km (u,v,w)	DSN Vel, m/s (du, dv, dw)	DSN Corr (uvd, vud, udv, vdu)
3-Orbit	[0.5, 1.0, 0.2]	[0.95, 0.50, 0.01]	[-1.00, -1.00, 0.00, 0.00]
2-Orbit	[3.0, 4.8, 1.0]	[4.83, 2.84, 0.01]	[-1.00, -0.94, 0.00, 0.00]
1-Orbit	[4.5, 7.2 1.5]	[7.24, 4.26, 0.01]	[-1.00, -0.94, 0.00, 0.00]

Table 1. DSN Lunar Tracking Performance

The descent and landing trajectory used in this study adopts a profile utilized by the Safe and Precise Landing Integrated Capabilities Evolution (SPLICE) program that lands near Shackleton crater. The nominal downrange versus altitude profile (blue) along with the corresponding trajectory dispersions (maroon) for a 3 Orbit-based Deep Space Network (DSN) update is shown in Figure 4 where the red dots highlight event

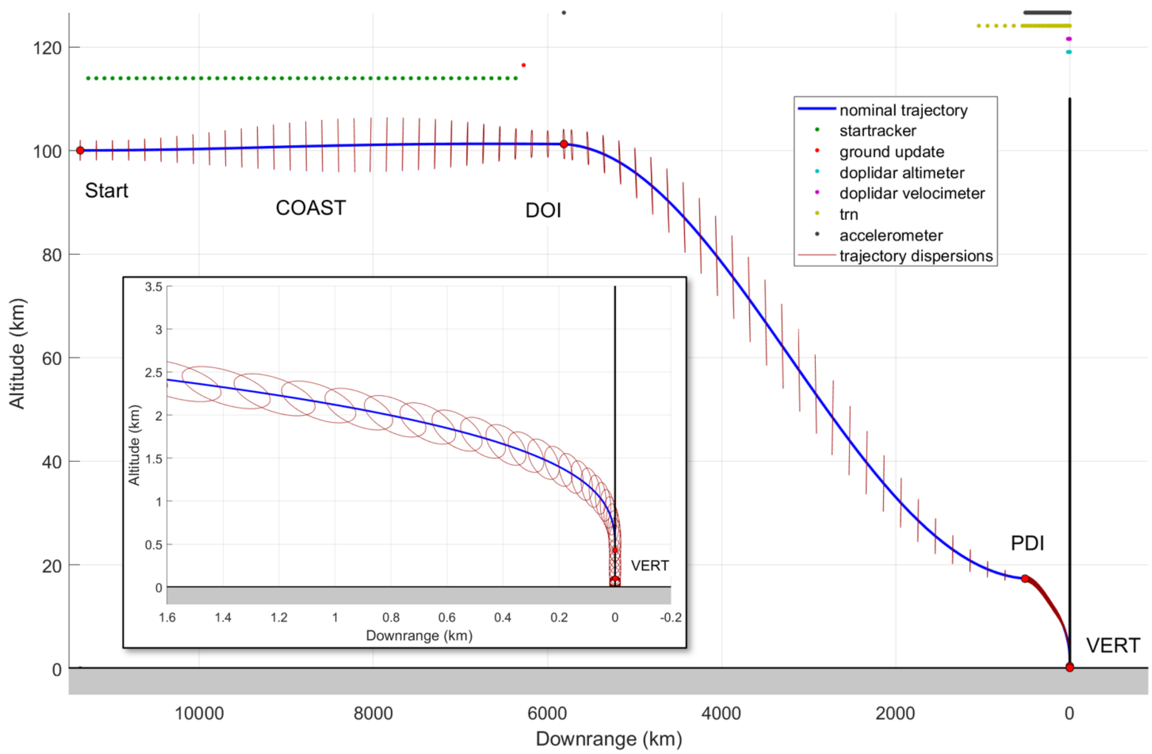
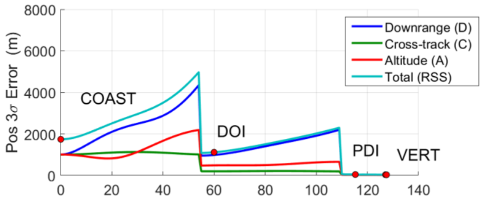


Figure 4. Trajectory Dispersion with 3 Orbit-based DSN Update

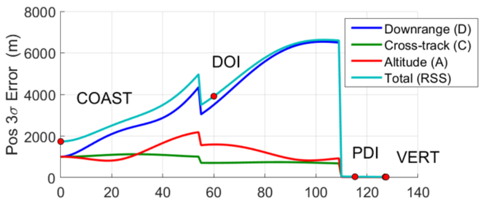
epochs. The sensor utilization is also indicated at the top of the plot with markers emphasizing when the various sensors are activated. For example, the star tracker provides attitude updates until 5 minutes prior to the DOI burn. At the deactivation of the star tracker measurements, a DSN ground update is then uplinked to the lander to support the execution of DOI. The TRN system then becomes active prior to the PDI burn and once powered flight is initiated the accelerometer measurements are processed. During approach and landing, the altimeter and velocimeter provide surface relative measurements. The time history of the relative navigation errors are shown in Figure 5 where Figure 5(a) emphasizes the relative navigation performance for a DSN update representing a 3-orbit tracking period, Figure 5(b) captures a 2-orbit scenario, and Figure 5(c) a 1-orbit tracking case.

A summary of the relative navigation errors and relative trajectory dispersions at touchdown (TD) along with the relative trajectory dispersions at PDI and the delta-v dispersions are provided in Figure 6. Although landing footprint dispersions and navigation errors still depend on the TRN, altimeter, and velocimeter; the delta-v dispersions and the trajectory dispersions at PDI (the TRN-on altitude) are sensitive to the DSN



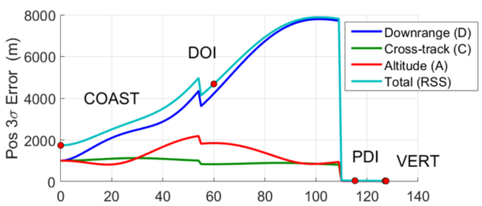
Event Name	Sim Elapsed Time (h:mm:ss)	3-sig D Pos Err (m)	3-sig C Pos Err (m)	3-sig A Pos Err (m)	3-sig |Pos| Err (m)	3-sig D Vel Err (m/s)	3-sig C Vel Err (m/s)	3-sig A Vel Err (m/s)	3-sig |Vel| Err (m/s)	3-sig X Att Err (deg)	3-sig Y Att Err (deg)	3-sig Z Att Err (deg)	3-sig |Att| Err (deg)
COAST	0:00:00	1005	1000	1005	1738	1.00	1.00	1.00	1.73	0.050	0.050	0.050	0.087
DOI	1:00:00	983	196	484	1113	0.40	0.19	0.82	0.93	0.010	0.009	0.009	0.016
PDI	1:55:18	24	23	24	41	0.07	0.09	0.10	0.16	0.034	0.041	0.034	0.063
APRCH	2:07:06	20	19	17	32	0.12	0.15	0.07	0.20	0.024	0.023	0.026	0.042
VERT	2:07:30	19	20	4	28	0.16	0.12	0.05	0.20	0.024	0.023	0.025	0.041
LANDED	2:08:19	20	21	3	29	0.16	0.13	0.03	0.21	0.025	0.023	0.026	0.042

(a) Relative Navigation Errors with 3-Orbit DSN Update



Event Name	Sim Elapsed Time (h:mm:ss)	3-sig D Pos Err (m)	3-sig C Pos Err (m)	3-sig A Pos Err (m)	3-sig |Pos| Err (m)	3-sig D Vel Err (m/s)	3-sig C Vel Err (m/s)	3-sig A Vel Err (m/s)	3-sig |Vel| Err (m/s)	3-sig X Att Err (deg)	3-sig Y Att Err (deg)	3-sig Z Att Err (deg)	3-sig |Att| Err (deg)
COAST	0:00:00	1005	1000	1005	1738	1.00	1.00	1.00	1.73	0.050	0.050	0.050	0.087
DOI	1:00:00	3505	708	1593	3915	1.18	0.67	2.97	3.27	0.010	0.009	0.009	0.016
PDI	1:55:18	24	24	25	42	0.08	0.10	0.11	0.17	0.034	0.041	0.034	0.063
APRCH	2:07:06	20	19	17	32	0.12	0.15	0.07	0.20	0.024	0.023	0.026	0.042
VERT	2:07:30	19	20	4	28	0.16	0.12	0.05	0.21	0.024	0.023	0.026	0.042
LANDED	2:08:19	20	21	3	29	0.16	0.13	0.03	0.21	0.025	0.023	0.026	0.042

(b) Relative Navigation Errors with 2-Orbit DSN Update



Event Name	Sim Elapsed Time (h:mm:ss)	3-sig D Pos Err (m)	3-sig C Pos Err (m)	3-sig A Pos Err (m)	3-sig |Pos| Err (m)	3-sig D Vel Err (m/s)	3-sig C Vel Err (m/s)	3-sig A Vel Err (m/s)	3-sig |Vel| Err (m/s)	3-sig X Att Err (deg)	3-sig Y Att Err (deg)	3-sig Z Att Err (deg)	3-sig |Att| Err (deg)
COAST	0:00:00	1005	1000	1005	1738	1.00	1.00	1.00	1.73	0.050	0.050	0.050	0.087
DOI	1:00:00	4223	833	1845	4684	1.35	0.80	3.59	3.92	0.010	0.009	0.009	0.016
PDI	1:55:18	24	24	25	42	0.08	0.10	0.11	0.17	0.034	0.041	0.034	0.063
APRCH	2:07:06	20	19	17	32	0.12	0.15	0.07	0.20	0.024	0.023	0.026	0.042
VERT	2:07:30	19	20	4	28	0.16	0.12	0.05	0.21	0.024	0.023	0.026	0.042
LANDED	2:08:19	20	21	3	29	0.16	0.13	0.03	0.21	0.025	0.023	0.026	0.043

(c) Relative Navigation Errors with 1-Orbit DSN Update

Figure 5. Relative Navigation Errors for Varying DSN Performance Results

ground tracking solution. For example, dispersions on DV usage increase from 5 m/s to 12 m/s for 3- to 1-orbits DSN ground tracking accuracies. The coloring of results in this table is based on results from previous analysis and is used to indicate what levels of dispersions were close to (or beyond requirements). Similarly, for DV impacts, a notional level of 10 m/s was used for comparison. These results would need to be assessed against a particular program's requirements and mission design.

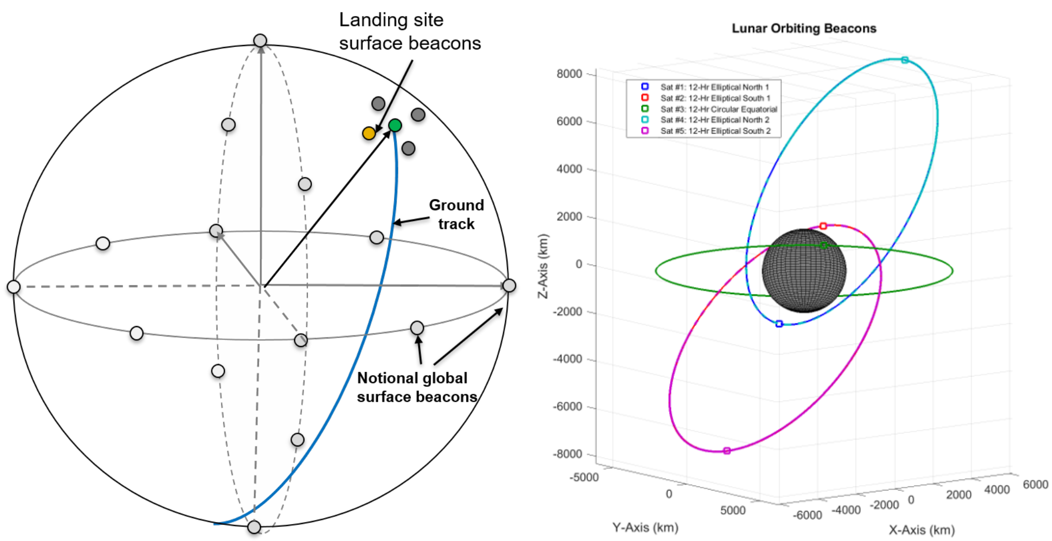
GN&C PERFORMANCE METRICS	TD Rel Navigation Errors (3s)			TD Rel Trajectory Dispersions (3s)			PDI Rel Trajectory Dispersions (3s)			Delta-v Disp (3s)
Sensor Suite	|Pos| (m)	|Vel| (m/s)	|Att| (deg)	|Pos| (m)	|Vel| (m/s)	|Att| (deg)	DnRng (m)	CrTrk (m)	Alt (m)	Disp (m/s)
DSN 3-Orbits + TRN + ALT + VEL	29	0.21	0.042	29	0.25	3.463	2412	199	631	4.49
DSN 2-Orbits + TRN + ALT + VEL	29	0.21	0.042	29	0.25	4.183	6429	695	960	10.37
DSN 1-Orbits + TRN + ALT + VEL	29	0.21	0.043	29	0.25	4.470	7592	817	984	12.15

Figure 6. Landing Analysis Summary

Integrated Sensitivity to Architecture Options - Alternate Sensor Suites

Building upon the previous section, this case investigates alternate solutions to a selected sensor suite to support precision landing. Given an accurate DSN ground update prior to DOI that contain trajectory dispersions and navigation errors at PDI, can certain sensors be removed or what other viable options exist that should be considered as replacements to the previous baseline sensor suite that can support the performance requirements? These alternate cases include an altimeter, gyro, and star tracker with the following additional sensors 1) DSN Only, 2) DSN, altimeter, and velocimeter, 3) DSN and TRN, 4) DSN and a radar, 5) DSN and surface beacons, 6) DSN, surface beacons, and orbiting beacons, 7) DSN, surface beacons, and TRN, and 8) DSN, surface beacons, and radar.

The modeling of the lunar surface and orbiting beacons are depicted in Figure 7. A single surface beacon, or the lunar communication terminal (LCT), is assumed as shown in Figure 7(a), located 2 km up-range and 2 km off-track of the landing site. There is a potential to include other global surface beacons (gray) strategically placed around the surface or clustered near the landing site. For now, they are not included. The location of the surface beacon is assumed to be known within 30 m, 3-sigma. The lunar orbiting beacons in Figure 7(b) are based on the Lunar Relay Satellites (LRS) which is proposed to have a constellation of five satellites in 12-hour orbits; 2 in a northern elliptical orbit, 2 in a southern elliptical orbit, and one in a circular equatorial orbit. The initial knowledge and dispersion of each orbiting beacon is assumed to be 1 km, 3-sigma. The consideration of both surface and orbiting beacons highlights the interplay with other sensor systems and how they could be augmented with networking or in-situ elements to improve performance and impact sensor selection.



(a) Surface Beacons

(b) Orbiting Beacons

Figure 7. Lunar Surface and Orbiting Beacons

The impacts of alternate sensor configurations on integrated GN&C performance in terms of relative navigation errors and relative trajectory dispersions at touchdown along with the total delta-v dispersions are summarized in Figure 8. It becomes clear that without any surface relative measurements, precise landing is not feasible. These results also suggest that without a TRN system, satisfying both delta-v dispersion constraints and touchdown footprint dispersion requirements becomes rather difficult. The only exception is the case when surface and orbiting beacons are considered. If the infrastructure supported the utilization of beacons, they can help come close to meeting the current precision landing performance requirements.

NAVIGATION ARCHITECTURE DESIGN

Given the results above, there is a clear opportunity to take advantage of in-situ assets and alternate infrastructure-based approaches to provide enhanced navigation accuracy for vehicle operating near, on, and around the moon such as presented in [13]. The results in the previous sections show how the impacts of onboard knowledge improvements tie to both reduced state dispersions and through that delta-velocity requirements in order to fly along a prescribed trajectory. This section of focuses on how the placement of the potential infrastructure impacts a variety of mission scenarios.

GN&C PERFORMANCE METRICS	TD Rel Navigation Errors (3s)			TD Rel Trajectory Dispersions (3s)			PDI Rel Trajectory Dispersions (3s)			Delta-v Disp (3s)
Sensor Suite	|Pos| (m)	|Vel| (m/s)	|Att| (deg)	|Pos| (m)	|Vel| (m/s)	|Att| (deg)	DnRng (m)	CrTrk (m)	Alt (m)	Disp (m/s)
DSN 3-Orbits	3765	5.88	0.070	3765	5.88	1.937	2412	199	631	3.34
DSN 3-Orbits + ALT + VEL	1659	2.42	0.066	1659	3.29	6.528	2412	199	631	45.67
DSN 3-Orbits + TRN	37	0.29	0.047	39	0.31	3.466	2412	199	631	4.36
DSN 3-Orbits + RADAR	1347	0.11	0.060	1348	5.76	75.23	2412	199	631	70.31
DSN 3-Orbits + RADAR + TRN	26	0.10	0.041	26	0.31	3.326	2412	199	631	4.54
DSN 3-Orbits + Surface Beacon	214	0.87	0.062	216	0.87	140.5	2412	199	631	23.23
DSN 3-Orbits + Surface Beacon + Orb Beacons	57	0.10	0.037	58	0.51	21.90	812	105	330	3.59
DSN 3-Orbits + Surface Beacon + TRN	24	0.23	0.045	24	0.25	3.467	2412	199	631	4.21
DSN 3-Orbits + Surface Beacon + RADAR	82	0.11	0.052	84	1.45	70.20	2412	199	631	23.08

Figure 8. Impacts on Vehicle Requirements

The scenarios captured below are intended to provide a variety of mission approaches to help inform both placement as well as impact to mission. These were selected based around mission design trades that are used to inform and constrain variety of integrated aspects, including orbital dwell times, active crew time, phasing between orbits, as well as conditions such as local lighting at descent. The cases involved include: a vehicle in a polar low lunar orbit simulating a dwell prior to initiating powered descent, a vehicle on a direct descent from a NHRO orbit simulating a vehicle traveling directly from Gateway to a polar lunar landing, and ascent from the lunar surface.

For the first two mission scenarios, the analysis focuses on the placement of ground and orbital assets to help inform placement and understand interactions between various locations. This is primarily intended to help guide early deployment, where the infrastructure may be limited to one or two assets. To understand the impacts of navigation accuracy given the supporting assets, the analysis utilized a covariance-based study. In this assessment, the knowledge uncertainty of the vehicle was tracked along the reference trajectory. While not being able to capture trajectory dispersions (and representative delta-v impacts from planned correction maneuvers), this does provide an overview of sensitivity to each potential asset. Each of the elements was assumed to be able to support a range and range-rate measurement between the vehicle of interested and the reference point. Different errors were considered for surface assets vs orbital assets to capture the impacts of enhanced calibration knowledge of fixed assets on the lunar surface enabling more accurate measurements. A one-sigma of 100 m/.001 m/s was assumed for orbital asset accuracies and 10m /.0001 m/s was used for surface assets for range and range-rate observations. This is used to capture the simplification of dynamics for a fixed asset versus an orbital asset leading to a better state estimate and ability to calibrate. The actual measurement process is not identified here, but it is assumed for early missions to either be a one-way or two-way radiometric ranging techniques similar in signal definition to that in existing standards [14].

The following table identifies the assets considered in the scenarios. These were selected to provide an initial range of options for mission scenarios. The *frozen* highly elliptical orbit in other studies was not included for comparison due to its extensive coverage [15]. Future work is planned to use this toolset to asses a large range of assets supporting these mission, and assess considerations such as orbital phasing, redundant sensors, and eventual concerns such as availability (important for two-way coherent ranging processes). These represent areas of high significance such as the lunar poles and existing orbits that missions may be operating within where local assets could be easily deployed (polar, NRHO, and equatorial).

Acronym	Description
EQ	Two orbital assets phased 180 degrees apart in 100x100 km Lunar Orbit
POL	Two orbital assets phased 180 degrees apart in 100x100 km Polar Lunar Orbit
LNP	Ground asset located near the Lunar North Pole
LSP	Ground asset located near the Lunar South Pole
NRHO	Orbital asset in an NRHO orbit

The analysis processed for both of the following analysis scenarios was conducted in three phases. First, FreeFlyer * was used to assess a standard Earth-based state update given the geometry with the three standard Deep Space Network ground stations assuming full availability and nominal errors. This analysis included a notional amount of time to allow for ground validation of the calculated solution prior to vehicle upload and application. This is specifically important for DSN-only in low lunar orbit where the age of the fix from the ground should be considered. For an operational process with high confidence and experience, this time for review can be reduced to the point of supply a real-time update of the current real-time ground-computed solution. This provides a baseline of what could be expected from Earth-based operations.

Next the baseline error inputs were assessed using covariance analysis to show position and velocity over the reference trajectory. The following scenarios were considered in this analysis: no aids, each aid individually, and all aids enabled. A notional requirement of 100 m and 1 m/sec 3-sigma per axis was used to provide insight to early mission design scenarios. These results provide input to the transient behavior of each system and final uncertainty at the end of the trajectory and will be discussed in detail.

Lastly, a combinatorial analysis was conducted looking at all combinations of support infrastructure in addition to each individual element (and no support). In addition to architecture options, each scenario was also assessed based on the time between measurement updates (either 1, 60, or 600 seconds) to capture sensitivities to measurement rates. These are then plotted in terms of increasing complexity to help guide insight to higher level interactions between architecture sets and identify key systems of interest. The results for each scenario are given and described below.

Augmenting Vehicle in LLO Orbits

The first scenario assessed was for a vehicle in a parking or transition orbit. For this analysis, a 100 km x 100 km circular polar orbit was assumed. This captures a mission where a vehicle has transitioned into a temporary orbit in order to perform activities such as system checkouts, correct for any errors due to insertion into the lunar orbit, or preparation for powered descent (similar to how deep space missions perform navigation fixes before and after major trajectory corrections to design the maneuver and then evaluate its performance in preparation for forward planning). The primary metric of interest would be the knowledge error (either onboard or from a Earth-based tracking network) after multiple orbits. Reducing knowledge errors directly impacts the ability to optimize the initial de-orbit burn to begin powered descent, helping to reduce trajectory dispersions around the nominal mission design. The analysis assumed the in-situ assets as described above.

To understand baseline capability, a notional ground-based orbit determination process was used to capture the effectiveness of ground-observations for this mission case. The results in Figure 9 show the clear impact of both the number of orbits of observations as well as the impact of ground processing time. Each color of the bar represents a different amount of time required to transition the ground solution to the vehicle. This effectively captures the errors form taking the navigation solution and propagating to the time the solution would be applied onboard (from the last measurement to current time). As can be seen, after two orbits, the position uncertainty is very close to the requirement. After three orbits, the system has adequate information to reduce the uncertainty for multiple processing times. For reference, each orbit takes approximately 120 minutes. One caveat of this model is the limited fidelity in terms of disturbance forces. For a crewed vehicle,

*https://ai-solutions.com/freeflyer-astrodynamic-software/

impacts such as outgassing, crew movement, or other disturbances may reduce the accuracy of the state solution.

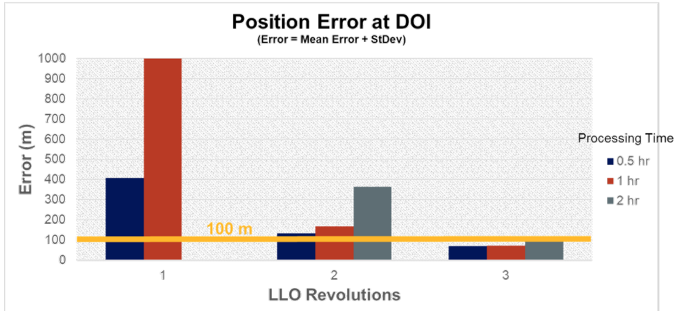


Figure 9. Nominal Capability for an Earth-based Solution

Figure 10 provides the results of a covariance analysis showing onboard knowledge uncertainty over the course of three orbits. The vertical drops in uncertainty show when specific aids come into view. The growth of error as a function of orbital dynamics can be seen between updates. These represent the propagated nature of velocity and position uncertainty over an orbit the crest in position error is correlated with a dip in velocity error. Clear takeaways from this analysis is the polar beacons are able to reduce the uncertainty to within requirements after 3 passes. This shows the impact of phasing on the mission design and time required in orbit. It is also important to note the benefit of an NRHO-based asset in this scenario, due to the geometry being more conducive to multiple contacts, whereas the phasing between the local satellites with regard to the target vehicle limits the number of contacts over a limited number of orbits.

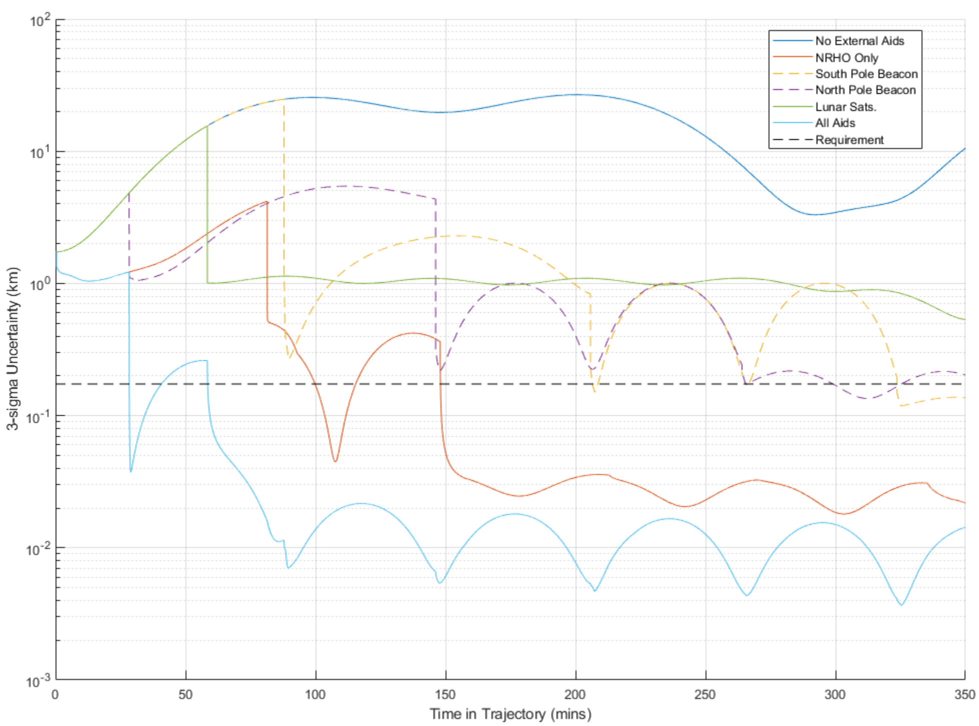


Figure 10. LLO Position Uncertainty

The last figure focuses on the interactions between combinations of assets. The set of all possible references together is the far-right bar in Figure 10. Seen in this figure, the accuracy of the system eventually is driven by the measurement errors themselves moreso than number of assets or geometry (as seen by the flat performance for larger infrastructure sets). Figure 11 provides insight this analysis showing the magnitude (calculated as a base-10 logarithm) of the position error in meters after the end of 3 orbits for various combinations of infrastructure (along the horizontal axis). Matching the previous results, the NRHO asset by itself is able to reduce the errors to the desired level. The combination of a polar beacon with an orbital beacon is able to come close to the required level and may be acceptable to missions. The sensitivity to the NRHO asset is clearly apparent, where combining that with any other in-situ location helps greatly reduce errors due to the increased observation. Another trend apparent is the sensitivity to the navigation measurement rate. The third axis (into the page) provides three selections of updates rates. For all cases an update rate of 1 Hz is needed to reduce errors to within requirements, showing the sensitivity to reducing observation errors. Similarly it is possible that higher rate measurement systems may be able to relax infrastructure constraints at the cost of more complex and capable hardware.

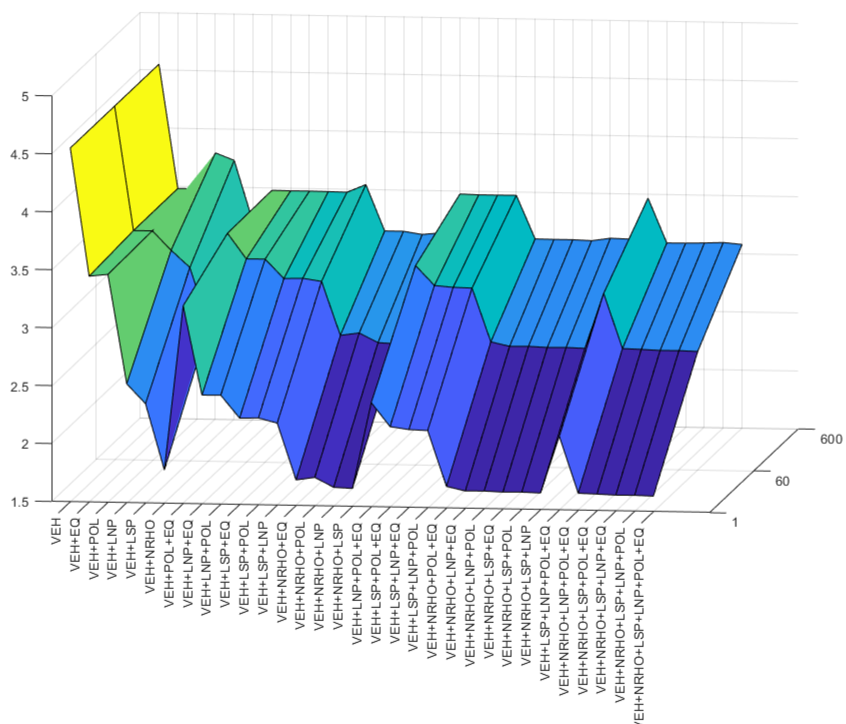


Figure 11. Architecture Assessment

Augmenting Vehicle on NRHO Direct Descent

An alternate mission scenario considers a direct transfers from an NHRO orbit down to LLO. This transfer takes approximately 12 hours and represents a transition directly into powered descent to land in a polar region. Since number of orbits is no longer a variable of interest, this analysis focused on knowledge uncertainty at the Lunar Orbit Insertion. This trajectory provides an alternate trajectory providing insight into the impact of geometry on observability.

The first analysis focuses on the ability of ground observations to produce an accurate state estimate. The results of this analysis are shown in Figure 12 below. The requirement of 100 meters uncertainty is easier met due to the extended duration of observations and visibility back to Earth. Forward work could include assessments of reduction of ground-pass time (though for a human mission, it would be expected that coverage to a ground station would be continuous during transit operations) to either optimize the observation time or show sensitivity to limited availability of ground assets. Again for this scenario, detailed disturbance models were not used, and would provide an impact to the final accuracy expected.

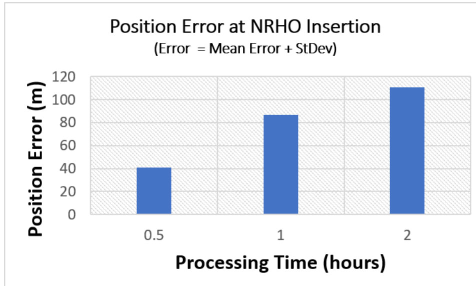


Figure 12. Nominal Capability for an Earth-based Solution

Time history of the covariance from each scenario is provided in Figure 13. This shows the performance of each individual in-situ resource as well as all assets included in an operational network. Similar to the above results, the long observation time allows for along duration of observations to reduce errors. One takeaway is that due to the geometry of the trajectory, the polar located ground beacons are not in view until late in the mission. While this would allow for improving onboard state knowledge, the burden for correcting trajectory dispersions would be with the onboard algorithms, due to the limited before final descent. Conversely, the satellites in lunar orbit (both polar and equatorial) provide early benefit and can help quickly reduce knowledge errors, enabling early trajectory correction maneuvers to reduce trajectory dispersions and optimize orbital insertion conditions. Another observation from this data is the limited ability of the NRHO placed asset to reduce errors. Due to the relative geometry between the two assets, early in the trajectory the observability is limited mainly serving to slow down error growth. As the vehicle approaches lunar orbit, the varying observability enables better observations, and thus a reduction in errors, particularly as the vehicle passes over the polar regions. Similar to the polar beacons scenario, while this does improve the knowledge to the required level, it will not allow for earlier trajectory dispersion corrections and place the burden on the initial orbit insertion burn to reduce trajectory dispersions. This impacts the needs for additional margin on the vehicle's DV capability.

Lastly, the impact of multiple systems was assessed. The results of this analysis are given in Figure 14. Each axis has the same units and meaning as in the previous section in Figure 11. The results here again show that either orbital asset provides the greatest benefit to the knowledge accuracy at insertion. Similarly adding a surface bacon to either scenario also enables a slight reduction in accuracy (though primarily at the end of the trajectory). The limited impact of the beacons is primarily due to the limited observation time due to the trajectory design. It is expected that a surface beacon with better observation geometry would also help to improve state knowledge earlier in flight.

Support during Descent and Ascent

Earlier results in this article detailed the impacts of surface beacons on final descent. These elements can help provide additional observability and onboard knowledge improvement, helping to provide backup , redundancy, and potential replacement to other onboard navigation sensor systems. This continues to be an active area of research and key application of in-situ navigation aids [13], [16], [7].

Analysis was also performed to capture the impact of in-situ infrastructure on ascent trajectories. Similar to earlier results in this article, the results are directly dependent on the location of the references. For example, a reference beacon near the landing site will help maintain vehicle knowledge during the early parts of ascent, but once the vehicle is out of line of sight, other systems are needed to maintain onboard accuracy. This is essentially the descent problem in reverse and the same results apply. For example, the same concerns with

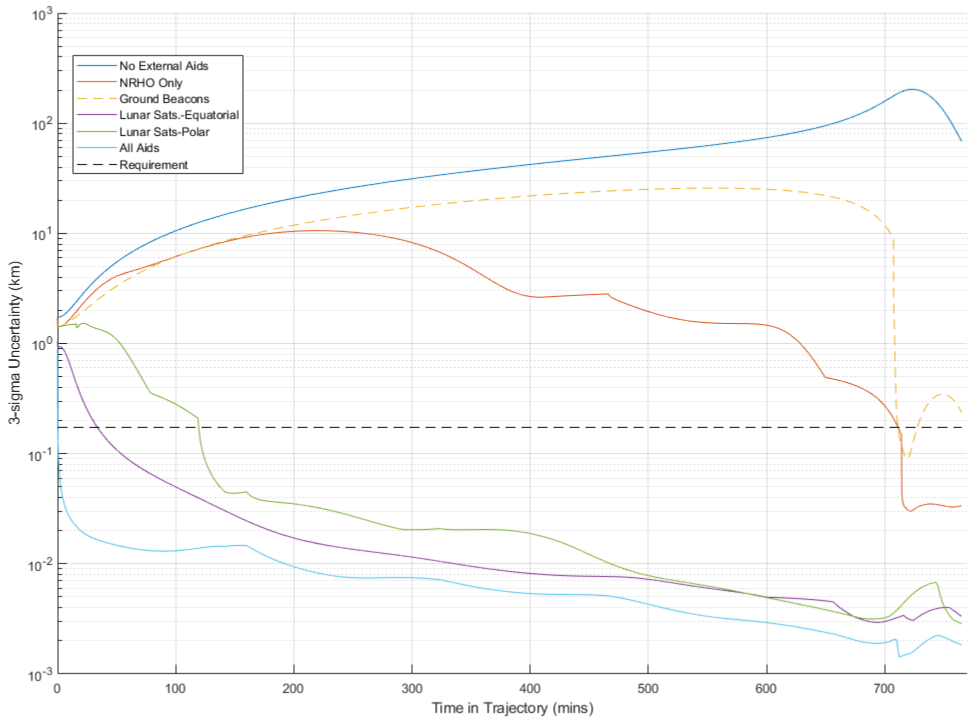


Figure 13. LLO Position Uncertainty

loitering in lunar orbit prior to descent also apply for ascent in terms of crew active time and error growth prior to leaving a transition orbit to either return to NRHO assets or direct to Earth.

Sensitivity to Beacon Locations

In addition to showing how local infrastructure can aid vehicle near the Moon, their exact location can have significant impacts on the ability to provide measurement support and affect the geometry of the observations. ALHAT-focused analysis [17] was conducted assessing widely dispersed beacon locations near the landing site to show their impact on landing accuracy. This study focused on within 10s of km's of the landing site. The results showed that having reference points ahead of and off the main approach path allowed for the greatest reduction in landing error. The rationale for being off the approach corridor is to provide increase geometry to reduce off-course errors. Similarly, having the reference signal placed ahead of the desired landing site enables correction on both the initial approach as well as the final descent a lunar orbit later. This helped to bring in navigation measurements earlier into the mission profile, greatly improving accuracy. This may seem counter intuitive to having a beacon specifically at a landing site itself. If the vehicle were using the beacon as a target it would be feasible, but in final approach the ranging errors become on the order of the desired landing accuracy (10's to 100's of meters), and more accurate sensors are used to guide final approach (such as higher accuracy altimeters with accuracies better than a cm). Similarly, having a beacon on the flight path provided great observation into navigation errors along the direct-approach direction, but provided little to reduce off-course errors. The optimal solution was to have down down-range and cross-range beacons. To validate the results of this earlier study and to asses the impact to the scenarios identified, a similar analysis was conducted.

The two scenarios were revisited to asses ground infrastructure capability. For this case, the metric of interest was the total time of observation between the ground asset and the space vehicle. For the analysis, it

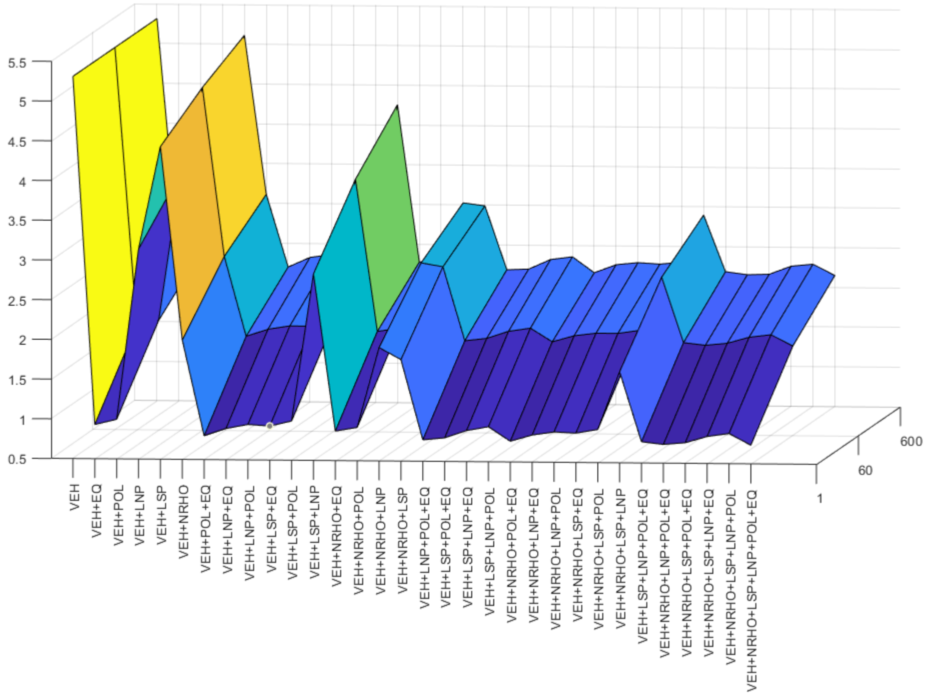


Figure 14. Architecture Assessment

was assumed that a 90 degree field of view from the beacon centered around local vertical to close a link and generate a measurement. For each, beacons were distributed evenly across the lunar surface. Following this, the vehicles were propagated along the notional trajectories to capture an integrated time in view between the spacecraft and each ground location. The results from the analysis were integrated to show the time in view for each surface location for each trajectory.

Figure 15 below shows the results for the LLO scenario. For this scenario, it can clearly be seen the large capability for viewing beacons at the poles due to the repeated observations and long passes. Similarly, the results show a course of locations along the orbital trajectory that have limited observability over the multiple orbits. The location here is directly driven by the phasing of the orbit. If the analysis were to be extended to show a larger number of orbits, this would spread to include most of the lunar surface having a similarly averaged contact time for a spacecraft in lower orbit (being driven by the precession of the orbit). But in this same scenario, the polar regions would vastly out-perform any equatorial assets. This could be corrected by allowing for a larger field of view to the surface beacons or planning trajectory phasing to take advantage of pre-deployed assets. Ideally a well-spread out network of support infrastructure would allow support of a range of approach vectors.

Similar results can be seen when evaluating the direct descent from NRHO to LLO in Figure 16. For this scenario, an equatorial region is seen as the prime area of observation to the spacecraft. This is primarily due to the phasing from the NRHO orbit to the LLO. Based on the relative orientation, different areas of the moon will be in this prime region. This is primarily due to long approach from NRHO, and limited lunar rotation during that time. And similar to the LLO scenario, the polar regions also show significant observation time between the ground assets and the an approaching spacecraft.

Based on these results, the sensitivity to mission phasing is very apparent, and the use of any ground beacons will be dependent on the mission profiles. Conversely, the polar regions provide a high level of promise for placing references, primarily due to the high level of robustness in visibility once the spacecraft is in lunar orbit. Similarly, for a planned concentrated series of missions to these polar ares [2], placing local

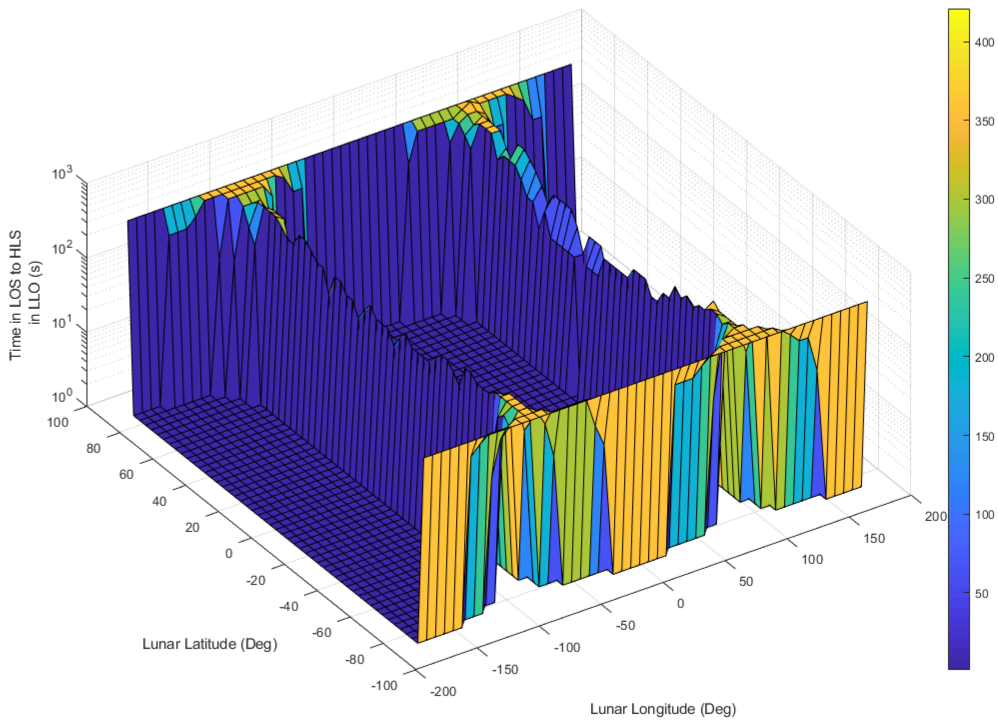


Figure 15. Impact of Ground Beacon Location for LLO Scenario

resources nearby can support multiple missions. Similarly, opening up the observation constraints will also expand the coverage times. The caveat primarily impacting this though is the inclusion of surface features into the analysis. Particularly for the polar regions, if placing infrastructure into craters, the observation may be limited by local surface features.

Summary of Results

The previous sections assessed multiple scenarios to show the impacts that of local infrastructure, whether they are surface or orbital elements. The key takeaway from the analysis is the strong sensitivity to the trajectory and mission design of interest. For early missions, it will be difficult to develop a limited infrastructure to support multiple scenarios. A combination of both orbital and surface assets provided the greatest benefit and could be used to limit(or even forego) Earth-based navigation support. The location of that orbital assets was strongly dependent on the mission scenario. One caveat from this analysis is the limited consideration of orbital options. Reference orbits such as highly elliptical frozen orbits were not included at the time of analysis and are of high priority for further results. Similarly studies assessing increasing numbers of satellites (above the 2 baseline scenario here were not included in order to provide a manageable design space for this study). These trades are all next steps in the analysis process as the mission and potential infrastructure continues to mature.

ARCHITECTURE IMPACTS

While the above sections show the capability and sensitivity to in-situ infrastructure, it does not address the specifics of implementation of said resources. The analysis assessed at a high level the impact on navigation accuracy (and additional the combined impacts on knowledge and trajectory dispersions for the descent analysis). Several assumptions were made in the trades that would need to be revisited as system options mature

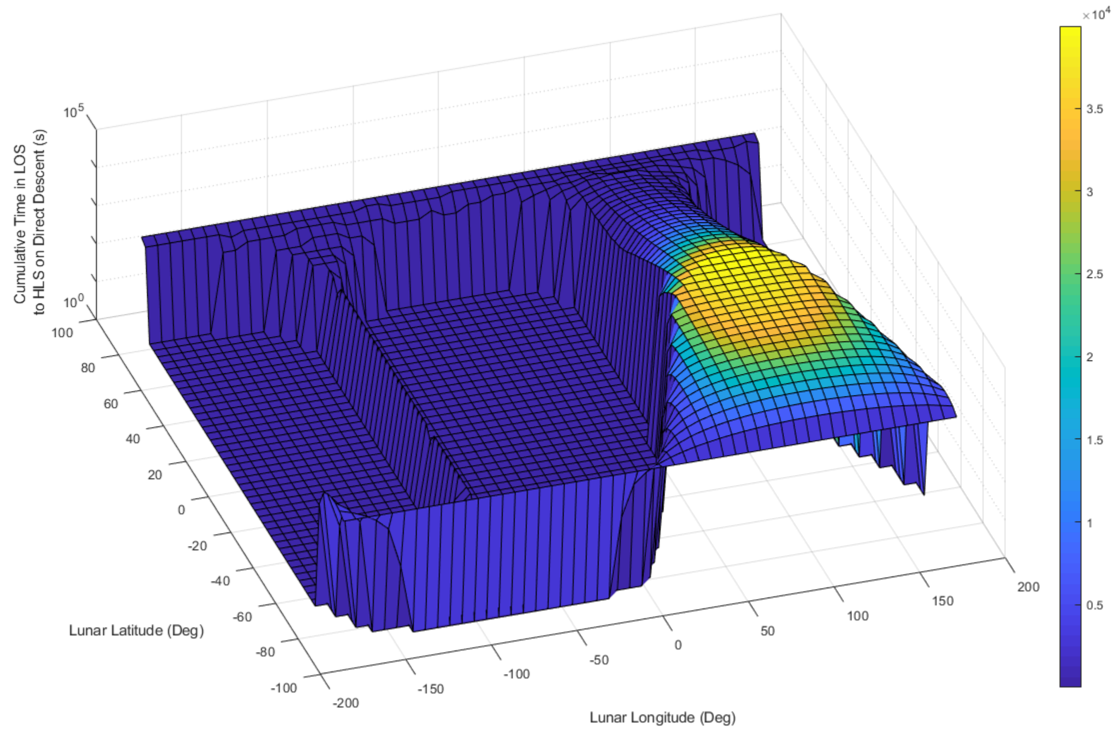


Figure 16. Impact of Ground Beacon Location on NRHO Scenario

and infrastructure investments are made. Similarly, as new technologies come online, the use of in-situ infrastructure needs to be revisited in terms of investment costs versus in-situ capability across the lifetime and operational costs of each. Conversely, aspects of having a multi-sensor and robust infrastructure has benefits beyond the purely performance-driven realm, enabling the need of back-up and independent systems from a user perspective for improved reliability and redundancy.

Beacon operational needs

Two primary metrics impacting the accuracy of the infrastructure are the accuracy of the measurement itself and the command and control aspect of any in-situ network. For example, the scenarios assumed a fairly notional 100 m of ranging error for orbiting beacons and 10 m for landed systems. The accuracy of this is directly tied to the method being use to perform the navigation measurement. A range of approaches could be considered including one-way time of flight measurements and one-way Psuedo-noise Ranging (PN) methods as well as two-way ranging methods such as sequential ranging or coherent PN. Each of these has advantages and disadvantages that should be considered. One-way measurements can operate in a multi-user manner, but require accurate timing systems and high performing computing systems on the receiver (when limited assets are available). Similarly, the reference node requires tightly controlled reference timing signals for the generation of the source signal. Two-way ranging takes a large amount of burden off of the user, but requires enhanced coordination between the two assets to initiate a two-way communication pass, both in terms of scheduling and meeting pointing requirements to enable a cross-link. For a limited number of uses, this can be easily managed via inter-asset scheduling and timelines management, but grows increasingly complex as user numbers increase. Both systems point toward the need for sophisticated high accuracy clocks in lunar orbit such as Deep Space Atomic Clock (DSAC) [18] or other new developments.

In order to apply the measurements, both systems also require transfer of knowledge of the reference location. For surface beacons, this can be fairly straightforward due to its fixed location. For orbiting assets, the update is only as good as knowledge of the reference location you are measuring your distance from. As such, knowledge requirements of the orbiting elements will require sophisticated navigation algorithms and frequency augmentation with Earth observation or independent sensors. Similarly, methods need to be in place to share current ephemeris information among all assets. This impacts the larger architecture and drives for the need for coordinated approaches such as LunaNet * for deploying standards among multiple users.

Room for growth of other sensors

In contrast to relying on integrated architecture options, autonomous sensors provide an alternate approach to provide knowledge updates in flight. As mentioned at the beginning of this article, one fundamental sensitivity was to the ability of Terrain Relative Navigation to reduce knowledge errors during descent at lower altitudes and its sensitivity to initial errors. As these algorithms continue to mature and are improved to work at increasingly high altitudes, they will make a larger contribution to the overall mission design. For example, recent studies show the ability of similar algorithms capable of operating at 30-40 km altitude [19] as opposed to the max of 15 km considered here. Many of these technologies for passive optical navigation have a strong reliance on map observations and current lighting conditions.

Other options continue to be considered as well, such as autonomous optical navigation [20] which can operate at higher altitudes but is limited to camera parameters such as field of view and focal length in terms of operational altitude. This approach has been considered for human crewed vehicles in lunar orbit [21] and dates back to the Apollo missions [22]. Similarly, this approach is also being evaluated for use in NRHO orbit.

There is a bevy of other sensor options that could be considered for both anchoring the network or supporting user vehicles. These can include interferometric tracking from Earth, coordinated ranging through local assets [23], or the usage of GPS receivers in Lunar Orbit [24]. Another technology worth addressing is X-Ray Navigation [25], which has the potential to provide clock corrections as well as autonomous navigation observations for a reference platform. These provide an array of options to the system designer in the development of various integrated architectures. The selection of any approach will need to be a balance between investment in development and deployment of the technology vs. the longevity and number of users a mission can support against operational and deployment costs.

CONCLUSIONS AND FORWARD WORK

This article presents a detailed overview of both the sensitivity to and potential mitigation methods for vehicle knowledge improvement in lunar space. These initial errors flow through the system requirements, affecting designs and performance at such levels as delta-v allocation, mission phasing and timelines, and navigation sensor requirements. At a system level, these must all be balanced to help close the system architecture. For the present, standard procedures using ground-based tracking are adequate to meet these needs, given their availability during critical events. As the pace of operations ramps up with an increased pace of missions, it becomes increasingly important to reduce the burden on ground assets. Two approaches are possible: increased capability of autonomous onboard systems (such as TRN, for example) and/or the placement of navigation (simultaneously operating as potential communication infrastructure elements) aids within the lunar operational architecture. These can be surface or orbital assets. This article has provided insights to be considered when looking at the overall architecture, focusing on the interaction between the various mission scenarios (trajectory design) and operational capability (i.e. coverage). The two are inexorably linked, and must be considered. Thus, priorities must be balanced between robustness to mission scenarios and timeline of focused operational needs.

Similarly, these studies should be revisited over time as the long-term planning continues to evolve. For example, with increasing usage of elements in NRHO orbits (such as Gateway), these mission scenarios will begin to drive the need for local navigation to support autonomous proximity operations. Also, as trajectory design continues to mature, site availability will need to be continually re-assessed. For example, the DSN

*https://www.nasa.gov/feature/goddard/2021/lunanet-empowering-artemis-with-communications-and-navigation-interoperability results presented above for multi-orbit capabilities were based on requirements from earlier studies. While this article does include analysis for these orbits (the descent from NRHO to LLO, as well as operation within LLO), the exact timelines and coverage to ground stations need to assessed. Further studies have shown a sensitivity over multiple orbits to individual ground stations, such as impacts of the observation geometry on orbit determination accuracy.

One area that this study does not cover is support of ground navigation once on the surface. Other studies are in development to help develop infrastructure for both local (around a landing site) and global capability for surface assets such as unmanned or manned rovers and other lander missions. Additional trajectories can be included to show ground navigation accuracy given orbital assets. One limitation for this use case is that the accuracy requirements tend to be an order of magnitude or more for high precision science data evaluation and/or scenarios such as search and rescue. For example, knowledge requirements in Low Lunar Orbit may be on the order of 100's of meters, whereas on the surface, accuracy on the order of single meters (or more) may be required. For requirements such as these, more infrastructure or more complex observations (instead of a range and range-rate, such as a measurement of range and direction used in Very High Frequency Omni-Directional Range (VOR)) would typically be needed. This analysis could be performed with the same toolkit utilized here, but was outside of the scope at the time of writing.

An additional area that will continue to be of concern for early architecture deployments will be the phasing of any orbital assets. As shown above, the phasing of the orbit (in terms of the orbital alignment relative to the surface) will play in assessing visibility of mid-latitude assets. This is particularly true with missions with a limited number of dwell orbits prior to a powered descent as seen in the Low Lunar Orbit Scenarios above. Vehicles operating on approach or exit trajectories are more likely to see mid-latitude assets, permitted they are on the correct side of the moon facing the incoming (or outgoing) trajectory. For these scenarios, the power of any ground assets will play a large factor in acquiring any navigation measurements. Similarly for any orbital assets supporting local navigation, detailed studies will need to be performed to ensure link closure for any low power signals, and whether this requires pointing of antennas from orbital assets.

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