

SENSITIVITY OF OPTIMAL MIDCOURSE CORRECTION SCHEDULING FOR ROBUST CISLUNAR TRAJECTORY DESIGN

David Geller*, David Woffinden[†], Stefan Bieniawski[‡]

A new approach to optimal trajectory design is the determination of optimal trajectories that are robust to initial trajectory dispersions, navigation errors, maneuver execution errors, and environment modeling errors. This paper investigates the sensitivity of cislunar robust optimal trajectory design to launch date, duration of navigation measurement passes, and navigation measurement frequency. For a given cislunar trajectory from translunar injection (TLI) to lunar orbit insertion (LOI), the optimal locations of midcourse corrections, also known as trajectory correction maneuvers (TCM) are determined by minimizing the final $3\text{-}\sigma$ Δv subject to a final $3\text{-}\sigma$ position dispersion constraint for a given launch date, specified measurement pass duration prior to each maneuver, and measurement frequency. Optical navigation (OpNav) is assumed, and OpNav field-of-view (FOV) and lighting constraints are employed. These constraints turn out to be important elements of the problem. The sensitivity of the optimal TCM locations are then investigated by varying the launch date, duration of OpNav measurement passes, and the OpNav measurement frequency, and then re-optimizing the locations of the TCMs. Given the problem parameters provided herein, results show that while the optimal TCM locations with respect to TLI vary greatly from one launch date to another, their locations with respect to LOI are nearly invariant over a 2-month launch window. Results also show that in all cases the optimal location of the last TCM is found to be at the point where the OpNav lunar FOV constraint is first violated. For all other TCMs, OpNav measurement pass duration and measurement frequency can have a moderate to large affect on the optimal TCM locations.

INTRODUCTION

During the trajectory design process, a mission profile is typically created to satisfy specific mission objectives and constraints while optimizing performance metrics such as propellant mass or mission duration. Once this task is accomplished, the next question is whether the derived optimal trajectory is truly optimal and robust to uncertainties such as navigation errors, trajectory dispersions, maneuver execution errors, and environmental modeling errors. Often the derived optimal trajectory is based on traditional deterministic techniques and is not robust to these uncertainties. If the optimal deterministic trajectory is not robust to uncertainties, the trajectory design process must start over.

This research implements non-traditional robust trajectory optimization techniques for human lunar exploration based on linear covariance techniques. These proposed techniques are designed to minimize propellant mass subject to mission objectives and constraints, while simultaneously

*Professor, Mechanical and Aerospace Engineering Department, Utah State University Space Dynamics Laboratory, 1695 North, Research Park Pkwy, North Logan, UT, 84341

[†]Aerospace Engineer, GN&C Autonomous Flight Systems Branch, NASA Johnson Space Center, Houston TX, 77058

[‡]Principal Technologist for Autonomy and GN&C, Blue Origin LLC, Renton, WA, 98057

APPROACH

Linear Covariance Analysis

Linear covariance analysis (LinCov) is based on an augmented dispersion state vector (from the reference trajectory) consisting of both a true state vector and a navigation state vector. The navigation state vector consists of the inertial position and velocity of the spacecraft, and a set of 1st-order Markov processes (exponentially correlated random variables, or ECRVs) representing the spacecraft attitude, star-camera misalignment, and OpNav measurement biases (bearing angles and apparent angular diameter) for both the Earth and Lunar imaging. The true state vector is comprised of the same states as the navigation state plus actuator error states (scale-factor, misalignment, and bias). The LinCov analysis also includes OpNav measurement noise (bearing, apparent angular diameter, and pointing errors), maneuver execution error noise, and process noise representing environmental modeling errors.

The true and navigation trajectory dispersions are governed by a set of covariance propagation, update, and correction equations. Similarly, the navigation filter state error equations are also governed by a set of covariance propagation, update, and correction equations. The propagation equations for the true and navigation dispersion covariance and the navigation filter error covariance propagation, $C_a(t_k)$ and $P(t_k)$, respectively, are based on the cislunar dynamics and environmental uncertainties.

$$C_a(t_{k+1}) = \Phi_a C_a(t_k) \Phi_a^T + G_a Q_{D,a} G_a^T \quad (1)$$

$$P(t_{k+1}) = \Phi_n P(t_k) \Phi_n^T + G_n Q_{D,n} G_n^T \quad (2)$$

The matrices Φ_a , Φ_n , G_a , G_n , $Q_{D,a}$, and $Q_{D,n}$ are based on the linearized cislunar dynamics and environmental uncertainties.

The update equations for the dispersion covariance and the navigation filter error covariance are based on optical navigation measurements that include bearing and apparent angular diameter measurements to the Earth and Moon at time t_i .

$$C_a^+(t_i) = A_a(t_i) C_a^-(t_i) A_a^T(t_i) + B_a(t_i) R(t_i) B_a^T(t_i) \quad (3)$$

$$P^+(t_i) = [I - K(t_i) H(t_i)] P^-(t_i) [I - K(t_i) H(t_i)]^T + K(t_i) R(t_i) K(t_i)^T \quad (4)$$

where

$$K(t_i) = P(t_i) H(t_i)^T [H(t_i) P(t_i) H(t_i)^T + R(t_i)]^{-1} \quad (5)$$

The matrices A_a , B_a , R , and H are based on the OpNav geometry and measurement noise.

The correction equations for the dispersion covariance and navigation filter error covariance are based on closed-loop TCM maneuvers at times t_m via navigation state feedback.

$$C_a^+(t_m) = M_a(t_m) C_a^-(t_m) M_a^T(t_m) + N_a Q_{w,a}^{act} N_a^T \quad (6)$$

$$P^+(t_m) = [I + M_n(t_m)] P^-(t_m) [I + M_n(t_m)]^T + N_n Q_{w,n}^{act} N_n^T \quad (7)$$

The matrices M_a , M_n , N_a , N_n , $Q_{w,a}^{act}$, and $Q_{w,n}^{act}$ are based on the TCM targeting algorithm and maneuver execution errors.

Optimization Problem Formulation

In general, the optimization problem is to minimize a cost function based on Δv subject to a constraint on the position dispersion at the final time. In previous work,^{1,2} the cost function was based on the Δv dispersion across all TCMs, $\sum_{m=1}^N \sigma_{\delta\Delta v}(t_m)$. In this work, the LOI maneuver correction Δv , $\sigma_{\delta\Delta v}(t_{LOI})$, and the post-LOI velocity dispersion, $\sigma_{\delta v}(t_{LOI}^+)$, are added to the cost function to account for an LOI correction and post-LOI TCMs that are typically required to remove post-LOI velocity dispersions.

$$\begin{aligned} \text{Problem 1 : } & \text{minimize} && \sigma_{\delta v}(t_{LOI}^+) + \sigma_{\delta\Delta v}(t_{LOI}) + \sum_{m=1}^N \sigma_{\delta\Delta v}(t_m) \\ & \text{subject to} && \sigma_{\delta r}(t_{LOI}) \leq \sigma_{\delta r}^{req} \end{aligned} \quad (8)$$

LinCov Embedded in a Genetic Optimization Algorithm

A LinCov analysis tool based on Eqs. 1-7 is embedded in a genetic algorithm (GA) optimizer and provides the value of a cost function to the GA. This is illustrated in Fig. 2. The GA iteratively calls the LinCov analysis tool with different sets of optimization parameters (TCM locations) until the optimal solution is found. The GA fitness function is the cost function in Eq. 8 plus a penalty when the 3- σ dispersion constraint is violated. MATLAB's GA function is utilized, and all analysis in this paper is conducted for 50 generations with 30 samples per generation. These values were found to produce the most consistent and repeatable results.

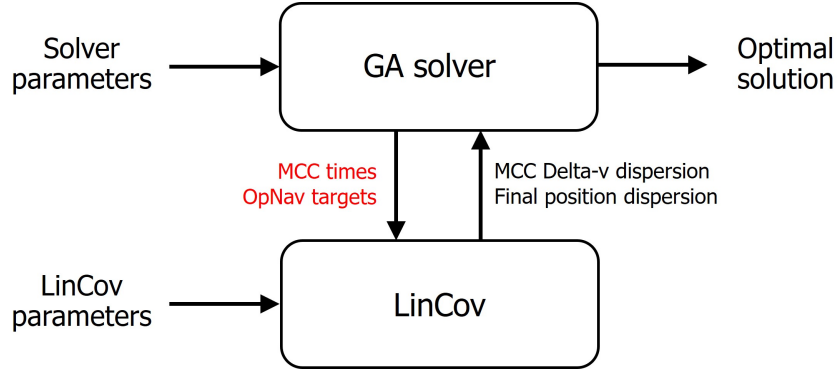


Figure 2. LinCov embedded in a MATLAB genetic algorithm (GA) optimizer

PROBLEM SETUP

This section covers the key modeling parameters within the LinCov analysis. It describes error models for measurements and maneuvers, initial condition uncertainties, and other operational assumptions. Referenced tables are listed in the Appendix.

OpNav measurements consist of the apparent centroid location and apparent angular diameter of a target celestial body. OpNav measurement errors are modeled as a combination of an ECRV bias, OpNav measurement noise, and OpNav pointing error, also modeled as white noise. Star tracker measurement errors are modeled as a misalignment and measurement noise. The specific camera parameters used in this analysis are provided in Table 1.

The TCMs are designed to target the reference LOI position, and the LOI maneuver is designed to target the reference LOI velocity. All maneuvers are impulsive with maneuver execution errors

due to misalignment, scale factor, bias, and white noise. The misalignment, scale factor, and bias are modeled as ECRVs. Table 2 lists each error model component and its corresponding value for the Reaction Control System (RCS) and main engines. It is assumed that RCS thrusters are used for TCMs while main thrusters are used for the nominal maneuvers which occur at TLI and LOI.

Table 3 lists the initial dispersions and navigation errors for the vehicle's translational and rotational states. Position and velocity uncertainties are expressed in a UVW reference frame, where the U-axis points in the radial direction, V-axis points in the downrange direction, and W-axis points in the crossrange direction (analogous to a local vertical, local horizontal frame). The initial dispersions are increased further by TLI maneuver execution errors. As a correction procedure, a fixed trim burn is performed immediately after TLI. The time of this maneuver is fixed and is not considered in the optimization process. The associated $\sigma_{\delta\Delta v}$ is also fixed.

Table 4 and Fig. 3 describe various operational constraints and assumptions. The nominal OpNav measurement pass duration is 2 hrs long and is always constrained to end 30 minutes prior to a maneuver. In the process of searching for an optimal solution, if consecutive maneuvers are placed less than 2.5 hrs apart, the measurement pass is reduced to ensure the 30-minute gap is enforced. Likewise, maneuvers are constrained to occur at least 30 minutes apart. In the event where maneuvers are separated by exactly 30 minutes, no measurements are taken in between them.

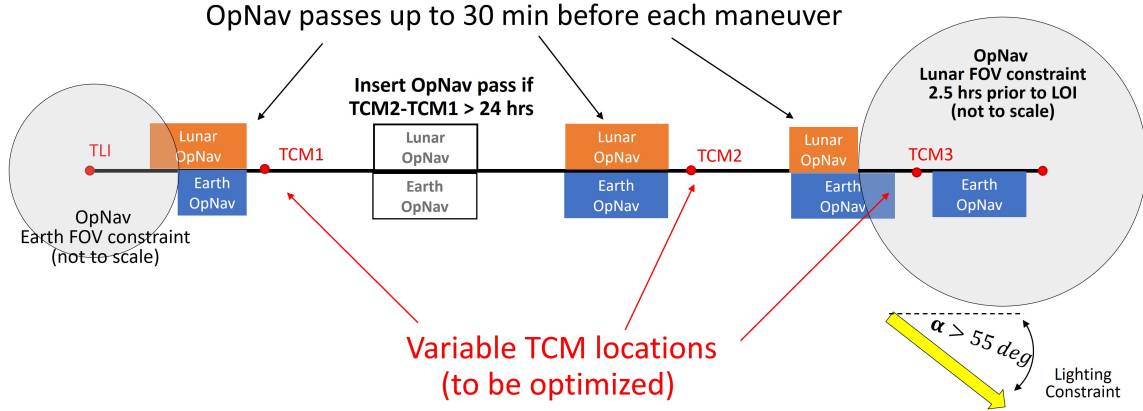


Figure 3. Mission operational constraints and assumptions)

The OpNav field of view (FOV) constraint shown in Table 4 is dependent on camera properties and equal to 16 degrees. If the apparent angular diameter of the target celestial body exceeds the FOV constraint, no OpNav measurements are taken. For the reference trajectory shown in Fig. 1 and an OpNav FOV constraint of 16 degrees, the last opportunity for lunar OpNav measurements is approximately 2.5 hrs prior to LOI. This will be very important in the analysis below.

Similarly, the lighting constraints in Table 4 indicate that lunar OpNav measurements are available only when the Sun is more than 55 degrees off the line-of-sight (LOS) to the Moon, and Earth OpNav measurements are available only when the Sun is more than 30 degrees off the LOS to the Earth. The analysis below will show that these constraints are important as well.

Lastly, to ensure that navigation never goes more than 24 hrs without lunar or Earth OpNav measurements, an OpNav pass is always inserted between two maneuvers when they are separated by more than 24 hrs.

SENSITIVITY OF TCM LOCATION TO LAUNCH DATE

This section presents the sensitivity of TCM location to launch date. NASA's Copernicus software was used to generate six reference trajectories over a 2-month period. The optimal TCM locations for each of these trajectories is shown in Fig. 4. Although the duration of the trajectories from TLI to LOI (in the first column) vary from 4.3 to 5.5 days, the optimal TCM locations highlighted in orange are nearly constant with respect to LOI. TCM 1 shows the most variability ranging from 32.2 hrs to 45.2 hrs prior to LOI. The optimal locations of TCM 2 are within a few minutes of 4.5 hrs prior to LOI, and the optimal locations of TCM 3 are within a couple of minutes of 2 hrs prior to LOI.

	TLI->LOI Days	TCM 1 Hrs-LOI	TCM 2 Hrs-LOI	TCM 3 Hrs-LOI	DV (m/s) 3-sigma	Pos Disp 3-sigma (km)	Vel Disp 3-sigma (m/s)
Day 1	5.3	41.1	4.53	1.95	7.4	12.0	7.5
Day 11*	4.3	32.2	4.57	1.99	6.9	12.0	7.6
Day 21	4.4	36.6	4.59	2.00	6.8	12.1	7.6
Day 33*	5.3	41.1	4.54	1.95	7.4	12.0	7.6
Day 42	4.5	36.9	4.55	1.97	7.2	12.0	7.6
Day 54	5.5	45.2	4.49	1.97	7.5	12.2	7.7

*Lighting constraints turned off

Figure 4. Sensitivity of TCM location and mission performance to launch date

The results for TCM 3 are particularly important. Recall that the lunar FOV constraint and the loss of lunar OpNav measurements occurs approximately 2.5 hrs prior to LOI. Recall also that there is a 30-minute gap constraint between the last OpNav measurement and a maneuver. Thus, it becomes clear that the optimal location of TCM 3 is selected such that the closed-loop system takes full advantage of lunar OpNav measurements right up until the lunar FOV constraint is violated, and then executes TCM 3 30 minutes later.

The remaining data in Fig. 4 show surprisingly consistent overall performance over the 6 reference trajectories. While the total TCM Δv varies slightly, the final 3- σ post-LOI position and velocity dispersions are nearly constant.

Lastly, it is noted that the Day 11 and Day 33 reference trajectories both violated OpNav lighting constraints for long periods of time. Because of this, navigation errors were very large, TCM Δv was very large, and the optimizer was unable to find a solution that satisfied the 20 km final position dispersion constraint. Because of this, the OpNav lighting constraints were turned off to obtain the data in the table for Day 11 and Day 33.

Fig. 5 shows all six of the reference trajectories over the 2 month launch window, each in its own perifocal plane. Not only are the reference trajectories in their respective perifocal planes very similar, but the optimal locations of TCM 2 and TCM 3 are nearly identical, and the optimal locations of TCM 1 are very similar. The TCM 1 locations are all well outside the lunar sphere of influence (SOI), the TCM 2 locations are well inside the SOI, but outside the lunar FOV constraint, and the TCM 3 locations are all 30 min inside the FOV constraint. In hindsight, these results are

not too surprising. Since all the reference trajectories have the same final mission constraints (e.g., circular orbit over the landing sight), they all look nearly identical in their respective perifocal planes inside the lunar SOI, providing evidence as to why the last two optimal TCMs are always at the same location over the 2-month launch window.

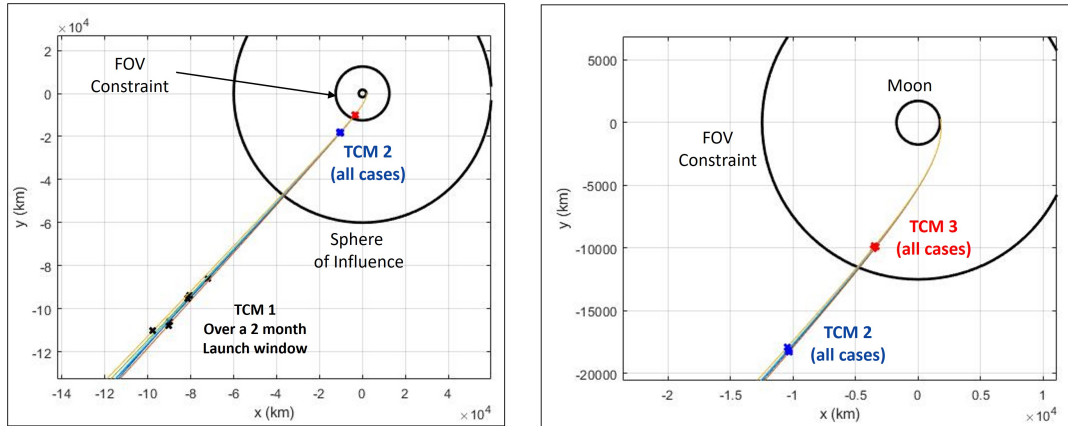


Figure 5. Six reference trajectories in their respective perifocal planes and optimal TCM locations are shown (left), and enlarged (right)

SENSITIVITY OF TCM LOCATION TO OPNAV PASS DURATION

In this section the sensitivity of optimal TCM locations to OpNav navigation pass duration is investigated. For this analysis the OpNav duration is varied from 10 min to 3.5 hrs, while all other problem parameters and operational constraints are held fixed (and presented in the Appendix). Only one reference trajectory (Day 1) is utilized. The results of this analysis are shown in Fig. 6 .

All data is displayed as a function of the OpNav duration (x-axis). The top-left plot shows the total $3\text{-}\sigma\Delta v$ associated with the 3 TCMs plus the LOI correction maneuver. The top-right plot shows the $3\text{-}\sigma$ post-LOI position dispersion. The bottom-left plot shows the $3\text{-}\sigma$ post-LOI velocity dispersion, and the bottom-right plot shows the optimal locations of the TCMs in terms of hours prior to LOI. An enlarged view of the TCM 2 and TCM 3 locations as a function of the OpNav duration is shown to the right.

Some conclusions from this data are apparent. First, Δv and dispersion performance associated with the optimal TCM locations is nearly flat for OpNav durations greater than 1 hr, and noticeably degrades for OpNav durations less than 1 hr. Second, the optimal TCM 1 location moves further from LOI with increasing OpNav duration, varying from as little as 25 hrs prior to LOI to as much as 55 hrs prior to LOI. This illustrates the idea that when improved navigation is available, in this case due to longer OpNav passes, the optimal TCMs locations can be executed earlier to reduce overall Δv . Third, optimal location of TCM 2 exhibits the same sort of trend as TCM 1, but varies only from 3 hrs to 6 hrs prior to LOI. And lastly, the optimal TCM 3 location is remarkably constant, fixed at 2 hrs prior to LOI, and invariant to OpNav duration. As noted in the sensitivity to launch date analysis, the optimal location of TCM 3 is selected such that the closed-loop system takes full advantage of lunar OpNav measurements right up until the lunar FOV constraint is violated.

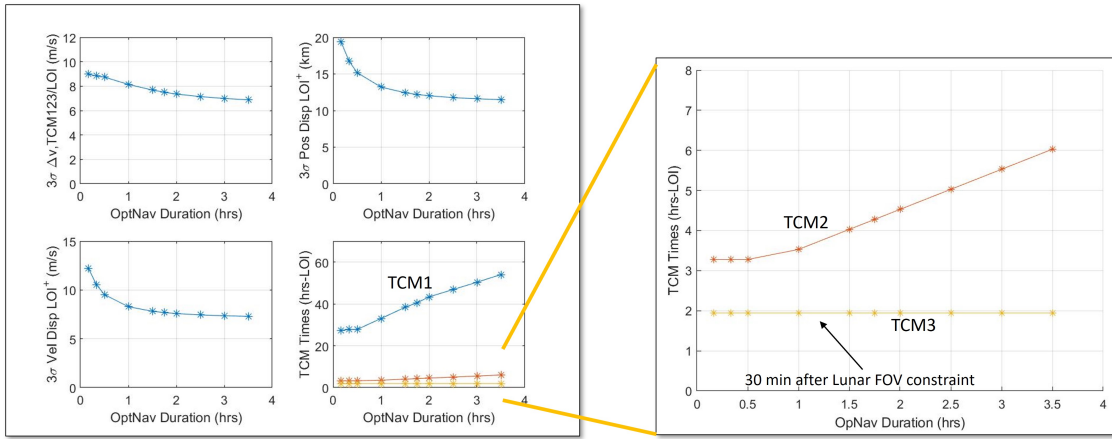


Figure 6. Sensitivity of TCM location and mission performance to OpNav navigation pass duration (left), and enlarged (right)

Fig. 7 shows the TCM locations as a function of OpNav duration superimposed on the Day 1 reference trajectory in the perifocal plane. All the optimal TCM 1 locations are clearly outside the lunar sphere of influence (SOI) and move further from the SOI with increasing OpNav duration. The optimal TCM 2 locations are well inside the SOI, but all lie outside the lunar FOV constraint and move further from the FOV constraint with increasing OpNav duration. And lastly, all the optimal TCM 3 locations are fixed at 30 min inside the lunar FOV constraint and do not vary with OpNav duration.

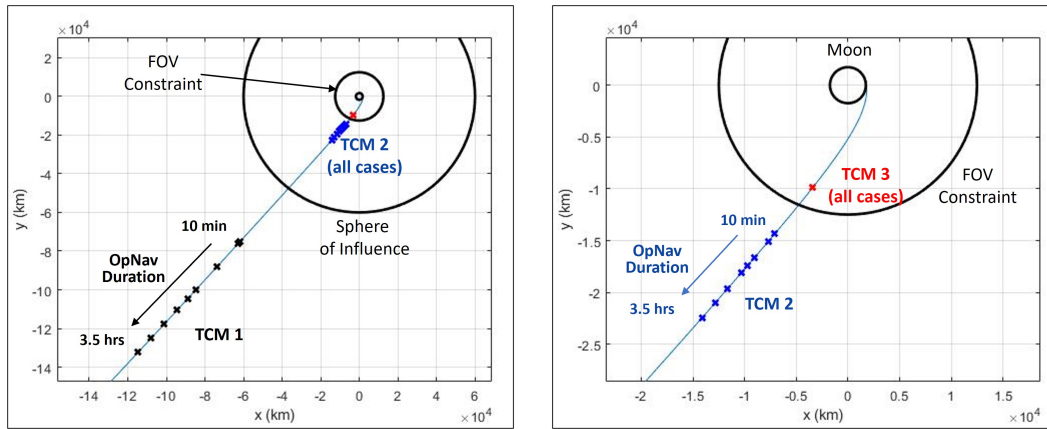


Figure 7. Day 1 trajectory in the perifocal planes and optimal TCM locations as a function of OpNav duration (left), and enlarged (right)

Since the lunar FOV constraint is such an important factor in these results, it was decided to investigate the effect of a forced, unconstrained, 1 hr OpNav measurement pass just before the FOV constraint, independent of all other OpNav passes and maneuvers. The results of this analysis are presented in Fig. 8.

The effect of this additional unconstrained OpNav pass is minimal. Performance is only mildly improved, and the optimal TCM locations are only slightly modified. All the optimal TCMs move further away from LOI. TCM 3 moves exactly 30 min further away from LOI to a position that

places it right on the FOV constraint, the same position where the last lunar OpNav measurement is obtained. It is also noted that for small values of OpNav duration (e.g., ≤ 1 hr), the optimal location of TCM 2 moves significantly away from the LOI. The reason for this is still under investigation.

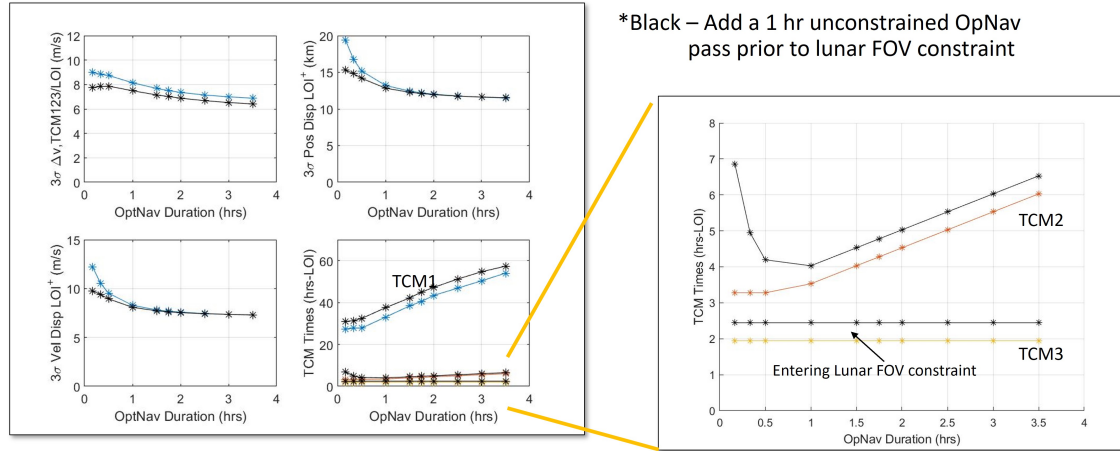


Figure 8. Sensitivity of TCM location and mission performance to OpNav navigation pass duration (left), and enlarged (right)

SENSITIVITY OF TCM LOCATION TO OPNAV MEASUREMENT FREQUENCY

In this final sensitivity analysis, the OpNav measurement frequency will be varied while holding all problem parameters and operational constraints fixed (presented in the Appendix) and utilizing only one reference trajectory (Day 1).

Fig. 9 shows the results of this sensitivity analysis. The dashed and dotted lines show Δv performance, post-LOI dispersion performance, and optimal TCM locations as a function of increasing measurements frequency ranging from $\Delta t = 300$ to $\Delta t = 0.3$ measurement interval.

Some conclusions from this data are apparent. First, Δv and dispersion performance notably improve with increasing measurement frequency up to approximately a $\Delta t = 3.0$ sec measurement interval. Beyond this, e.g., $\Delta t = 0.3$ sec, performance improvement is limited. Second, the optimal locations of TCM 1 and TCM 2 move dramatically away from LOI with increasing measurement frequency up to $\Delta t = 3.0$ sec with minimal change at higher frequencies. This again illustrates the idea that optimal TCMs are executed earlier to reduce overall Δv when improved navigation is available, in this case due to higher measurement frequency. The bumps seen in the high measurement frequency TCM 2 results ($\Delta t = 3.0$ sec, 0.3 sec) are a reflection of the relative insensitivity of Δv performance to the TCM 2 locations. And lastly, the optimal TCM 3 location is remarkably constant, fixed at 2 hrs prior to LOI, and invariant to OpNav measurement frequency.

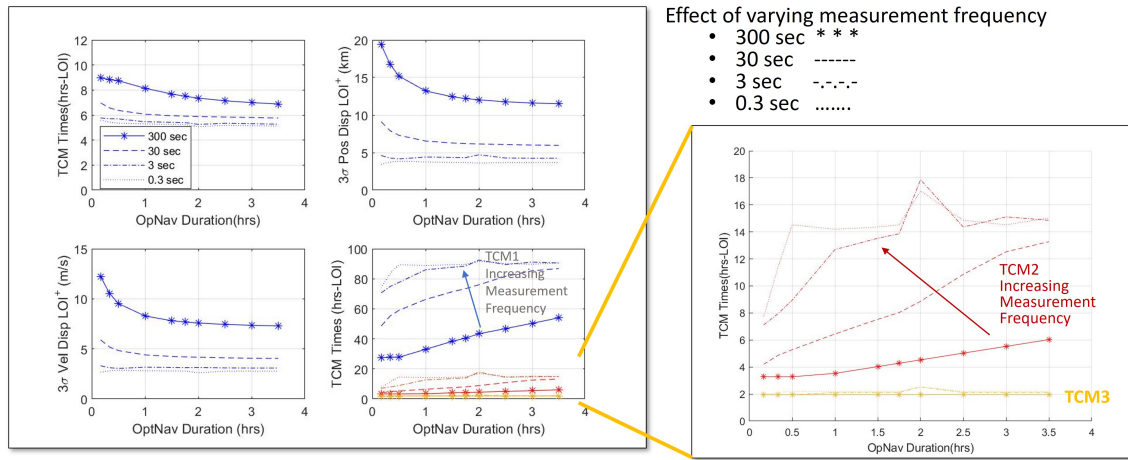


Figure 9. Sensitivity of TCM location and mission performance to OpNav measurement frequency (left), and enlarged (right)

One last point needs to be made. The OpNav measurement error model utilized in this paper is driven more by measurement noise than measurement bias. Because of this, higher measurement frequency does a better job of averaging out the effects of noise which in turn results in smaller navigation errors. If another OpNav error model had been used, one driven by bias instead of noise, the effect of increasing measurement frequency might not be as noticeable.

CONCLUSION

The sensitivity of the optimal TCM locations to launch date, OpNav measurement duration, and OpNav measurement frequency was investigated. Results show that over a 2-month launch window, the locations of the final two optimal TCMs are relatively invariant with respect to LOI. The first optimal TCM, which is significantly outside the lunar SOI, varies by less than half a day over the same 2-month window. Interestingly, since all the reference trajectories have the same final mission constraints, they all look nearly identical in their respective perifocal planes inside the lunar SOI, providing evidence as to why the last two optimal TCMs are always at the same location over the 2-month launch window.

Another key conclusion is the importance of the lunar FOV constraint. In all cases, whether varying launch date, OpNav duration, or OpNav measurement frequency, the final optimal TCM was always slightly inside or on the edge of the lunar FOV constraint. This reflects the fact that the usefulness of OpNav measurements is inversely proportional to range or range-squared, i.e., OpNav measurements become more useful as the vehicle approaches the Moon. Thus, the optimal location of TCM 3 is selected such that the closed-loop system takes full advantage of lunar OpNav measurements right up until the lunar FOV constraint is violated. It should also be noted that Earth OpNav measurements are still available inside the lunar FOV constraint, however, their usefulness at such large distances from the Earth is such that they have no impact on the optimization cost function and are thus not utilized.

Another key conclusion is based on the observation that the first two optimal TCMs generally move further away from LOI as navigation accuracy improves whether due to longer OpNav durations, or higher OpNav measurement frequencies. This illustrates the idea that when improved

navigation is available, optimal TCMs are executed earlier to reduce overall Δv . This also reflects the targeting scheme (position targeting) and the objective of the cost function to minimize Δv .

Lastly, as expected, Δv and position/velocity dispersion performance improve with increasing navigation accuracy, whether due to longer OpNav duration, or higher OpNav measurement frequency.

Finally, there are two important reminders: 1) the OpNav error model utilized in this paper is driven by measurement noise. If an error model driven more by bias had been utilized, the effect of increasing measurement frequency might not be as noticeable; and 2) all the results generated for this paper are based on position targeting for the TCMs and velocity targeting for the LOI maneuver. The results of this paper may change if other more sophisticated targeting algorithms are applied and is thus a future area of investigation.

REFERENCES

- [1] D. K. Geller, S. Shuster, and D. Woffinden, "Robust Cislunar Trajectory Optimization via Midcourse Correction and Optical Navigation Scheduling," *AAS 22-065, AAS Guidance and Control Conference, Breckenridge, CO, February 2022*, 2022.
- [2] D. Woffinden, S. Shuster, D. K. Geller, and S. Bieniawski, "Robust Trajectory Optimization and GNC Performance Analysis for NRHO Rendezvous," *AIAA 22-564, AAS/AIAA Astrodynamics Conference, Charlotte, NC, August 2022*, 2022.
- [3] K. Jin, D. K. Geller, and J. Luo, "Robust Trajectory Design for Rendezvous and Proximity Operations with Uncertainties," *Journal of Guidance, Control, and Dynamics*, Vol. 43, No. 4, 2020, pp. 741–753.
- [4] N. B. Stastny and D. K. Geller, "Understanding Optimal Two-Burn Relative Trajectory Transfers with Maneuver Errors and Dispersion Requirements," *AAS 20-601, AIAA Astrodynamics Specialists Conference, Lake Tahoe, NV, August 2020*, 2020.
- [5] K. Jin, D. K. Geller, and J. Luo, "Development and validation of linear covariance analysis tool for atmospheric entry," *Journal of Spacecraft and Rockets*, Vol. 56, No. 3, 2019, pp. 854–864.
- [6] R. S. Christensen and D. K. Geller, "Linear covariance techniques for closed-loop guidance navigation and control system design and analysis," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, Vol. 228, No. 1, 2014, pp. 44–65.
- [7] N. B. Stastny and D. K. Geller, "Autonomous optical navigation at Jupiter: a linear covariance analysis," *Journal of Spacecraft and Rockets*, Vol. 45, No. 2, 2008, pp. 290–298.
- [8] N. Leiter and D. K. Geller, "Linear Covariance Techniques for Closed-Loop Attitude Determination and Control Analysis," *Itzhack Y. Bar-Itzhack Memorial Symposium on Estimation, Navigation, and Spacecraft Control*, Springer, 2012, pp. 453–476.
- [9] D. K. Geller, "Linear covariance techniques for orbital rendezvous analysis and autonomous onboard mission planning," *Journal of Guidance, Control, and Dynamics*, Vol. 29, No. 6, 2006, pp. 1404–1414.
- [10] R. S. Christensen and D. K. Geller, "Closed-Loop Linear Covariance Analysis for Hosted Payloads," *Journal of Guidance, Control, and Dynamics*, Vol. 41, No. 10, 2018, pp. 2133–2143.
- [11] D. K. Geller and D. P. Christensen, "Linear covariance analysis for powered lunar descent and landing," *Journal of Spacecraft and Rockets*, Vol. 46, No. 6, 2009, pp. 1231–1248.
- [12] E. Kollin, "Optical Navigation Measurement Model Memo," *NASA Engineering Memorandum, FldDyn-CEV-17-77*, 2017.

APPENDIX

Tables 1- 4 list relevant LinCov parameters and nominal constraints and operations.

Table 1. Nominal OpNav and star tracker measurement errors.

Description	Value	Units
OpNav measurement noise ($3\text{-}\sigma$)	Kollin ¹²	
OpNav measurement bias ($3\text{-}\sigma$)	0.075	mrاد
OpNav pointing error ($3\text{-}\sigma$)	45	arcsec
Star tracker misalignment steady-state ($3\text{-}\sigma$)	0.3	deg
Star tracker noise ($3\text{-}\sigma$)	4.2	arcsec

Table 2. Nominal RCS and main engine maneuver execution errors.

Description	Value		Units
	RCS Thrusters	Main Thrusters	
Misalignment steady-state ($3\text{-}\sigma$)	30	4.5	mrاد
Misalignment time constant	2.78	2.78	hr
Scale factor steady-state ($3\text{-}\sigma$)	3	0.45	%
Scale factor time constant	2.78	2.78	hr
Bias steady-state ($3\text{-}\sigma$)	50	600	mm/s
Bias time constant	2.78	2.78	hr
Noise ($3\text{-}\sigma$)	50	600	mm/s

Table 3. Nominal initial dispersions and navigation errors.

Description	Value ($3\text{-}\sigma$)	Units
Position dispersion (U,V,W)	(10, 20, 2)	km
Velocity dispersion (U,V,W)	(15, 6, 5)	m/s
Attitude dispersion (per axis)	0.5	deg
Position estimation error (U,V,W)	(50, 50, 50)	m
Velocity estimation error (U,V,W)	(0.05, 0.05, 0.05)	m/s

Table 4. Nominal constraints and operations.

Description	Value	Units
Notional OpNav measurement pass duration	2	hr
Time between last OpNav measurement and maneuver	30	min
Minimum time between maneuvers	30	min
OpNav measurement frequency	300	sec
OpNav FOV constraint	16	deg
Lighting Constraint (Moon)	± 55	deg
Lighting Constraint (Earth)	± 30	deg