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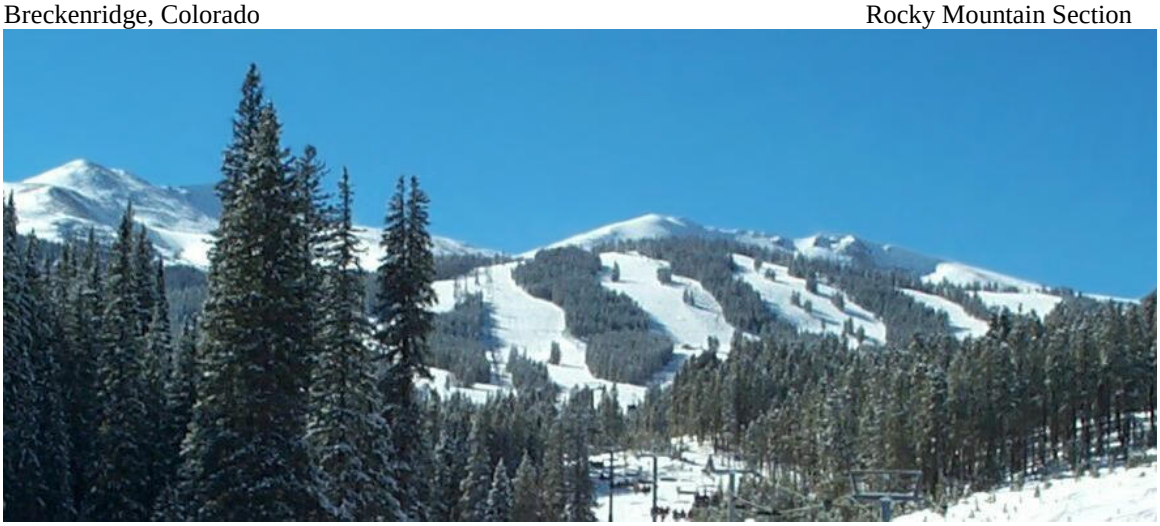

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LUNAR NAVIGATION ARCHITECTURE DESIGN CONSIDERATIONS

Dr. Christopher D'Souza,[*] Joel Getchius,[†] Dr. Greg Holt[‡], and Dr. Michael Moreau[§]

The NASA Constellation Program is aiming to establish a long-term presence on the lunar surface. The Constellation elements (Orion, Altair, Earth Departure Stage, and Ares launch vehicles) will require a lunar navigation architecture for navigation state updates during lunar-class missions. Orion in particular has baselined earth-based ground direct tracking as the primary source for much of its absolute navigation needs. However, due to the uncertainty in the lunar navigation architecture, the Orion program has had to make certain assumptions on the capabilities of such architectures in order to adequately scale the vehicle design trade space. The following paper outlines lunar navigation requirements, the Orion program assumptions, and the impacts of these assumptions to the lunar navigation architecture design. The selection of potential sites was based upon geometric baselines, logistical feasibility, redundancy, and abort support capability. Simulated navigation covariances mapped to entry interface flight-path-angle uncertainties were used to evaluate knowledge errors. A minimum ground station architecture was identified consisting of Goldstone, Madrid, Canberra, Santiago, Hartebeeshoek, Dongora, Hawaii, Guam, and Ascension Island (or the geometric equivalent).

INTRODUCTION

In contrast to NASA's Apollo missions, NASA's Constellation Program is aiming to establish a long term presence on the lunar surface. In that spirit, a lunar transportation system ferrying humans and cargo from Earth to a fixed lunar surface point and back is being designed consisting of the Orion Crew Exploration Vehicle, the Altair lunar lander, the Earth Departure Stage (EDS), and both of the Ares launch vehicles. Many of these Constellation elements will nominally depend on the yet-to-be defined lunar navigation architecture as the primary source for navigation state updates. Orion in particular has baselined this operations scenario for much of its absolute navigation needs. However, due to the uncertainty in the lunar navigation architecture, the Orion program has had to make certain assumptions on the capabilities of such architectures in order to adequately scale the vehicle design trade space The following paper outlines lunar navigation requirements, the Orion program assumptions, and the impacts of these assumptions to the lunar navigation architecture design.. In a general sense, this architicture includes Earth-based ground

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direct tracking, lunar in-situ radiometrics, and onboard optical navigation capabilities. Special attention in this study is paid to Earth-based ground direct tracking and the geometrical distribution of tracking sites to support nominal and contingency operations in a varity of flight phases.

BACKGROUND

Figure 1 illustrates the Constellation mission design for a Lunar Sortie (seven day surface stay) mission.

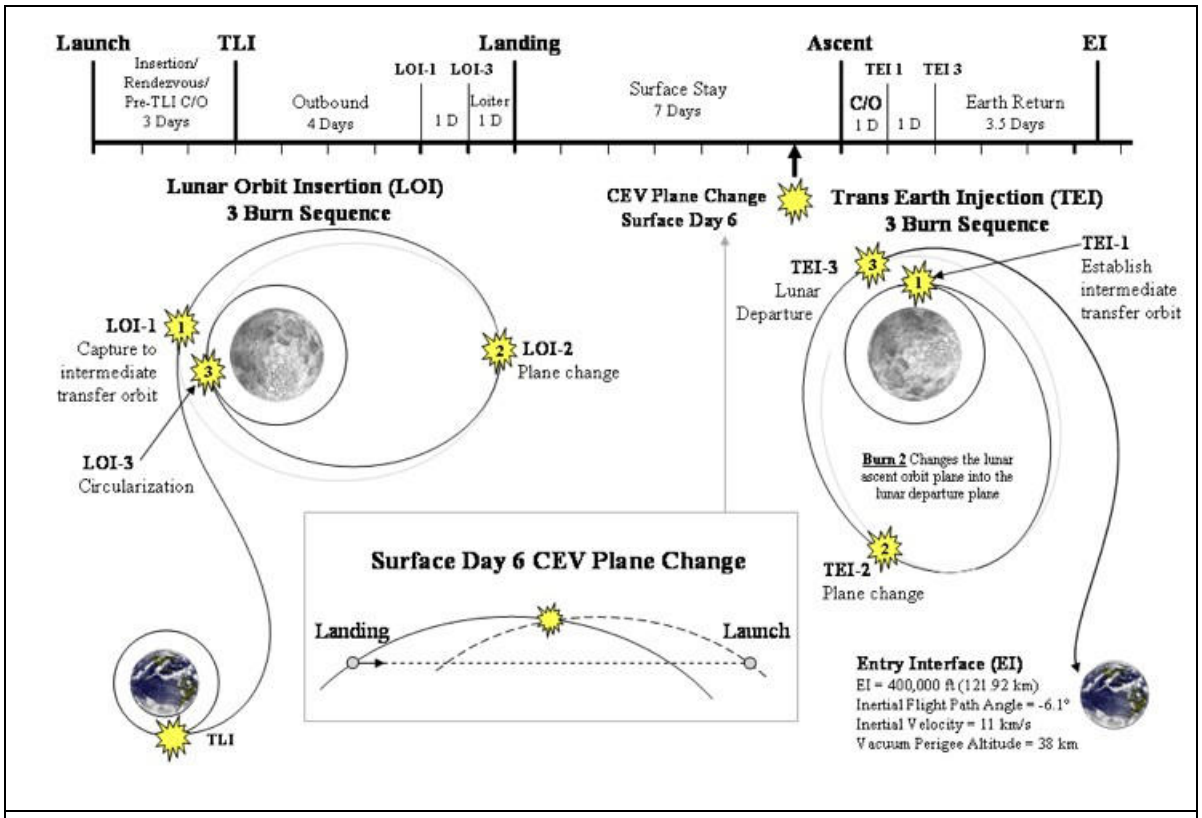

Figure 1: Illustration of a Sample Constellation Lunar Mission for a Seven-Day Lunar Surface Stay[1]

Orion is launched separately from the EDS / Altair stack in low Earth orbit. Orion then performs rendezvous and docking operations to mate with the EDS / Altair stack. The EDS performs the initial Trans Lunar Injection (TLI) burn to place Orion and Altair on lunar trajectory. The EDS is jettisoned shortly thereafter. During the coast flight to the Moon, four Trajectory Correction Maneuvers (TCMs 1 – 4) are performed to optimize the lunar arrival conditions. In lunar orbit, the Altair vehicle performs three Lunar Orbit Insertion burns (LOI 1 – 3). LOI-1 captures the mated vehicles into a high eccentricity lunar orbit. LOI-2 changes the plane of the lunar orbit so the appropriate landing site is achievable. LOI-3 circularizes the orbit about the Moon. Once in the circular orbit, Altair undocks from Orion and lands on the Moon at the desired landing site. After the lunar surface operations have been completed, the ascent stage of Altair lifts off from the lunar surface and performs a rendezvous with Orion. Once the crew and supplies have transferred from the Altair ascent stage to the Orion vehicle, the Altair ascent stage is jettisoned and Orion reverses the three burn LOI sequence with a three burn Trans-Earth Injection (TEI) sequence. TEI-3 places Orion on an Earth-return trajectory. During the Earth-return coast,

three TCMs (TCMs 5 – 7) are performed to optimize Earth arrival conditions. Prior to entry, Orion jettisons its Service Module component and then may perform one of two types of entries:

1. A ballistic entry (utilized in the case of contingencies such as loss of communications).
2. A skip entry where the Orion vehicle skips out of the atmosphere and re-enters. The skip entry allows for Orion to better control its landing site.

The absolute navigation design for each of these vehicles in LEO consists of Global Positioning System (GPS) measurement processing and Inertial Measurement Unit (IMU) sensed velocities for position and velocity determination. Star trackers perform attitude determination. However, the focus of this paper is navigation for lunar transit, lunar orbit, and Earth return. For these phases of flight, the baseline absolute navigation design uses propagated ground-generated radiometric solutions uplinked to the vehicles. Note that Orion does have an optical navigation capability for use in the case of loss of communications, however optical navigation is not the focus of this paper.

REQUIREMENTS

Figure 2 illustrates the Constellation program requirements flow.

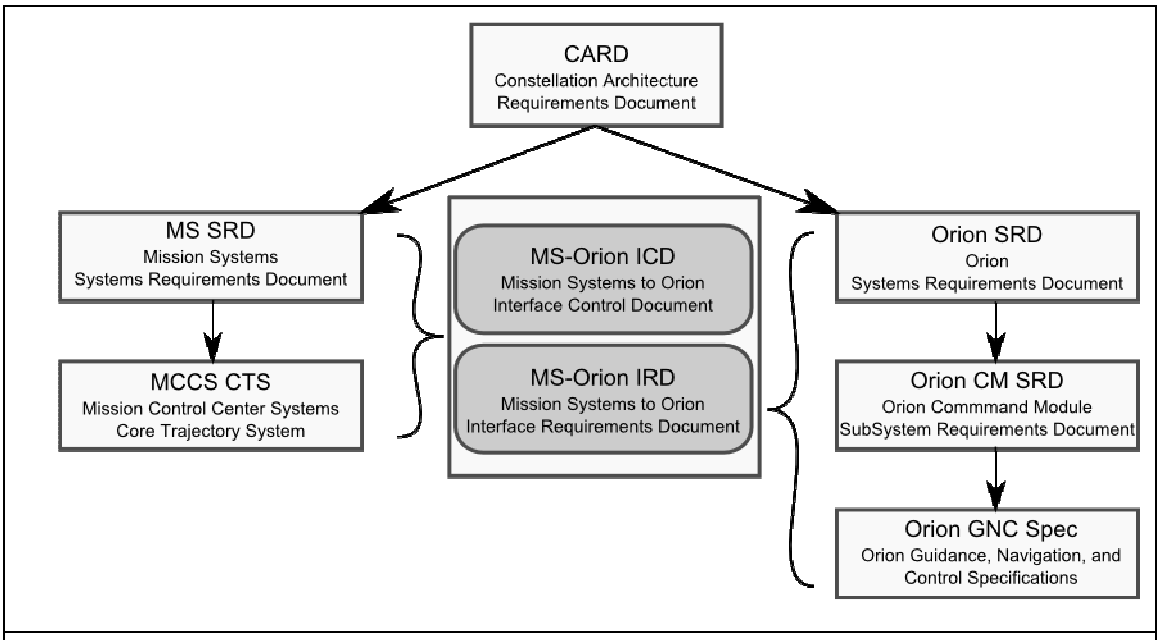

Figure 2: Illustration of Constellation Program Requirements Flow

The Constellation Architecture Requirements Document (CARD) establishes the high level requirements for the Constellation program. This is where requirements such as global lunar access, anytime return, and precision water landing reside. The CARD also establishes the requirement that the Mission Systems project will independently calculate the navigation state of Constellation vehicles. Note that Mission Systems includes the mission operations team at NASA-JSC – and therefore the navigation flight controllers.

The next level of requirements, include the project Subsystem Requirements Documents (SRD), which are the NASA decomposition of the CARD requirements for the various projects. For the Orion project, requirements such as Orion shall navigate within six hours (to support any-time return) and the total amount of translational delta-velocity required to support a mission are documented here.

The final level of requirements documentation (continuing with Orion project as an example) includes the GNC Subsystem Specifications document. At this level, the CARD and SRD requirements are decomposed to verifiable requirements on the Orion navigation system. The Orion Orbit GNC MODE team is responsible for technical decomposition of these requirements. Therefore, this document will contain required navigation state uncertainties prior to each translational maneuver. Such a requirement ensures that the Orion maintains the delta-velocity budget for which the propellant tanks are sized. Another driving requirement for the Orion navigation system concerns the allowable dispersions of entry-interface flight path angle. To meet the requirement on precision water landing, a skip entry profile is utilized and necessitates a tight entry flight path angle corridor (on the order of 0.12°)[*].

As mentioned previously, the navigation design for lunar transit, lunar orbit, and Earth transit consists of the uplink of ground calculated navigation solutions from radiometric measurements. Such measurements include 2-way range, 2-way Doppler, and 3-way Doppler from Earth-based ground direct tracking. Additionally, proposals have been made to augment the lunar navigation architecture with Lunar Relay Satellites (LRS). Figure 3 illustrates the concept of LRS, which would provide TDRS-like functionality to Constellation elements in lunar orbit and on the lunar surface (communications and tracking).

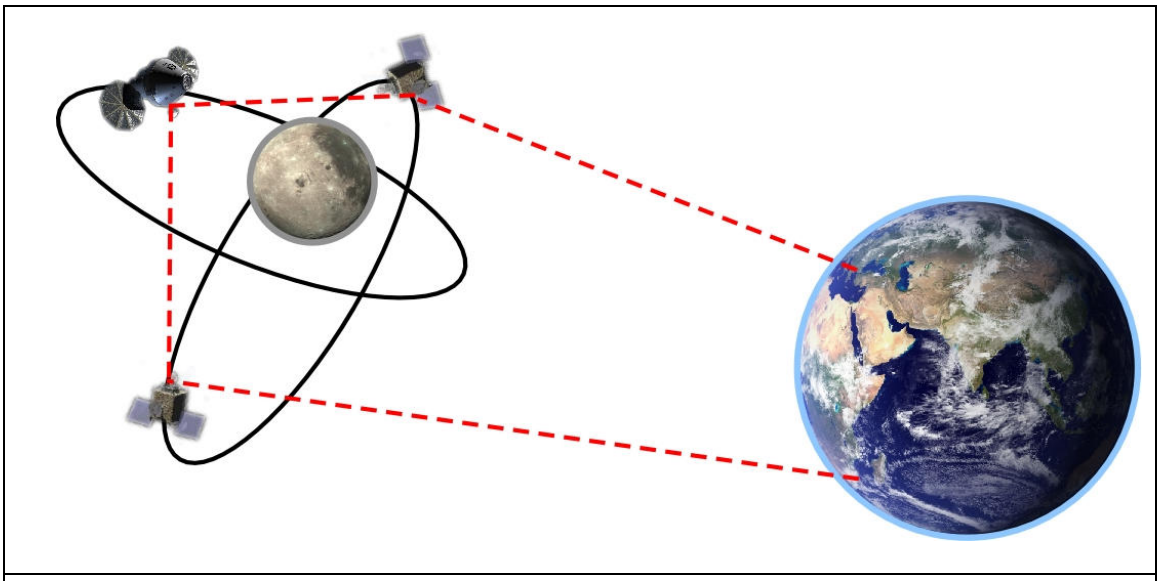

Figure 3: Lunar Relay Satellites Augmenting the Navigation Architecture

[*] The entry flight path angle requirement presented here is considered preliminary. Iterations on this parameter are ongoing and will be updated as appropriate.

Clearly, LRS would provide an enhanced capability for lunar missions allowing Mission Systems to communicate with Constellation elements on the Moon's far side. In addition, the addition of LRS measurements will only serve to improve the navigation performance by providing additional tracking capability, including on the Moon's far side where Earth based ground tracking does not have line of sight. However, if one assumes that LRS would have little or no utility in lunar transit or Earth return flight, then the addition of LRS does not eliminate the need for a robust Earth-based ground direct tracking capability. To illustrate this, consider the sensitivity of entry flight path angle to a delta-velocity (Figure 4).

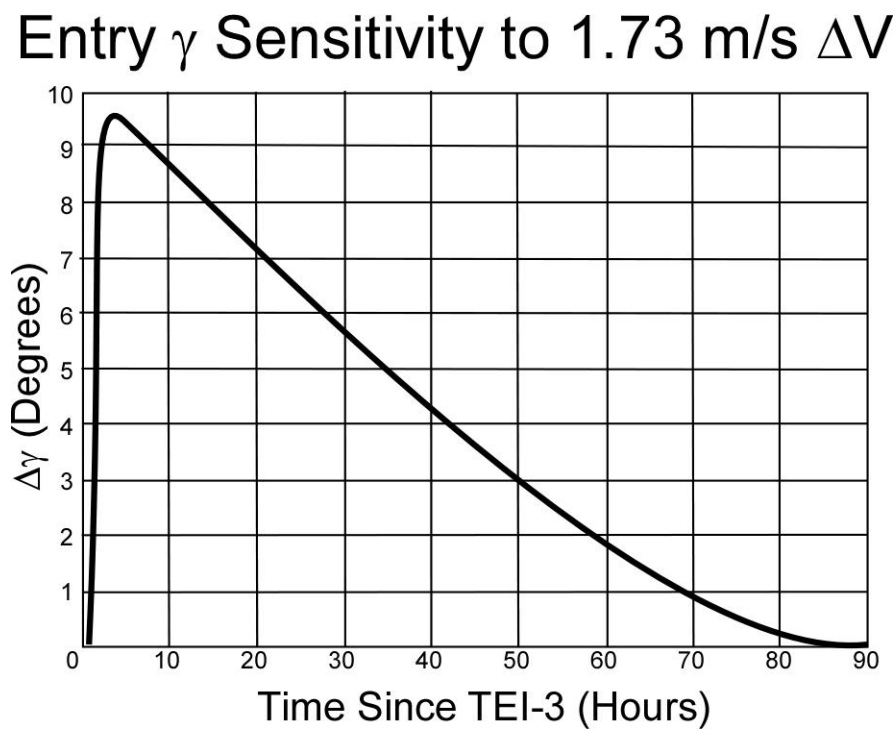

Figure 4: Sensitivity of Entry Flight Path Angle to ΔV.

Figure 4 shows that during Earth transit flight, small delta-velocities imparted on the Orion vehicle can have a significant impact on the entry interface conditions. Such delta-velocities may be imparted on the vehicle from vehicle venting (CO_2 for atmosphere conditioning and urine vents), reaction control jet firings for attitude maintenance, or reaction control jet firings for attitude maneuvers. These small perturbing accelerations on the vehicle are colloquially known in the navigation community as "flak". Clearly, the presence of flak not only may cause the vehicle to fly a trajectory outside of the entry flight path angle corridor, but the timing of the flak is also a concern. For example, a flak event that occurs after a TCM maneuver targeting calculation may result in the burn calculation being invalid, or even worse, may result in a detrimental burn. Therefore, a capability for short arc solutions (generating a navigation state with only minutes of tracking data) is an important feature of the Earth-based ground direct tracking infrastructure.

As the entry flight path angle is a driving requirement and the entry flight path angle is particularly sensitive to changes in velocity during Earth transit, the remaining focus of this paper is on Earth-based ground direct tracking and its capability to resolve the entry flight path angle.

DERIVATION OF THE ORION ORBIT MODE TEAM POSITION

Assumptions and Constraints

Previous analyses[3] have demonstrated the sensitivity of navigation performance to the location of Earth-based ground tracking assets. Particularly important to navigation performance is the maintenance of a North-South and East-West baseline. To illustrate this, consider Figure 5 which demonstrates the sensitivity of the entry flight path angle knowledge for an Earth return trajectory.

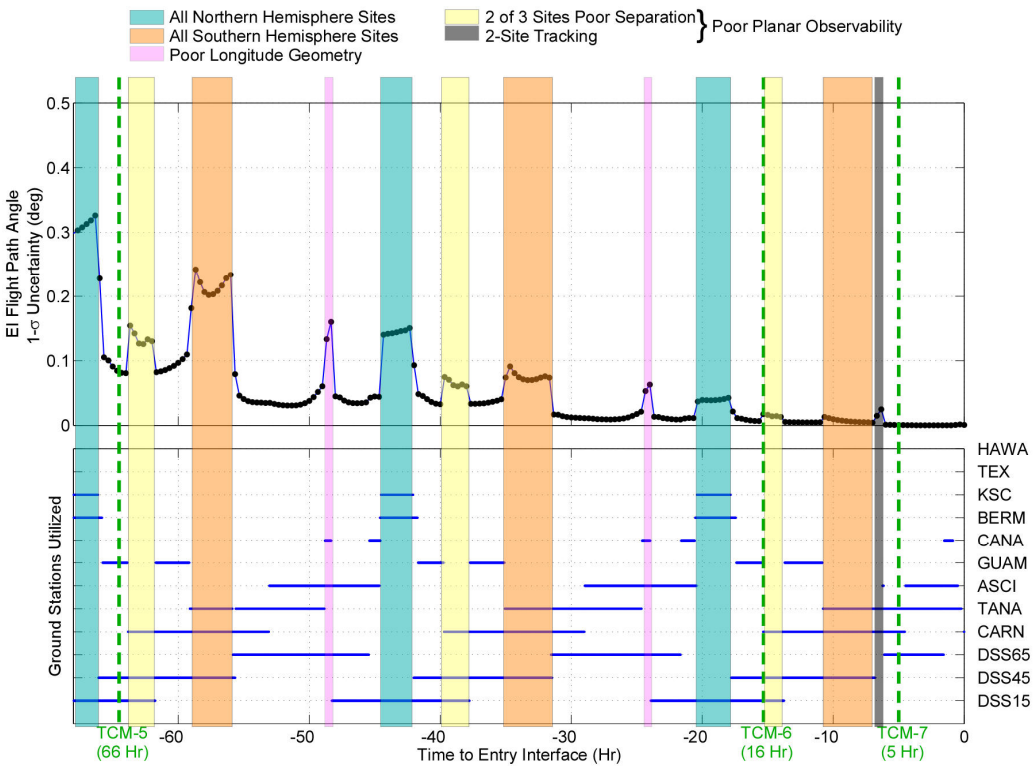

Figure 5: 1σ Entry Flight Path Angle Uncertainty for an Earth Return Trajectory Utilizing a Sample of Apollo-Era Ground Network Trackers[2]

Note that these results were generated assuming the ground station architecture that was available during Apollo (i.e., the locations of trackers were representative of the Apollo network). The Orion MODE team has used an assumption, agreed-upon by Constellation Systems Integration, that any future navigation architecture would have the performance of the Apollo network in terms of geometric visibility and ability to generate short arc solutions.

While the current three station DSN-only network does provide East-West and North-South geometry, it is insufficient for Orion lunar missions because of its inability to generate short-arc solutions[3]. Additionally, such a network does not necessarily provide continuous tracking for all permutations of Orion mission design[3]. Finally, the three station DSN network is susceptible to

rapidly degenerating navigation performance with the loss of a single site. Therefore, with the realization that budget and schedule constraints likely preclude a replica of the Apollo network, Orion MODE team engineers set out to determine the minimum number of ground stations needed to support lunar missions. The selection of potential sites was done based on the following criteria:

1. The maintenance of a North-South and East-West baseline.
2. The logistical feasibility of a site (site must either have government or commercial assets currently in place or have sufficient infrastructure to support a ground station).
3. Redundancy.
4. Support of abort operations / anytime return.

Practically, criterion 1, 3, and 4 means continuous tracking from at least four trackers for most of the mission. Continuous tracking from three trackers (with at least one in the opposite hemisphere – North or South) would satisfy criterion 1 and 4, but such architecture would not be single fault tolerant to loss of the station located in the opposite hemisphere. For example, if two trackers were located in the Northern hemisphere and one in the Southern hemisphere, failure of the Southern hemisphere tracker causes a loss of North-South baseline observability.

To satisfy criterion 4, the Orbit MODE team considered sites from the Deep Space Network (DSN), the Department of Defense (DoD) – preferably sites with some tracking capability regardless of current ability to support lunar missions, and finally Universal Space Network's (USN) PrioraNet.

The Orion Orbit MODE team believes that a ground station architecture consisting of the stations listed in Table 1 (or with comparable geometry) is the minimum necessary in order to support lunar missions.

Table 1
ORION MODE TEAM GROUND STATIONS

Station	Notes
Goldstone, California	DSN Station
Santiago, Chile	USN Station
Ascension Island	Former Apollo station, C-band tracking facility
Hartebeesthoeck, South Africa	USN Station
Madrid, Spain	DSN Station
Dongora, Australia	USN Station
Guam	Former Apollo station, US military installation
Canberra, Australia	DSN station
Hawaii	USN Station

The nine stations were selected based on coverage and navigation analyses that will be discussed below. Note that the Orion analyses do not consider link budgets, tracking multiple vehi-

cles, redundancy of trackers at a particular site, etc. These studies assume that the trackers at the proposed sites are dedicated to the Orion vehicle and scheduling is also not an issue. In other words, the studies are purely an exercise in the geometrical sensitivities to ground station architectures.

The Spacecraft Tracking Data Network (STDN) simulation, which has been well documented, served as the primary analysis tool[3]. The assumptions and filter constraints do not deviate from the references. To evaluate navigation performance, single STDN runs were performed with a variety of navigation architecture assumptions. The covariances from these runs were then mapped to entry flight path angle uncertainty via Equation (1) and Equation (2)[*]:

$$\gamma_{EI} = \Psi \Phi P \Phi^T \Psi^T \tag{1}$$

where

$$\Psi = \frac{\partial \gamma}{\partial \bar{x}} \tag{2}$$

The primary trajectory for study is the CFP-1 trajectory[4], based on a seven day lunar surface stay with a 3.5 day return trajectory to Earth. If additional trajectories are utilized, they are noted appropriately. Recall that for Earth-return trajectories, entry flight path corridor uncertainty is desired to be less than 0.12°, 3σ, at entry interface. This figure includes knowledge and delivery errors, so the navigation accuracy will necessarily be some fraction of this corridor. The particular budgeting of this error is ongoing work within the design team.

Analysis Results

The initial backbone of any ground station architecture will most certainly be the DSN. For the purposes of these analyses, the DSN is assumed to consist of trackers located at Goldstone (California, USA), Madrid (Spain), and Canberra (Australia).

As mentioned previously, the DSN-only network is insufficient to support lunar missions because of its inability to generate short arc solutions, its potential lack of continuous tracking, and the lack of site redundancy. However, augmenting the DSN with USN trackers has been proposed. Therefore, consider a ground network consisting of the DSN augmented by Santiago, Hartebeesthoeck, and Dongora. As shown in Figure 6, this ground network architecture provides a significant gap in the North-South baseline coverage prior to Trajectory Control Maneuver 7 (TCM 7).

[*] Refer to the Notation section of this paper for a key of variables.

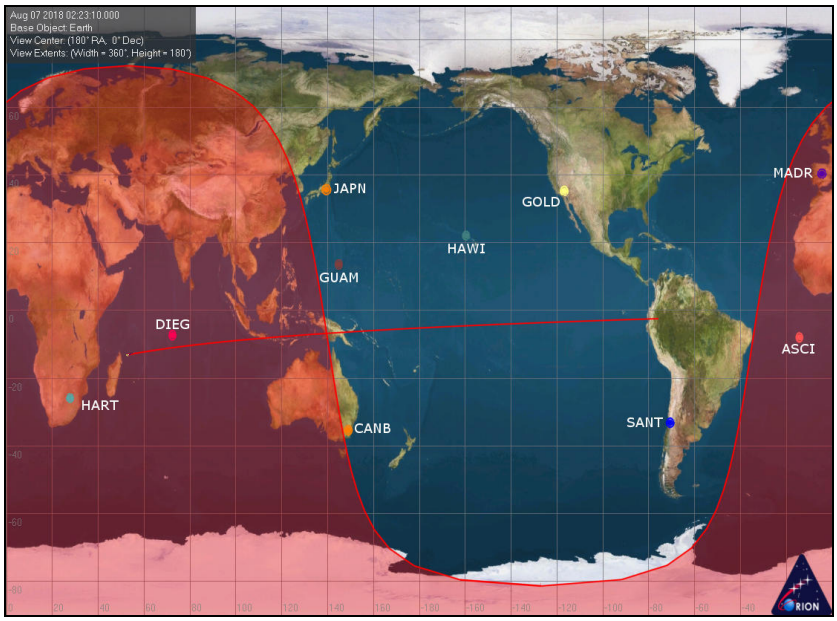

Figure 6: Ground Station Visibility at TCM-7. Note trajectory moves from East to West.

An examination of Figure 7 demonstrates how the entry flight path angle uncertainty is increased during the periods of tracking with just Dongora, Hartebeesthoek, and Canberra (all Southern hemisphere stations) which has a poor North – South geometry.

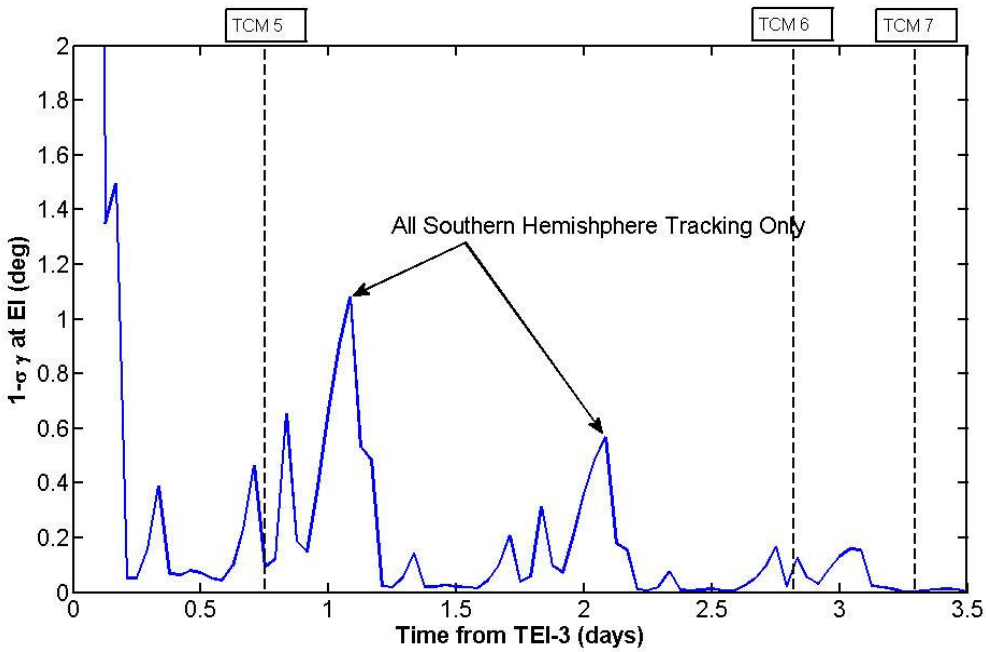

Figure 7: 1σ Entry Flight Path Angle uncertainty for Earth-return trajectory for a ground station architecture consisting of DSN augmented with Santiago, Hartebeesthoek, and Dongora.

Initially, it was thought that a ground station at Guam would close the gap for the North-South baseline. However, two issues arise with selection of Guam:

1. Guam's longitude is close to that of Canberra meaning that the East-West baseline may not be sufficient.
2. As will be shown later, the navigation performance of this six station network augmented with Guam quickly deteriorates past the CFP-1 TCM's .

Because of this, Hawaii was found to be more effective with respect to the navigation performance and the Orion operational timeline. To illustrate this, consider Figure 8.

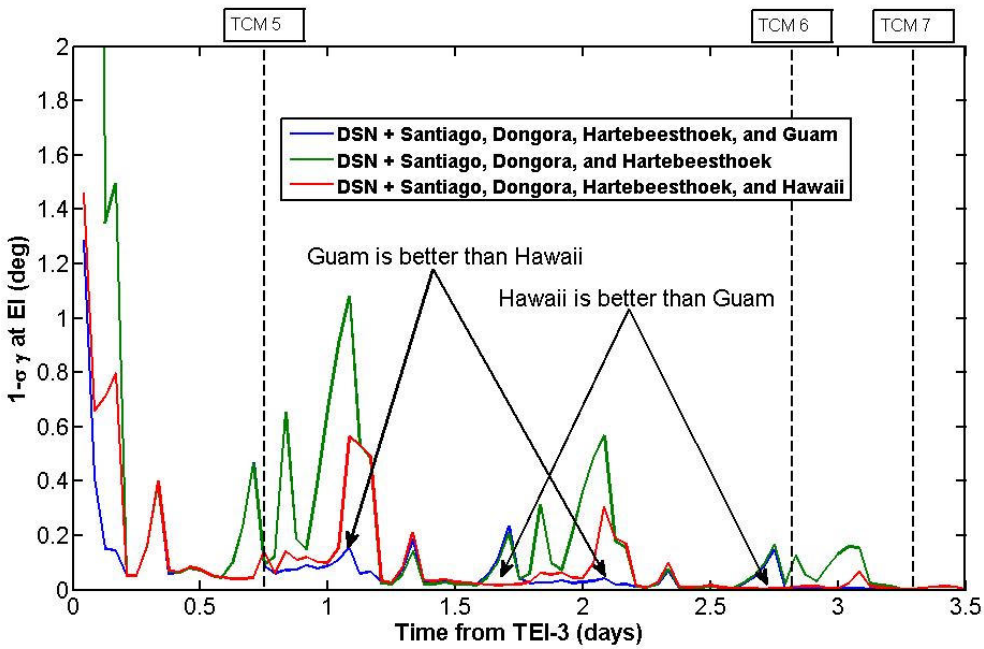

Figure 8: 1σ Entry Flight Path Angle for Earth-return trajectory for a ground station architectures consisting of DSN augmented with Santiago, Hartebeesthoek, and Dongora. Architectures are then traded with Guam and Hawaii

In Figure 8, the entry flight path angle uncertainty for the same Earth return trajectory utilized in Figure 7 is plotted. However, two additional runs are included, one with Hawaii and one with Guam. While utilizing Guam generally results in better navigation performance, near TCM-6 the uncertainty in the entry flight path angle starts to increase. Operationally, if TCM-6 were to be delayed a few hours, the navigation uncertainty will increase. Conversely, the utilization of Hawaii provides consistent navigation performance about TCM-6. Therefore, it is more desirable to have Hawaii rather than Guam in the navigation architecture.

Note that at this point, a seven station ground architecture has been derived that satisfies criterion 1 and 2 for the *nominal* timeline for a *specific* Earth return trajectory only. A closer look at Figure 8 shows that there are significant spikes in entry flight path angle uncertainty, due to poor tracking geometry, that could make it problematic for abort operations or anytime return. This is particularly true if an abort operation necessitates a maneuver during one of these spikes. Therefore, it is desirable to have a navigation architecture capable of minimizing or eliminating these spikes throughout a mission. Additionally, criterion 3 - redundancy - has yet to be addressed.

To begin, adding Guam to the seven station network would add an additional level of redundancy for the periods of tracking where Hawaii would be the only Northern hemisphere tracking facility. In other words, with the addition of Guam, the ability to have North-South observability would be single-fault-tolerant to loss of Hawaii. This is particularly important since this tracking geometry (Pacific Ocean sites) currently manifests itself near the TCM maneuvers.

While the addition of Guam helps, a closer examination of Figure 8 reveals periods where the flight path angle uncertainty grows at the same rate and magnitude for the networks studied to date. Specifically, the flight path angle uncertainty spikes between day 1 to day 1.5 and day 2 and 2.5. To further illustrate this, consider Figure 9 which plots the entry flight path angle uncertainty for an Earth return trajectory utilizing the DSN, Santiago, Hartebeesthoek, Dongora, Guam and Hawaii.

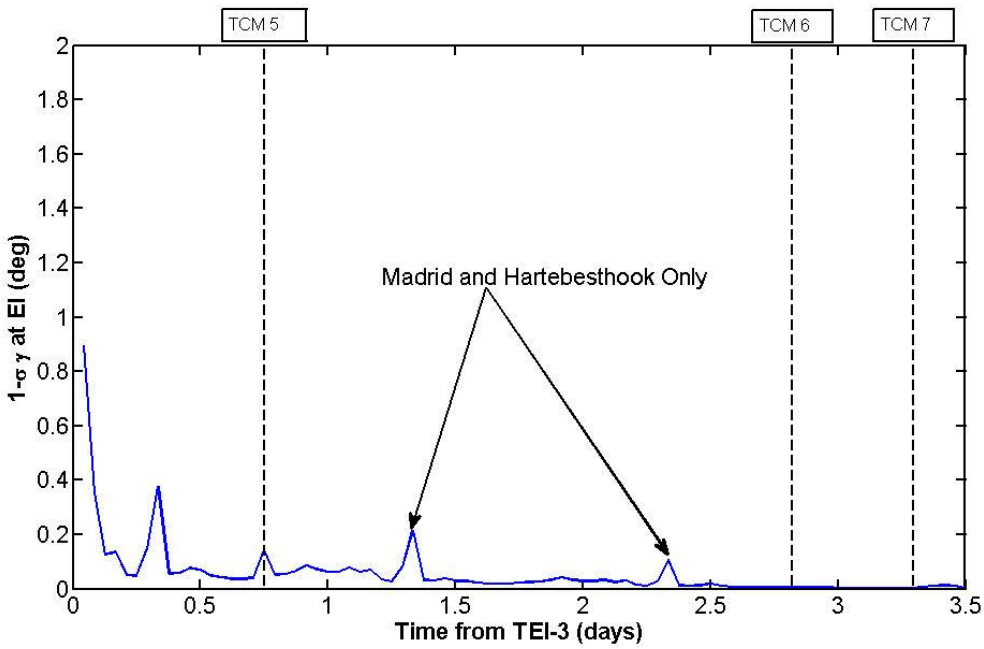

Figure 9: 1σ Entry Flight Path Angle for an Earth-return trajectory utilizing DSN, Santiago, Hartebeesthoek, Dongora, Guam and Hawaii

The growth in these uncertainties is due to tracking only available from Madrid and Hartebeesthoek. This combination of stations has weak observability into the East-West baseline and is obviously not redundant. Therefore, to close this tracking gap, locating a tracker in the Atlantic Ocean would be optimal.

Two tracking site locations were considered in order to close this "Atlantic Ocean" gap. The first is located at Merritt Island, Florida where a soon to be decommissioned Apollo tracking facility still exits. The other site is Ascension Island, where C-band tracking facilities currently exist. Figure 10 compares the navigation performance from the eight station network augmented with either Merrit Island (MILA) or Ascension Island.

These results indicate that Ascension Island rather than Merrit Island is more effective at closing the geometrical observability gap, which matches the Figure 5 result showing minimal common visibility between MILA and Madrid or Canberra. Therefore, a nine station network consisting of the DSN, Santiago, Ascension Island, Hartebeesthoek, Dongora, Guam, and Hawaii has

been shown to constantly provide the requisite geometrical observability for an Earth return trajectory to support a nominal mission and any time return or abort.

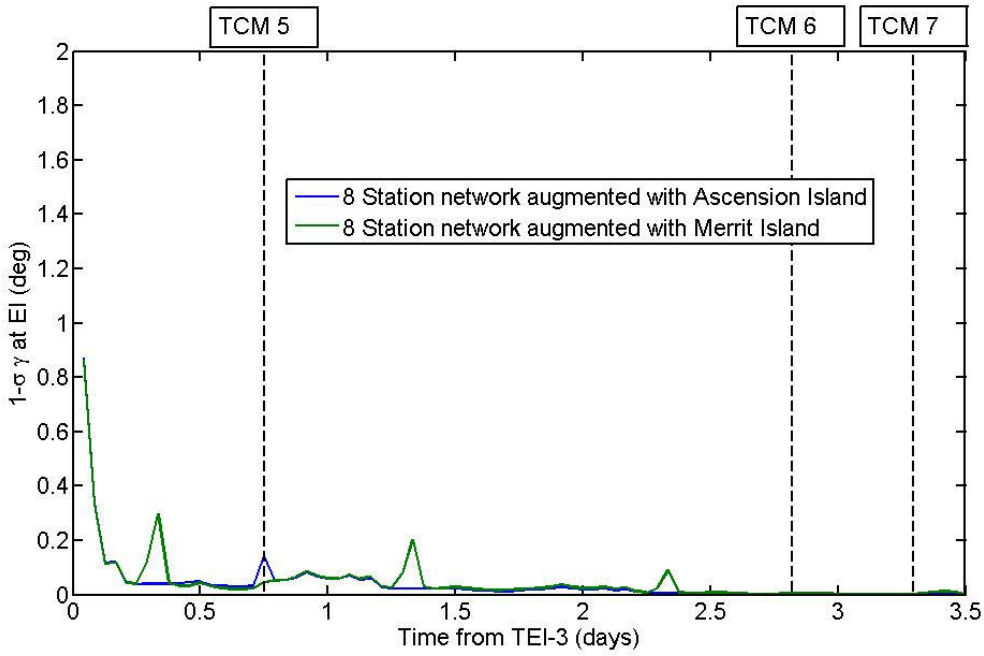

Figure 10: 1σ Entry Flight Path Angle uncertainty for an Earth return trajectory utilizing DSN, Santiago, Hartebeesthoek, Dongora, Guam, Hawaii and either MILA or Ascension Island

Because this network is nicely scattered about the Earth, Figure 11 demonstrates it provides near continuous tracking from at least four trackers and continuous tracking from three trackers (except close to the Earth where such geometry is not feasible and not needed).

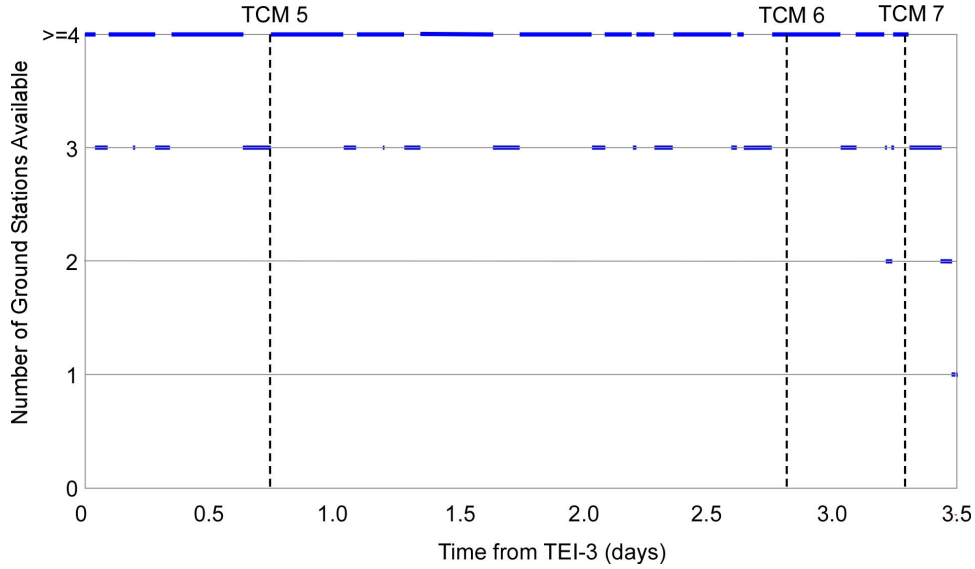

Figure 11: Number of trackers available for nine station architecture on a lunar return

Therefore, as all Orion entry trajectories will converge to the same Earth fixed entry corridors, it is a reasonable expectation that such a 9 station network will provide the necessary coverage for almost any feasible trajectory. To be sure, a run was conducted for a trajectory segment between TEI-2 and TEI-3 for the case when the Moon is located at the minimum Earth fixed latitude. This particular trajectory was fairly troublesome as the DSN only network was unable to provide continuous tracking and communications because Canberra is on the far side of the Earth. Figure 12 demonstrates that not only is there continuous tracking with this 9 station network, but for the entire arc there are at least three stations tracking concurrently and for most of the arc at least four stations are tracking.

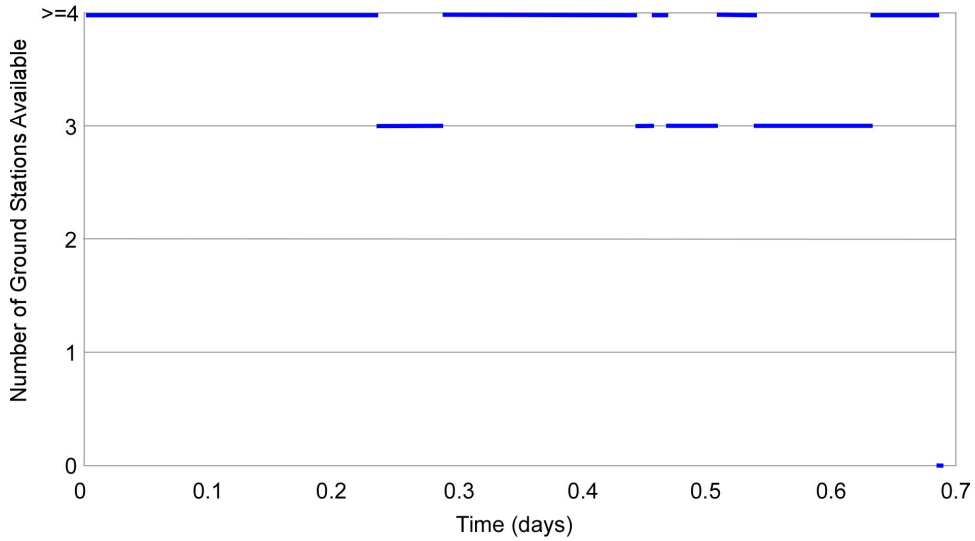

Figure 12: Number of trackers available for low Earth fixed lat. from TEI-2 to TEI-3

CONCLUSION

Based on completed Orion analyses, Orion Orbit MODE Team engineers have determined geometric sensitivities of navigation performance to ground station architectures. Leveraging off of this knowledge, Orion Orbit MODE Team engineers selected candidate ground stations from existing NASA, DoD, or commercial assets.

From these studies, the Orion Orbit MODE team feels that a minimum ground station architecture should include the geometric equivalent of DSN, Santiago, Hartebeesthoek, Dongora, and Hawaii. However, such a network would not necessarily be able to support abort operations / any-time return and is not site redundant. To address these issues, the Orion Orbit MODE team feels that a ground station architecture should also include assets at Guam and Ascension Island.

Finally, it should be noted that the work here presented is not a promotion of any particular lunar navigation architecture. The Orbit Orion MODE is open to nearly any and all manifestations of a lunar navigation architecture as long as it has the performance characteristics (accuracy and short arc capability described above). It is left as open work to develop metrics that will allow for the characterization of the performance of various architectures that is independent of mission phase. It is also important to ensure that such metrics correspond to navigation performance, short arc capability, and applicability to various architectures. Since geometry has been identified as a driving consideration, an evaluation of various dilution of precision algorithms is currently under way.

ACKNOWLEDGMENT

The authors would like to give their continual thanks to Dr. Timothy Crain, the Orion Orbit GNC MODE team lead, for his technical leadership in this effort.

NOTATION

γ	Flight path angle
Φ	State transition matrix
Ψ	Matrix of Partial Derivatives (flight path angle with respect to the state)
CARD	Constellation Architecture Requirements Document
DoD	Department of Defense
DSN	Deep Space Network
EI	Entry interface [defined in NASA programs at an altitude of 121.92km (400,000 ft)]
GPS	Global Positioning System
LOI	Lunar Orbit Insertion
IMU	Inertial Measurement Unit
P	The navigation covariance matrix
SRD	Subsystem Requirements Document
STDN	Spacecraft Tracking and Data Network
TEI	Trans-Earth Injection
TCM	Trajectory Correction Maneuver
TLI	Trans-Lunar Injection
USN	Universal Space Network
x	Orion inertial six element state

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